

A Study on High-Accuracy and Efficient Machining Utilizing Water with Compound for Environmental Conservation

(環境保全のために水を使用した高精度・高効率な加工に関する研究)

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ABSTRACT

Eco-friendly manufacturing associated with energy saving has become common request in today's industrial activities. Enhancing machining performances for the improvement of product's quality, time-saving, and low-cost production are also essential. One approach to enhancing machining performance is to apply cutting fluids during machining. However, the usage of cutting fluids in machining process has effects on both environment and human health. Meanwhile, usage of water in machining is still restricted. Therefore, the objective this study is to developed some countermeasures for utilizing water during machining and at the same time reduces the environmental impact. Thus, the alternative cooling of using strong alkaline water was proposed and evaluated to obtain its impacts on these aspects. In this study, some proposed techniques for using water during machining were developed. Since resonance of a machine tool is difficult to avoid without changing the cutting condition, therefore, the simple and easy technique to change machine tool resonant frequency was developed in order to maintain the cutting condition. In this study, the use of the water mixed with polymer PEO to change machine tool resonance frequency is proposed. To achieve the optimum result, this method was combined with the reinforcing of machine structure and the changing of the position of support's point. The effectiveness of this study was later evaluated by the real cutting experiment to measure the surface roughness of the cutting result. It was observed from this study that water can be used to change the machine tool resonance. Besides using water for controlling machine resonance, a new cooling technique of using strong alkaline water for drilling was also developed. Since strong alkaline water consists of 99.9% water, the test by submerging various types of machine tool related materials in it was firstly performed to investigate the effect of strong alkaline water in inducing corrosion. For improving cooling efficiency, the

method by supplying strong alkaline water with microbubbles was developed. The evaluation was later done by performing drilling test using a trough-hole drill. At final, the cutting tool life and cutting surface roughness are investigated and evaluated by experiments. Since the result of drilling by cooling using strong alkaline water is better than the conventional cooling, another cooling method was proposed by submerging the machine tool completely in the strong alkaline water. This method was proposed with an objective to suppress thermal deformation of the machine tool. In the evaluation of this method, the changes in the temperature of machine body without submerging, with submerge condition in the strong alkaline water, and by adding with microbubble were all investigated. The thermal deformation of the bench lathe machine was measured and compared. Since cutting evaluation using the bench lathe machine during immersion condition is difficult, the evaluation was performed by cut under strong alkaline water using the NC milling machine. Lastly, the tooltip temperature, the cutting tool life, and the cutting surface roughness are all investigated and evaluated by experiments. In addition, the simple assessment of the environmental impact is also performed by comparing the conventional wet cutting and cutting using cooling of strong alkaline water.

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CONTENTS

ABSTRACT.....	iii
ACKNOWLEDGEMENT.....	v
CONTENTS.....	vii
LIST OF TABLES.....	xi
LIST OF FIGURES.....	xii
 Chapter 1: INTRODUCTION	 1
1.1 The importance of the environmental conservation.....	1
1.2 Utilization of water in manufacturing	2
1.3 The effect of water to the quality of cutting process	3
1.4 Conventional utilization of water in machining.....	5
1.5 Objective of research, scope, and composition of thesis.....	7
 Chapter 2: PROPERTIES OF WATER	 13
2.1 General properties of water	13
2.2 Properties of water relating to the industrial application.....	14
2.2.1 Cleaning agent.....	14
2.2.2 Water's specific heat.....	17
2.2.3 High evaporative cooling	18
2.2.4 Density	18
2.2.5 Induce corrosion.....	19
2.3 Alkaline water as a coolant.....	21
2.4 Process of alkaline production.....	23
 Chapter 3: DEVELOPMENT OF CONTROL TECHNIQUE REGARDING RESONANCE ON A MACHINE TOOL FOR THE ESTABLISHMENT OF OPTIMUM CUTTING CONDITION	 25
3.1 Introduction	25
3.1.1 The effect of the machine resonance to the cutting process	27

3.1.2 Conventional countermeasures for avoiding resonance on machine tool	28
3.1.3 Control methods to control density, stiffness and support position	30
3.1.4 Proposed method for controlling resonant frequency	31
3.2 Investigation using CAE simulation for the control factors (density, stiffness and supports).....	36
3.2.1 Injection of water for reducing resonant frequency.....	38
3.2.2 Reduce weight (lower density) and reinforce the structure (higher rigidity) for increasing resonant frequency	44
3.2.3 Changing support positions for changing resonant frequency and its mode shapes.....	50
3.3 Experimental evaluation for control method using bench lathe.....	52
3.3.1 Experimental evaluation for control method using bench lathe machine.....	54
3.3.1.1 Control factor I	54
3.3.1.2 Control factor II.....	57
3.3.1.3 Control factor III.....	60
3.3.2 Optimum combination for three countermeasures of control factors.....	63
3.4 Evaluation by real cutting.....	65
3.5 Summary.....	69
 Chapter 4: DEVELOPMENT OF FORCED COOLING TECHNOLOGY ON DRILLING USING ALKALINE WATER WITH MICROBUBBLE	
4.1 Introduction	71
4.2 The characteristic of the strong alkaline water added with microbubbles	72
4.2.1 The characteristic of strong alkaline water	72
4.2.2 The characteristic of the microbubbles	76
4.3. Drilling processing by supplying strong alkaline water mixed with microbubble on the through-hole drill.....	83
4.3.1 Tool temperature	83
4.3.2 Surface roughness	86
4.3.3 Tool life	90
4.4. Summary.....	93

Chapter 5: DEVELOPMENT OF IMMERSED MACHINE TOOL AND MACHINING IN THE STRONG ALKALINE WATER FOR REDUCTION OF CO ₂	95
5.1 Introduction	95
5.1.1 Research background	95
5.1.2 Proposed technique	96
5.2 Corrosion resistance of machine elements in strong alkaline water	97
5.3 Improvement of heat transfer coefficient of strong alkaline water by adding microbubbles	104
5.4. Investigation of the vibration, thermal deformation of bench lathe and the processing quality under immersed condition	108
5.4.1 Investigation of the vibration	110
5.4.2 Investigation of the temperature change and thermal deformation.....	113
5.4.3 Processing quality of immersed cutting method.....	122
5.4.3.1 Evaluation of tool tip temperature	123
5.4.3.2 Evaluation of tool life	125
5.4.3.3 Evaluation of surface roughness	126
5.5 Summary.....	128
 Chapter 6: ENVIRONMENTAL IMPACT OF MACHINING USING COOLING OF STRONG ALKALINE WATER	129
6.1. Introduction	129
6.2. Study method for the assessment of strong alkaline water.....	130
6.2.1 Goal and scope of the study	130
6.2.2 Study method	131
6.2.3 Calculation approaches	132
6.3 Simple assessment for machining using cooling of strong alkaline water.....	133
6.3.1 Inventory for development of cutting technology under strong alkaline water with microbubbles	133
6.3.2 Inventory of drilling technology using strong alkaline water with microbubbles	136
6.3.3 Inventory for immersing machine tool and machining in the alkaline water for CO ₂ reduction.....	140

6.4 Impact analysis for machining using strong alkaline water	143
6.4.1 Impact to the environment	143
6.4.2 Impact to the human health	147
6.5 Summary.....	149
 Chapter 7: CONCLUSIONS	151
 REFERENCES	157
 APPENDICES.....	171
1. Appendix I: Dissertation in Japanese version	
2. Appendix II: Dissertation in Tetum version	

LIST OF TABLES

Table 2.1 Important compounds for alkalinity	23
Table 3.1 Explanation of three parameters for resonant frequency control	32
Table 3.2 Properties of the PEO polymer.....	35
Table 3.3 Specification of the bench lathe for experiment.....	53
Table 3.4 Parameter for control factor I	54
Table 3.5 Parameter for control factor III.....	60
Table 3.6 Optimum combination for three countermeasures	63
Table 3.7 Cutting condition for evaluation of this method.....	66
Table 4.1 The specification of strong alkaline water device.....	73
Table 4.2 Test condition for changes of alkaline water pH.....	73
Table 4.3 Condition for corrosion test.....	75
Table 4.4 Results of the materials tested in strong alkaline water with pH12.5 (for two month).....	75
Table 4.5 Specification of microbubble device	76
Table 4.6 Specification of NC milling machine used in experiment	87
Table 4.7 Drilling condition for evaluation of forced cooling of alkali water with microbubble	88
Table 5.1 Specification of the strong alkaline water device.....	98
Table 5.2 Condition for the corrosion test.....	98
Table 5.3 Results of the proof test for two month in alkaline water with pH12.5 ...	102
Table 5.4 Specification of the bench lathe for experiment.....	109
Table 5.5 Cutting conditions for evaluation of tool tip temperature	124
Table 5.6 Cutting conditions for evaluation of tool life	125
Table 6.1 CO ₂ emission of conventional wet cutting and cutting under strong alkaline water with microbubbles.....	135
Table 6.2 CO ₂ emission of the conventional wet cutting and drilling using cooling of strong alkaline water with microbubbles.....	139
Table 6.3 CO ₂ emission of conventional wet cutting and cutting by submersion machine tool in strong alkaline water.....	142
Table 6.4 Properties of strong alkaline water	148
Table 6.5 Effect of strong alkaline water to human health.....	148

LIST OF FIGURES

Fig.1.1 Flow chart of this research on high-accuracy and effective manufacturing utilizing water for environmental conservation.....	8
Fig.2.1 pH value of some common substance	15
Fig.3.1 Resonance modes from preliminary results of free vibration analysis	29
Fig.3.2 Schematic view of several techniques for controls of appearance density and stiffness in a machine tool	30
Fig.3.3 Explanation of several parameters and countermeasures for the control of the resonance frequency in a machine tool	34
Fig.3.4 Experimental setup and photograph of method to measure damping ratio of water and polymer	35
Fig.3.5 Curve fit of damping ratio measurement between experimental and simulation	35
Fig.3.6 The relationship between polymer percentage and damping ratio (Experimental result)	36
Fig.3.7 FEM model for investigation for influence regarding density, stiffness, and supports	37
Fig.3.8 Frequency response of the bench lathe with different densities (Calculation using FEM)	39
Fig.3.9 Frequency response of the bench lathe with different stiffness (Calculated using FEM).....	45
Fig.3.10 Frequency response of bench lathe with different supports (FEM calculation).....	51
Fig.3.11 Photograph of the experimental setup.....	53
Fig.3.12 Experimental set up and the model of bench lathe machine	53
Fig.3.13 Model and photograph of the experimental setup for control factor I	54
Fig.3.14 Relationship between spindle speed (in resonance) and the amplitude of vibration by control of density (Experimental results).....	55
Fig.3.15 Model and photograph of the experimental set up for control factor II.....	57

Fig.3.16 Relationship between spindle speed and the amplitude of vibration by control of stiffness and light weight (Experimental results)	58
Fig.3.17 Model and figure of the experimental setup for control factor III and the model of bench lathe	60
Fig.3.18 Relationship between spindle speed (in resonance) and the amplitude of vibration by control of support (Experimental results)	61
Fig.3.19 Amplitude of vibration at optimum density, stiffness and support (Experimental results)	64
Fig.3.20 The photograph of bench lathe machine with combination control.....	66
Fig.3.21 Frequency response of the bench lathe with control of resonance frequency (Experimental results)	67
Fig.3.22 Amplitude of vibration when operating machine at 2784 min^{-1}	67
Fig.3.23 Result of vibration oscillation of bench lathe during cutting from Y direction (Experimental results)	68
Fig.3.24 Surface roughness of the work piece using control resonant frequency (Experimental result).....	68
Fig.4.1 Variation of pH values at different temperatures	74
Fig.4.2 Photograph of microbubbles device	76
Fig.4.3 Distribution of bubble size in microbubbles ^[4-10]	77
Fig.4.4 Experiment setup for measurement of the lifetime of air bubbles in alkaline water.....	77
Fig.4.5 Appearance of different bubble sizes in strong alkaline water inside vessel.....	78
Fig.4.6 Relation between bubble size and its life in strong alkaline water	78
Fig.4.7 Experimental setup for measuring amount of microbubble in alkaline water	79
Fig.4.8 Experimental results for amount of air in alkaline water.....	80
Fig.4.9 Experimental setup for measuring heat transfer coefficient of alkaline water with bubbles.....	81
Fig.4.10 Photograph of the rubber heater	81
Fig.4.11 Photograph of the pump	81
Fig.4.12 Relationship between the water quantity and the heat transfer coefficient.....	82

Fig.4.13 Experimental setup and position of thermocouples for measuring temperature on the edge of the drill	83
Fig.4.14 Photograph and the specification of ceramic heater	84
Fig.4.15 Temperatures on the edge of the drill for different cooling conditions	85
Fig.4.16 NC milling machine used in the experiment (Unit: mm).....	87
Fig.4.17 Experimental setup of evaluation by drilling	88
Fig.4.18 Surface roughness of the hole of the drilling using the forced cooling of strong alkaline water with microbubble.....	89
Fig.4.19 Photograph of edge of the drill for the judgment of the tool life	90
Fig.4.20 Relationship between the softening factor and the temperature ^[4-11]	91
Fig.4.21 Results of tool life regarding the drill using the forced cooling of alkaline water with microbubble	92
Fig.5.1 Photograph of the parts in strong alkaline water.....	99
Fig.5.2 Corrosion and discoloration by strong alkaline water.....	100
Fig.5.3 Bubble size distribution of micro bubble ^[4-10]	104
Fig.5.4 Relationship between bubble size and its life in strong alkaline water.....	105
Fig.5.5 Experimental setup for measuring heat transfer coefficient.....	106
Fig.5.6 Photograph of the experimental setup.....	106
Fig.5.7 Average temperature for various cooling methods	107
Fig.5.8 Relationship between alkaline, microbubble and 3600 min^{-1} with the heat transfer coefficient	108
Fig.5.9 Photograph of the experimental setup.....	109
Fig.5.10 Experimental setup for measuring amplitude of the vibration	110
Fig.5.11 Bench lathe resonant frequency measurement result by impact test.....	111
Fig.5.12 Amplitude of bench lathe operated coincides with machine resonance at 996 min^{-1}	112
Fig.5.13 Amplitude of bench lathe operated coincides with machine resonance at 3000 min^{-1}	113
Fig.5.14 Schematic view of the experiment using the bench lathe in strong alkaline water with microbubble	114

Fig.5.15 Temperature change of the bench lathe operated in different spindle speed	115
Fig.5.16 Schematic view of dial gauges setup for thermal deformation measurement.....	117
Fig.5.17 Thermal deformation of the bench lathe in strong alkaline water with microbubbles at the spindle speed 996 min^{-1}	118
Fig.5.18 Thermal deformation of the bench lathe in strong alkaline water with microbubbles at the spindle speed 3000 min^{-1}	119
Fig.5.19 Thermal deformation of the bench lathe in strong alkaline water with microbubbles at the spindle speed 3600 min^{-1}	121
Fig.5.20 Photograph of NC milling (Unit: mm).....	122
Fig.5.21 Experimental setup for measurement of tool temperature	123
Fig.5.22 Experimental results for tool tip temperature.....	124
Fig.5.23 Experimental setup for evaluation of tool life.....	125
Fig.5.24 Results of the tool life	126
Fig.5.25 Photograph of the surface roughness measuring device	127
Fig.5.26 Results of the surface roughness	127
Fig.6.1 Flow chart of LCA for conventional wet cutting and strong alkaline water.....	132
Fig.6. 2 Comparison of CO_2 emission for cutting inside strong alkaline water and microbubbles.....	144
Fig.6.3 Comparison of CO_2 emission for drilling using strong alkaline water with microbubbles	145
Fig.6.4 Comparison of CO_2 emission for machining under immersion of machine tool	146
Fig.6.5 Comparison of the potential impact to the global warming	147

Chapter (1)

INTRODUCTION

1.1 The importance of the environmental conservation

Nowadays, high-quality manufacture associated with environmental conservation is highly demanded in manufacturing and production. Since technology improvements enable people to conduct many aspects of operations far more efficiently now than a decade ago, consideration for environmental preservation is becoming increasingly important in product design and manufacture processes. Meanwhile, industry practices of safe operations and environmental protection have also evolved significantly in the past few decades. The various energy sources have been discovered ^{[1-1], [1-2]}, the high precision machineries have been built ^{[1-3], [1-4]}, and high-quality products have been produced to satisfy customers. However, researchers must consider in prioritizing environmental issues during production and manufacturing. Hence, improvement can be made without jeopardizing the environment. In addition, due to the pressure of pollution and technology, the biophysical environment is being degraded along with the time pass. Therefore, the awareness on the environmental issue has been created in order to prevent from the pollution and a harmful condition. Moreover, since global warming has become a major concern in recent years, environmental safety and prevention has become a main task which needs to be taken into account by engineers and researchers in producing and manufacturing new products.

Many approaches have been applied to conserving the environment in every area ^{[1-5], [1-6]}. In manufacturing and production, the environmental protection can be implemented in several ways, such as by cleaning manufacturing and

improving waste management or pollution controlling ^{[1-7], [1-8]}. The clean manufacturing is the approach that reduce, avoid, or eliminate the unnecessary use of harmful industrial materials and the generation of industrial wastes, pollutants, emissions, and discharges at the point of production, while the waste management or pollution control consist of environmental protection after industrial wastes, pollutants, discharges, and emissions have been generated. Given that water is the easiest substance that can be found on the earth, hence in this research, the clean manufacturing and waste management or pollution control approaches will be adopted to achieve high quality manufacturing and environmental safety by using water.

1.2 Utilization of water in manufacturing

Water is one of the most important substances on the earth that gives life. It can be found anywhere and used as primary needs in daily life. For industrial and manufacturing sectors, water is one of the resources that needed most. Industries that produce metals, woods, papers, chemicals, gasoline, oils, and other products use water in some part of their production process. For this reason, industries are reliant on water for all levels of production. It can be used as a cleaning agent, solvent, coolant, transport agent, and energy source. Most of the industrial water usage is manufacturing-related. Since many manufacturing processes produce large amounts of heat due to friction and chemical reactions, water is used to cool down machineries and equipments. Water is also used for lubricating and cleaning. Sometimes it is also included in products themselves, such as in food and beverage manufacturing. There are many applications of industrial water usage; however, virtually every manufactured product at some point requires water. As the technology advances, companies and researchers start to realize that water is one of the most important

resources that should be available to the industrial sector, hence the use of water in the industry is gradually improving. However, the direct use of water is still restricted in some area of manufacturing, like in metalworking production. The restriction of using water during machining is that water induces corrosion on the processing workpieces^{[1-9],[1-10]}. However, since water is the element that is easy to obtain, easy transport in large amount, and friendly to the environment, the present study is focused on developing new approaches for using water in machining. In fact, many methods and approaches using water-based coolant as cutting fluid have been developed^{[1-11],[1-12],[1-13]}, while most of the coolants contain additives to prevent corrosion and improve cooling efficiency. However, since some of the additives may not be friendly to human health and environment, the method of using high pH of water for machining is introduced in this study. This method can be used for reducing cutting heat generation on the tooltip and workpieces by the high cooling effect from the water. Given that the chemical passivity of materials in the water varies based on the pH level, further investigation is required. Nevertheless, it is expected that by using water with high pH, the cooling effect can be improved, processing cost can be reduced, and at the same time improve cutting accuracy and longer tool life. In addition, healthy environment can be maintained, hence will improve the ecosystem, human health, and well-being.

1.3 The effect of water to the quality of cutting process

As stated earlier, water is important and used almost in every sector of industries, however, the direct usage of water during cutting is still avoided. For this cause, the use of water for manufacturing is still very low. The corrosion that caused by water is negatively affecting product's improvement. In fact, that corrosion is a natural process, it occurs in an environment where the water presents. Just like water flows to the lowest level, all natural processes tend

toward the lowest possible energy states. For instance, iron and steel have a natural tendency to combine with other chemical elements to return to their lowest energy states. They frequently combine with oxygen and water, both of which are present in most natural environments, to form hydrated iron oxides which cause rusting. Yet, they are not single corrosion causer, other factors such as temperature, total dissolved mineral content, calcium hardness, alkalinity, and pH of the water are the other causes. In addition, the corrosion behavior of the material depends on the environment to which it is subjected, and the corrosive of an environment depends on the material exposed to that environment.

Corrosion in manufacturing has many negative impacts. When metal is corroded by water in manufacturing, it can affect the accuracy and the precision of the product. It also causes a defect on the workpiece and consequently brings the product's value down. In addition, corrosion can cause machine tools and precision equipments lose their efficiency, sudden failure, breakdown and shorter their life span. Other consequences to the environment will likely continue. The pollution due to escaping product from corroded equipment or due to a corrosion product itself can affect human health and integrity of aquatic ecosystems. The sudden failure of the machineries and equipments can cause breakdown of machines, fire, explosion, release toxic product which is considered unsafe for the environment. Moreover, the corrosion also affects the economic aspect that will lead to low market value.

On the other hand, apart from the corrosion disadvantage, there are more advantages that water can offer when corrosion phenomenon is prevented. The advantages are:

- High cooling effect,
- Availability and easy to obtain,
- Avoid waste,

- Low cost,
- Easy to transport,
- Environmentally friendly

With these advantages, many scholars have started to investigate early prevention of corrosion that caused by water.

1.4 Conventional utilization of water in machining

Although utilization of water during machining is still very low, it is growing. There are few conventional methods of using water for cooling and environmental care reasons. Some of these methods are:

[1] Cooling by water-based coolant,

[2] Lubrication

[3] Cleaning agent

However, the application of water by these methods is still not satisfactory.

For the fact [1], although the cooling by water-based coolant during machining is widely used in almost all production, the mix with the additive for corrosion prevention is a drawback. In fact, that some of the additives may contain an unknown chemical substance that can be harmful to the environment and human health for a period of time, this is undesirable ^{[1-14], [1-15]}. In addition, from the economic point of view, the cost of purchasing, transporting and disposing is considered high. Furthermore, since the coolant and solvent should not be disposed in any open environment, the disposal cost can become higher. Consequently, the demand for the improvement of the coolant and cutting fluid quality for environmental perspective is increasing in recent years. Thus, a water-based coolant is still not optimal and requires improvement.

For the fact [2], the usage of water for lubrication still low in industries and manufacture. The reason is that water has a faster rate of evaporation than oil or grease, therefore miscible oil is preferred for lubrication than water-miscible. Besides water evaporates easily when exposed to heat, it also causes rust and damages metal parts which would shorten machine tool's life. In addition, its fluidity makes it hard to keep in place, thus required to be reapplied frequently. However, regarding the environmental concern and the availability of its source, water is preferred most once the corrosion phenomenon is prevented. Till the present time, some researchers have studied for using water based fluid for lubrication ^{[1-16], [1-17]}. Nevertheless, since they are still not satisfiable, more improvement is required to increase the quality of lubrication and corrosion prevention.

For the fact [3], water based cleaning agent are widely used in industries and manufacture. For non-metal product, it can easily use water as a cleaner, however for metal material, water needs to be mixed with rust inhibit such as additive and solvent before used as a cleaner.^{[1-18],[1-19]} Some water-based cleaning agents use alkaline water with pH above 8.5 to dissolve and ease grease, oils, and fats. Other use water mixed additive for cooling and as cleaning agent to wipe chips away during cutting such as in grinding processing. Outside manufacture and machining area, there are many applications of using water as a cleaning agent compared to the water application during machining. Hence, the development on water as a cooling agent is needed for machining to improve the manufacture that care and friendly to the environment. With these facts, it is noted that there are not many application of water in machining; therefore, this study aims to develop and introduce the use of water in machining for environmental protection without degrading the quality and accuracy of the final result of production.

1.5 Objective of research, scope and composition of thesis

The objective of this research is to develop new methods of utilizing water for high-accuracy and effective machining for environmental conservation. By using water for cooling during the cutting process, the cooling effect can be improved, heat generating during cutting can be minimized, and the waste from machining can also be reduced. The improvement in cooling effect can suppress heat generation in tool tip and workpiece that can improve surface accuracy of the final result of the cutting. Meanwhile, the reduction of machining waste helps in lowering disposing cost and minimizes emitted gasses that hazardous to the environment and human health. Moreover, because of its expediency, availability, and fluidities, water can be easily managed and transported anywhere. Thus, this research is performed to define approaches for utilizing water in manufacturing and industries. The procedure and flow of the research are shown in Fig. 1.1. Chapter one (1) is the introduction of the paper which presents the background, objective, and brief information about the past and present approaches regarding the usage of water in manufacturing. In the chapter two (2), the property of water will be discussed and the corrosion resistance of various materials in water will be presented. In addition, the relationship between corrosion resistances to the alkaline water will also be evaluated and discussed to improve the resistance of materials to the corrosion phenomenon. In the chapter three (3), the proposed control techniques to control resonant frequency on the machine tool for establishment of an optimum cutting condition will be presented. The bench lathe machine will be used in this for the experiment. The control method will be presented and the optimum combination of three control factors will be evaluated and proposed as the optimum control technique. In the chapter four (4), the drilling technology using strong alkali water with microbubble will be discussed. A method to improve the cooling effect will be developed on the drill.

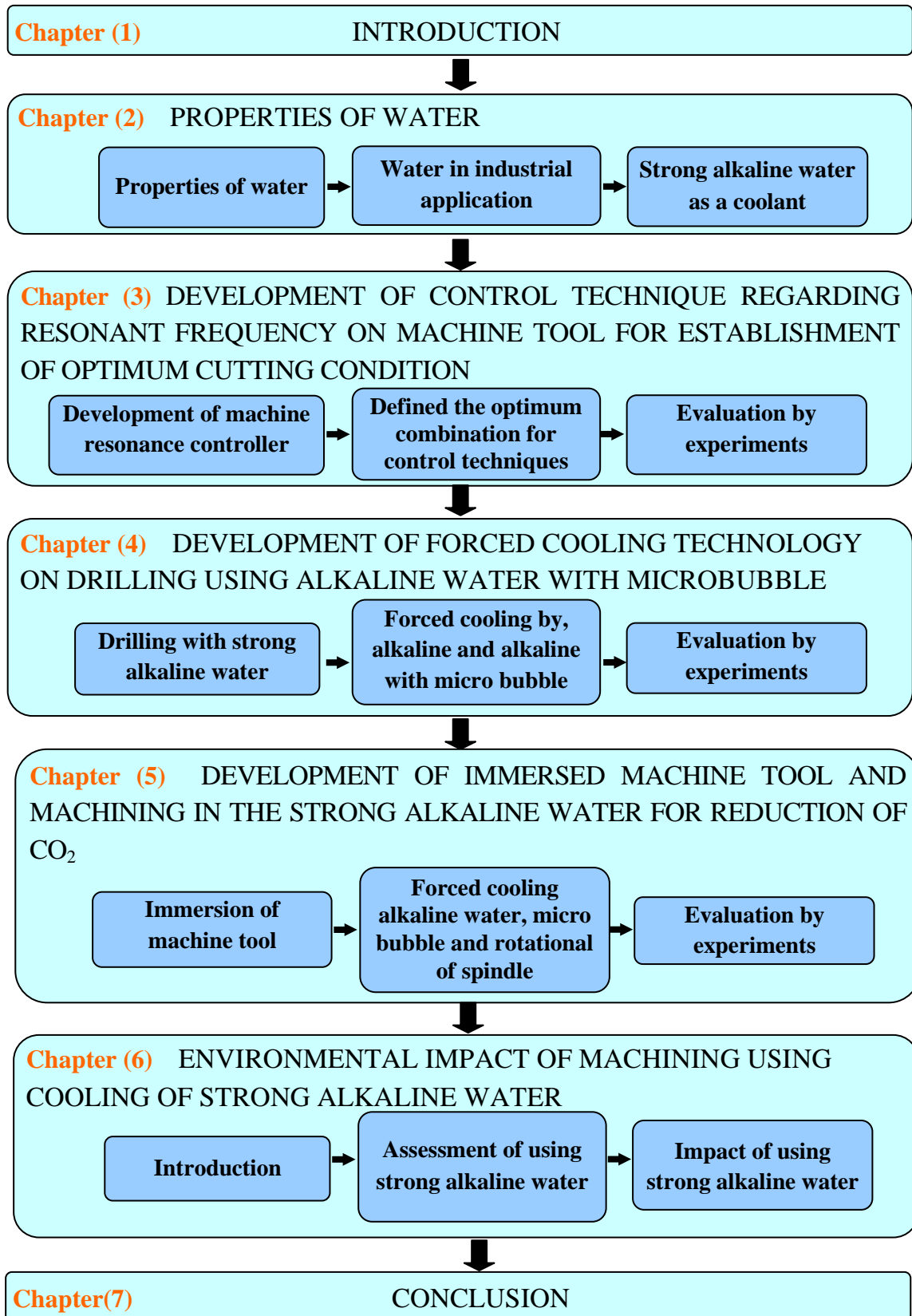


Fig.1.1 Flow chart of this research on high-accuracy and effective manufacturing utilizing water for environmental conservation

The cooling effect of strong alkali water with microbubble will firstly be investigated, and then heat transfer coefficient and tool life of the drill using strong alkali water with microbubble will be evaluated through an experiment. In the chapter five (5), the immersing machine tool and the machining in strong alkali water will be discussed. The same bench lathe machine that used in chapter 3 will be used in this experiment. Several elements of a machine tool will be firstly investigated for their resistance to strong alkaline water. Afterward, the bench lathe will be remodeled and submerged in the strong alkaline water. Thermal deformation of the spindle will also be measured for evaluation of accuracy. In addition, turning using bench lathe will also be performed for investigating the effect of water evaporation in the strong alkaline water. In chapter six (6), the simple assessment of using strong alkaline water during milling, drilling and turning processes will be assessed and discussed. The impact of the present study on the environment and the human health will be identified and evaluated. The final chapter (7) is the conclusion of this study.

Concretely, the structure of this research composed of those 7 chapters can be expressed as follows.

Chapter (1), “INTRODUCTION”: This chapter described the background, purpose of research and the relation with existing researches.

Chapter (2), “PROPERTY OF WATER”: This chapter describes the properties of water, which will be considered for the future research as a theoretical base and fact about water. The properties of the corrosion resistance of materials in water will be explained in this chapter. The corrosion resistance of each material to the strong alkaline water will be investigated. In addition, the technique to prevent water in inducing corrosion in the machine tool element will be discussed.

Chapter (3), “DEVELOPMENT OF CONTROL TECHNIQUE REGARDING RESONANCE ON A MACHINE TOOL FOR ESTABLISHMENT OF OPTIMUM CUTTING CONDITION”. In this chapter, the control techniques regarding resonant frequency will be developed. Three control factors are defined to be used for controlling machine resonance and the optimum control from each control factor will be combined to define the optimum combination control. Injecting water mix polymer, reinforce the structure and change the support position are three control techniques that will be used. The technique to improve the damping ratio of water will be discussed in this chapter. The Computer Aided Engineering (CAE) simulation for various countermeasures will be performed and discussed. Later, the optimum control factors from simulation analysis will be investigated by experimental evaluation to define the optimum combination of all three control factors. At last, the effectiveness of the optimum control factor will be evaluated by the real cutting experiment using the small bench lathe machine. The result of surface roughness of the cutting application will be measured, compared and discussed.

Chapter (4), “DEVELOPMENT OF FORCED COOLING TECHNOLOGY ON DRILLING USING ALKALINE WATER WITH MICROBUBBLE”: In this chapter, drilling technology utilizing strong alkaline water with microbubble will be developed. A drill with through-hole is used in this experiment. The cooling effect of strong alkaline water with microbubble will be firstly investigated by the experiment. Then, heat transfer coefficient of the drill with through hole will be evaluated for cooling capacity. In addition, the experimental evaluation of drilling experiment using cooling of strong alkaline water on Ti6Al4V, a material with low thermal conductivity and difficult to cut material, will be discussed for evaluation of the tool life. The effectiveness of the proposed method will also be discussed.

Chapter (5), “DEVELOPMENT OF IMMERSED MACHINE TOOL AND MACHINING IN THE STRONG ALKALINE WATER FOR REDUCTION OF CO₂”: In this chapter, the immersion of machine tool and the machining in strong alkali water will be evaluated and discussed. The corrosion resistance of the various machine tool elements to the strong alkaline water will be investigated and discussed. The modification and remodeling of bench lathe machine that used in this experiment will also be discussed. And also, thermal deformation of the machine spindle will be measured for evaluation of accuracy. In addition, turning using the bench lathe will be performed for the investigation of the effect of water evaporation using strong alkali water.

Chapter (6), “ENVIRONMENTAL IMPACT OF MACHINING USING COOLING OF STRONG ALKALINE WATER”: In this chapter, the simple assessment will be made to collect and calculate the impact of strong alkaline water usage to the environment and human health. Three machining processes such as milling, drilling and turning will be considered to be used for the assessment. The amount of carbon dioxide emitted during machining and oil disposal will be calculated. In addition, total CO₂ emission from the usage of conventional wet cutting and cutting utilizing strong alkaline water will be presented and compared. Moreover, the LCA study will be performed to evaluate and quantify the impact of a machining to the environment.

Chapter (7), “CONCLUSION”: Lastly, the conclusions of research work will be expressed in this chapter.

With the arrangement of the above 7 chapters, the study on high-accuracy and efficient machining utilizing water with compound for environmental conservation is performed, and the applicability of the developed technologies in the manufacturing industries is also considered.

Chapter (2)

PROPERTIES OF WATER

2.1 General properties of water

One of the things that make our planet special is the presence of liquid water. Water is fundamental to all life. Without it, every living thing would die. It covers about 71% of Earth's surface and it makes up 65-75% of our bodies (82% of our blood is water)^{[2-1],[2-2], [2-3]}. Water, with chemical formula known as H_2O , is generally perceived as transparent, odorless, tasteless and ubiquitous substance. The attachment of two hydrogen atoms to a single oxygen atom makes water known as the simplest compound of the two most common reactive elements found on earth. Uniquely, water is the only natural substance that can exist in all three physical states - solid, liquid, and gas - at the temperatures normally found on earth. Conversely, many other substances have to be super-heated or super-cooled to change states^{[2-4],[2-5]}. The gaseous state is when water vapors and can be found in the atmosphere. The liquid state is ubiquitous and can found in rivers, lakes, and oceans. The solid state of water appears as ice. Therefore, it makes water a unique substance.

Water has special properties because of the way hydrogen and oxygen atoms bond together to form a water molecule. It is also special in the way the molecules interact with each other. When a polar substance is put in water, the manifestation of two different polar quantities from water and polar substance attracted to each other. Hence, it makes water dissolve other polar substances very easily. And also, since the attractions cause the molecules of the new substance to be mixed uniformly with the water molecules, water can dissolve more substances than any other liquid. Because of this, it is often called the

"universal solvent" ^[2-7]. The dissolving power of water makes it even more important for supporting living things on earth. It carries dissolved minerals, chemicals, and nutrients wherever it goes, which is important for living things. Because of their polarity, water molecules are strongly attracted to one another, which gives water a high surface tension ^[2-8]. The molecules the water merges to form a type of "coating" on the water surface which is strong enough to support very light objects. For instance, some insects can walk on water because of the surface tension. Surface tension causes water to clump in drops rather than spreading out in a thin layer. It also allows water to move through plant roots and stems and the smallest blood vessels in the human body.

There are various properties of water; however, this paper will only focus on discussing properties of water that relating to the industrial application.

2.2 Properties of water relating to the industrial application

2.2.1 Cleaning agent

Water is the most common cleaning agent and has been used for many years in various fields in industries and manufacturers to remove dirt, including dust, stains, bad smells, and clutter on surfaces. As explained earlier, water has a property called surface tension which is good as a cleaner. Nevertheless, this property limits water's ability to become an excellent cleaning agent because not all soils, dirt, and stains can be cleaned by water. In the body of the water, each molecule is surrounded and attracted by other water molecules. However, at the surface, those molecules are surrounded by other water molecules only on the water side. Since a tension is created as the water molecules at the surface are pulled into the body of the water, it causes water to bead up on surfaces and slows wetting of the surface. Consequently,

the cleaning process is inhibited. Thus, surface tension must be reduced in order for water spreading and wetting surfaces for improving the cleaning process.^{[2-9], [2-10]} Water also keeps the soil suspended away from the clean surface, so it can be cleaned during the rinsing process. It works as an anti-redeposition agent. It is capable of wetting surface to penetrate the soil deposit, have the capacity to break the soil into fine particles, hold the small fine particles into suspension, and prevent the residues to redeposit on cleaned surface.^[2-11]

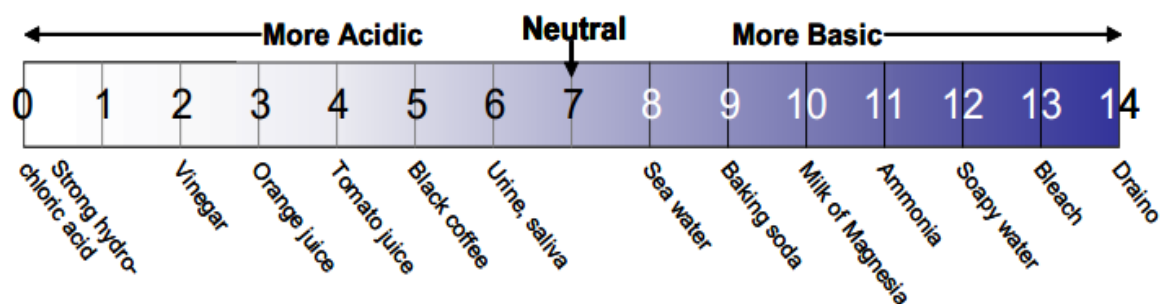


Fig.2.1 pH value of some common substance

Besides reducing surface tension to improve cleaning process, the specific pH of water can also improve the cleaning process. As mentioned earlier, since water is a universal solvent, it normally has various pH values. Hence, because of a very powerful polar solvent, cleaning agents normally water solutions that might be acidic, alkaline, or neutral, depending on the use. The pH value of some common substance is shown in Fig.2.1. pH 7 is neutral, less than 7 is acidic while more than 7 is basic or alkaline.

a. Alkaline cleaning agent

Alkaline cleaning agents have a pH-value above 7. Alkaline detergents are most effective in removing organic soils, for example, oils, fats, proteins, starches, and carbohydrates encountered in many industries. Alkalinity is

added to many detergents in order to improve their cleaning efficiency. Alkaline detergents work by hydrolyzing peptide bonds and breaking down large insoluble proteins into small and more easily soluble polypeptides ^[2-12]. In addition, they displace particles, emulsify oils, and dissolve oxides. Using this cleaning agent, the cleaning efficiency can be accomplished in two ways. Firstly, it improves the alkalinity. In this case, acidic soils are neutralized and thereby more easily removed. Meanwhile, organic soils such as fats, oils and proteins are emulsified. Many alkaline builders also soften the water during the cleaning operation. Secondly, there is an improved performance of other detergent components which helps in inhibiting the growth of microorganisms and chemical residue.

b. Acidic cleaning agent

Acidic cleaners are commonly used to brighten or etch metals and are effective at removing any mineral deposits or oxidation on surfaces ^[2-13]. Generally, acidic cleaners are also ideal for removing any starches, carbonates, and insoluble hydroxides. However, they are often used before cleaning using alkaline detergents because heavy soils and oils are generally unaffected by acid detergents. Acid detergents consist of organic and inorganic acids. The most common inorganic acids found are phosphoric, nitric, sodium acid sulfate and hydrochloric acids, whereas organic acids consist of hydroxyacetic, citric and gluconic acids ^[2-14]. Acid detergents are also used for the prevention or removal of water scale and aluminum oxide. Meanwhile, acid detergents are more effective against bacteria than alkaline detergents. Additionally, cleaning performance of acids can be greatly enhanced by adding an acid-stable surfactant ^[2-15], which promotes penetration of surface deposited and assisted in the process of rinsing at the end of the cleaning process.

c. Neutral cleaning agent

The neutral cleaning agent is a cleaner with a neutral pH of 6.5-7.5 pH. It is comprised primarily of a proprietary blend of non-ionic surfactants and other organic (carbon-based) ingredients that disperse different types of dirt. Neutral cleaners use a number of other chemical elements such as surfactants (Surface active agents) that break down the surface tension of liquids in order to work at removing dirt. ^[2-16]

2.2.2 Water's specific heat

Water has a high heat capacity, which is about 4.18 J/g°C, which means that, it resists temperature changes when it absorbs or releases heat. Specific heat is defined as the ratio of the heat capacity of a substance to the heat capacity of water. Specific heat, a measure of heat capacity, is the heat required to raise the temperature of 1 gram of water 1°C. With its high heat capacity, the change in water temperature is more slowly than other compounds that gain or lose energy.

The heat capacity of water caused by its hydrogen bonded structure. Although hydrogen bonds are weak, their combined effect is enormous. ^[2-17] As a result of hydrogen bonding among water molecules, it takes a relatively large heat loss or gain for each 1°C change in temperature. Hydrogen bonds require absorbing heat to break, and they release heat when they form. As heat is added to water, the energy first breaks hydrogen bonds and allows the molecules to move freely and faster which increase in temperature. Most of the heat is used to break hydrogen bonds and not much is left over to raise the temperature of the water. Hence, make it difficult to rise in temperature. Since temperature is a measure of the average kinetic energy of molecules (the rate at which they move), the temperature of the water rises slowly with the addition of heat. When the

temperature of the water drops slightly, many additional hydrogen bonds form and release a considerable amount of energy in the form of heat. ^[2-18]

Because of water can absorb a lot of heat with little change in temperature, it acts as a thermal buffer. On a small scale, water in a cell can absorb much heat with little change in temperature. On a larger scale, like in the ocean acts as a thermal buffer for the earth, resisting temperature change and creating a hospitable environment for life. ^{[2-19], [2-20]}

2.2.3 High evaporative cooling

Water has a high heat of vaporization which resists evaporation ^[2-21]. For water molecules to evaporate, which is a transition from liquid to the gas state, hydrogen bonds must be broken which requires heat energy. Because of the energy needed to break the hydrogen bonds holding a water molecule to its neighbors, more energy is required to evaporate liquid water than most other substances. To evaporate each gram of water at room temperature, about 580 calories of heat are needed, which is nearly double the amount needed to vaporize a gram of alcohol or ammonia. Water has a relatively high heat of vaporization at the boiling point (540 cal/g or 2260 J/g; Joule = 0.239 cal). Among liquids, water has the highest latent heat of fusion (334 J/g) which is also known as heat of fusion or the energy required to change a gram of a substance from the solid to the liquid state (or vice versa) without changing its temperature. ^{[2-22],[2-23]}

2.2.4 Density

The density of water is also unique in the way temperature affects its density. ^[2-24] It prevents water from freezing from the bottom up. Most substances increase in density as temperature decreases because the molecules making up the substance begin to move more slowly and get closer together. The density of

water increases as it is cooled to 4°C and then its density begins to decrease as the temperature decreases to 0°C, the freezing point of water. As the freezing point is approached, hydrogen bonds relax and form a crystal lattice that keeps molecules further apart than they are in the liquid water. ^[2-25]

2.2.5 Induce corrosion

The common reason why water is rarely used as cooling in some part of industries such as manufacturing and machining because it corrodes workpiece and other metal production. Corrosion is a natural process involving chemical or electrical degradation of metals in contact with water. The rate of corrosion is varying depending on the acidity of the water, its electrical conductivity, oxygen concentration, and temperature ^{[2-26], [2-27]}. Generally, rust forms due to the reaction of oxygen dissolved in water with iron. Rust is a common generic term to describe different oxides such as: Ferrous hydroxide Fe(OH)_2 , Oxide hydroxide Fe(OH)_3 , Ferric Oxy Hydroxide FeO(OH) , Iron oxide yellow $\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$, that form when iron corrodes ^[2-28]. The common form of rust is known as a red product: Fe_2O_3 . The oxygen in the air dissolves in the water and causes rust to form. There are always two distinct chemical reactions in a corrosion process, the basic chemistry of corrosion is:

1) Anodic dissolution of metal (Iron) that goes into solution (water)

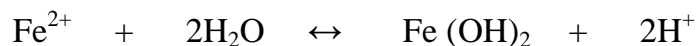
The anodic dissolution of iron can be written chemically as:

Elemental iron \rightarrow Ferrous iron + Electrons



The reaction produces ferrous iron and two electrons. The electrons then flow through the metal to the cathode. Meanwhile, the ferrous iron reacts with the water (the electrolyte) in the metal to produce rust and hydrogen ions.

Ferrous iron + Water \leftrightarrow Ferrous hydroxide + Hydrogen ions

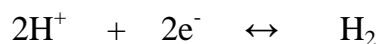


The rust builds up a coating over the anode surface. Ferrous hydroxide may then react with more water to produce another form of rust called ferric hydroxide, $\text{Fe}(\text{OH})_3$.

2) Cathodic reduction of oxygen dissolved into water

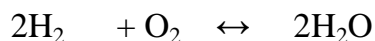
In cathodic reduction, the electron from the anodic dissolution leaves the metal and enters the water by reacting with hydrogen ions and forming hydrogen gas. The reaction can be express as:

Hydrogen ions + Electrons \leftrightarrow Hydrogen gas

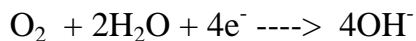


Dissolved oxygen in the water is able to react with the hydrogen gas surrounding the cathode:

Hydrogen gas + Oxygen \leftrightarrow Water

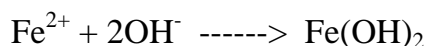


While water reacting with oxygen and ion electron forming hydroxide ion,



In the final reaction, the ferrous react with hydroxide ion (OH^-) to form $\text{Fe}(\text{OH})_2$ corrosion.

The final reaction is:



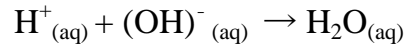
This oxide will then further reacts with hydrogen ion and oxygen to give the final red product: $\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$. Hence, the main catalyst for the rusting process is water. Iron or steel structures might appear to be solid, but water molecules can penetrate the microscopic pits and cracks in any exposed metal. The hydrogen atoms present in water molecules can combine with other elements to form acids, which will eventually cause more metal to be exposed.

2.3 Alkaline water as a coolant

As mentioned earlier that with large evaporation cooling, water is very good as a cooling medium, however, because normal water is considered neutral in its pH, it induces corrosion. Hence, to be able to use water to cool down any metal, it needs to be ionized to become more alkaline with high pH. By this, corrosion in a metal can be inhibited.

Alkaline water is water with a small amount of hydrogen ions $[\text{H}^+]$ in it and commonly known as ionized water with a pH level greater than seven. As explained earlier, pH is a measure of the acidic or basic (alkaline) nature of a solution. The concentration of the hydrogen ion activity in a solution determines the pH. Alkaline water does not eliminate corrosion if it has high electrical conductivity. When two different metals such as steel and brass are in contact with a solution which will conduct electricity, a galvanic cell is established. One of the metals will corrode in proportion to the electricity generated. As water

contains both H^+ and OH^- ions, if the quantity of H^+ exceeds that of the OH^- , the water becomes acidic. If there are more OH^- ions than H^+ , the water is alkaline. Pure water, which contains equal numbers of both ions, is considered neutral. The chemical equation for the formation of pure water is:



The degree of acidity or alkalinity on the pH scale ranges from about 0 to 14. As shown in previous Fig.2.1 Acidic solutions have pH values of less than 7, alkaline solutions more than 7. Pure water, being neutral, has a pH of exactly 7. For each 1-unit change in pH, the hydrogen ion concentration changes tenfold. For example, if the pH is 8, there are 100 times as many OH^- ions than H^+ ions (that is, $[H^+] = 10^{-8}$, $[OH^-] = 10^{-6}$).

Mathematically, this is expressed as:

$$pH = -\log [H^+]$$

In other words, the pH value is the negative power to which 10 must be raised to equal the hydrogen ion concentration. When water becomes more alkaline, hydrogen ions contain in the water become less, therefore, delays the occurrence of corrosion. Based on the corrosion properties of strong alkaline water ^[2-29] in the case of steel, the corrosion will not occur when the pH of strong alkaline water is more than 10.0. Some material likes nickel base alloys has chemical passivity between the range of pH 8.5 ~ pH 13.0. Chemical passivity is the characteristic of a metal being less affected by environmental factors such as water and air. Hence, in case of corrosion, the chemical passivity of material is the condition when a material does not affect by water or air in enhancing corrosion. Passivity is caused by the buildup of a stable, tenacious layer of metal

oxide on the surface of the metal. This oxide layer is formed by corrosion on a clean metal surface, where the corrosion products are insoluble in the particular environment to which the metal is exposed. Once the layer is formed, it acts as a barrier separating the metal surface from the environment, thus corrosion either decreases significantly or stops. Other materials such as titanium and titanium alloys, their chemical passivity range are below pH 13.0. Therefore, it is considered that pH between 8.0~13.0 do not corrode most of industrial materials.

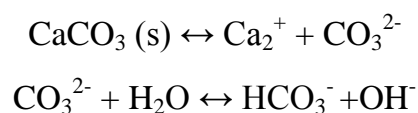
2.4 Process of alkaline production

Alkalinity is a measure of the capacity of water or any solution to neutralize acids. The most important compounds in water that determine alkalinity include the carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) ions. Carbonate ions are able to react with and neutralize 2 hydrogen ions (H^+) and the bicarbonate ions are able to neutralize H^+ or hydroxide ions (OH^-) present in water. Table 1 shows the important compounds for alkalinity.

Table 2.1 Important compounds for alkalinity

H^+	Hydrogen ion (acid)
OH^-	Hydroxide ion (base)
H_2CO_3	Carbonic acid
HCO_3^-	Bicarbonate ion
CO_3^{2-}	Carbonate ion
CaCO_3	Calcium carbonate (calcite)
$\text{CaMg}(\text{CO}_3)_2$	Dolomite lime
K_2CO_3	Potassium carbonate

One source of alkalinity is calcium carbonate (CaCO_3). Alkalinity can increase the pH (make water more basic), when the alkalinity comes from a mineral source such as calcium carbonate (CaCO_3). When CaCO_3 dissolves in water, the carbonate (CO_3^{2-}) can react with water to form bicarbonate (HCO_3^-), which produces hydroxide (OH^-):



The hydroxide ion (OH^-) is a strong base; hence an increase in OH^- concentration will cause the pH to increase.

In this research the strong potassium carbonate K_2CO_3 compound was used in generating strong alkaline water. Since only 0.1 % of strong alkaline water used in this research is from ionic potassium carbonate K_2CO_3 , while other 99.9 % are water, it is considered that strong alkaline water is safe for environment. Hence, a study on high-accuracy and efficient machining utilizing water with compound for environmental conservation is made and evaluated.

Chapter (3)

DEVELOPMENT OF CONTROL TECHNIQUE REGARDING RESONANCE ON A MACHINE TOOL FOR THE ESTABLISHMENT OF OPTIMUM CUTTING CONDITION

3.1 Introduction

Nowadays, since machining with minimum vibration is demanded for higher productivity, a study on developing new technique regarding controlling the resonant frequency for the establishment of optimum cutting condition is required to improve quality of production and manufacture. In order to higher productivity, the cutting conditions with parameters such as spindle speed, cutting speed, feeding and cutting depth must be in the optimum condition so that the achieved result can be optimum without further processing. The use of optimum cutting condition can shorter machining time, lower machining cost which resulting in higher productivity. The high productivity can increase the profit of the companies. Therefore, the selection of cutting condition is important in deciding profit and expenses of industries. ^{[3-1], [3-14]}

On the other hand, vibrations in machine tools still appear as a common problem in machining. It is natural for one structure to vibrate, however it is acceptable when the vibration does not exceed the tolerable level. ^{[3-7], [3-13]} Even machines in their best operating condition will have some vibration because of a minor defect. However, when machinery vibration increases or becomes excessive, some mechanical failure is usually the reason. ^[3-2] Vibration does not increase or become excessive for no reason at all. The condition such as unbalance, misalignment, worn gears or bearings and looseness cause the excessiveness of vibration. In some cases, these conditions can be avoided easily

when the machine tool stays in its best condition. However, the resonance of machine tool is the one that difficult to be avoided without change any condition of the system. Resonance can be either desirable or undesirable. Because it is natural that every machine has many resonant frequencies, resonance condition will always occur in machine tool when driving force match or the structure excited at one of its natural frequency.

The resonant frequency of a machine tool is determined by the structure of machine tool, its shape, size, properties of materials (Young's modulus and density) and supporting method. On the other hand, the optimum cutting condition is determined in accordance with the material of workpiece and the type of cutting tool and its material. However, during operating with selected optimum cutting condition, in some cases, the force-frequency of operating part coincides with the resonant frequency of machinery, large vibration will occur. At this situation, cutting condition has to be changed to avoid vibration, however, geometrical accuracy, tool life, and surface roughness will not be optimum. When this condition occurs, it can affect the cutting process and finishing surface of the workpiece. Hence, this condition is considered as a productivity problem in mass production.^{[3-1],[3-2],[3-3],[3-4]}

Therefore, in this paper, control techniques regarding resonant frequency of the bench lathe machine were developed by simplifying and modifying its structure by: (1) Controlling apparent density of machine tool by lighter machine tool's weight, (2) Controlling stiffness of the machine tool using reinforced frame with through hole, and (3) Controlling support point by changing the combination of the support position. With the application of these 3 control factors, the technology for controlling the resonant frequency of machine tool was developed and the experiments for evaluation of the proposed method were performed and investigated on small bench lathe machine.

3.1.1 The effect of the machine resonance to the cutting process

The resonance condition in machine tools can affect the cutting process in manufacture and production. As stated earlier, when machineries operate in resonance range, even high quality of a machine tool is used, cutting process and its result will not accurate compared to the processing outside the resonance range. Beside affect to the cutting process and its result, some other problems such as machine breakdown or injury of the operator may occur, when the oscillation continue over some period of time. In such condition, the resonant frequency needs to be altered to prevent further unexpected problems and errors.

The imprecise finishing result of machining can also affect the productivity in most productions ^[3-8]. The presence of resonance makes it difficult to use optimum cutting condition when the selected spindle speed coincides with the machine resonant frequency. When this condition occurs, the machine will strongly resonate and produce a large vibration that can affect the accuracy of the final cutting result. The poor accuracy and the defect of the work piece due to the large vibration will require another machining process to improve its quality, which is considered as time-consuming and lower productivity. Therefore, in such condition, other cutting condition using different spindle speed must be selected outside the range of the resonance frequency to avoid large vibration.

Most of the machine tools were designed to avoid their resonant frequencies by higher their rigidity and by giving specific spindle speeds to be used. However, because the resonance in small and medium machine tools always appear below the frequency of 100 Hz ^[3-3], it is difficult to avoid resonance when the machine with variable speed is used. Therefore avoiding spindle speeds that coincide with machine resonant by changing to another speed is still widely used in machining and manufacturing. Changing spindle speed may avoid resonant frequency, however, it also means a change in cutting condition, consequently

reduce the accuracy of cutting result. This condition considered as a problem for productivity.^[3-3~3-6] Therefore, in this research, the control technique regarding resonance frequency on a machine tool is considered to be investigated and developed for the establishment of optimum cutting conditions.

3.1.2 Conventional countermeasures for avoiding resonance on machine tool

There are many conventional countermeasures that have been used to avoid the resonance phenomenon on machine tool such as:

- [1] Change cutting condition by change spindle speed
- [2] Use damper to minimize vibration amplitude
- [3] Higher the rigidity by increase the size and weight of machine tool

However, these countermeasures are still not satisfiable.

For the fact [1], change cutting condition by change spindle speed to avoid resonant frequency is commonly used during manufacture in several industries and factories. However, changing spindle speed could modify the cutting condition. Consequently, the finishing cutting result will not be optimum, which is considered undesirable in most factories.^{[3-5], [3-6], [3-12]}

For the fact [2], use damper to reduce the vibration amplitude is nowadays widely used in industries and private works.^{[3-9], [3-10], [3-11]} The use of damper and shock absorber are very effective in reducing the vibration amplitude. However, because the complex machine tools normally have few resonant frequencies, the damper and absorbers are difficult to be used in variable resonant frequencies.^[3-1] In addition, it requires an extra amount of cost for the installation and modification of machines. Thus, the simple and low-cost control systems are preferable.

For the fact [3], higher the rigidity by increase machine tool's size and weight to higher resonant frequency is the perfect countermeasure to avoid resonance. However, the large and heavy weight machine tool required extra cost during

transportation and extra space of foundation for the machine to be placed, hence considered ineffective. Moreover, from the productivity consideration, many small size machineries to produce a multiple products at the same time is preferable than one huge costly machine. Therefore the big size with heavy-weight machineries is less demanding, especially in mass production industries.

Based on the above facts, in this study, the computation of data analysis is firstly performed before defining the control methods to control resonant frequency. The preliminary investigation by simplifying the bench lathe model was analyzed by CAE analysis. The frequency response of free vibration is examined. The five modes of resonant frequency with the resultant displacement of each mode are plotted with the results are shown in Fig.3.1. The deformation at the machine resonance shows that large deformation occurs near the headstock and motor base.

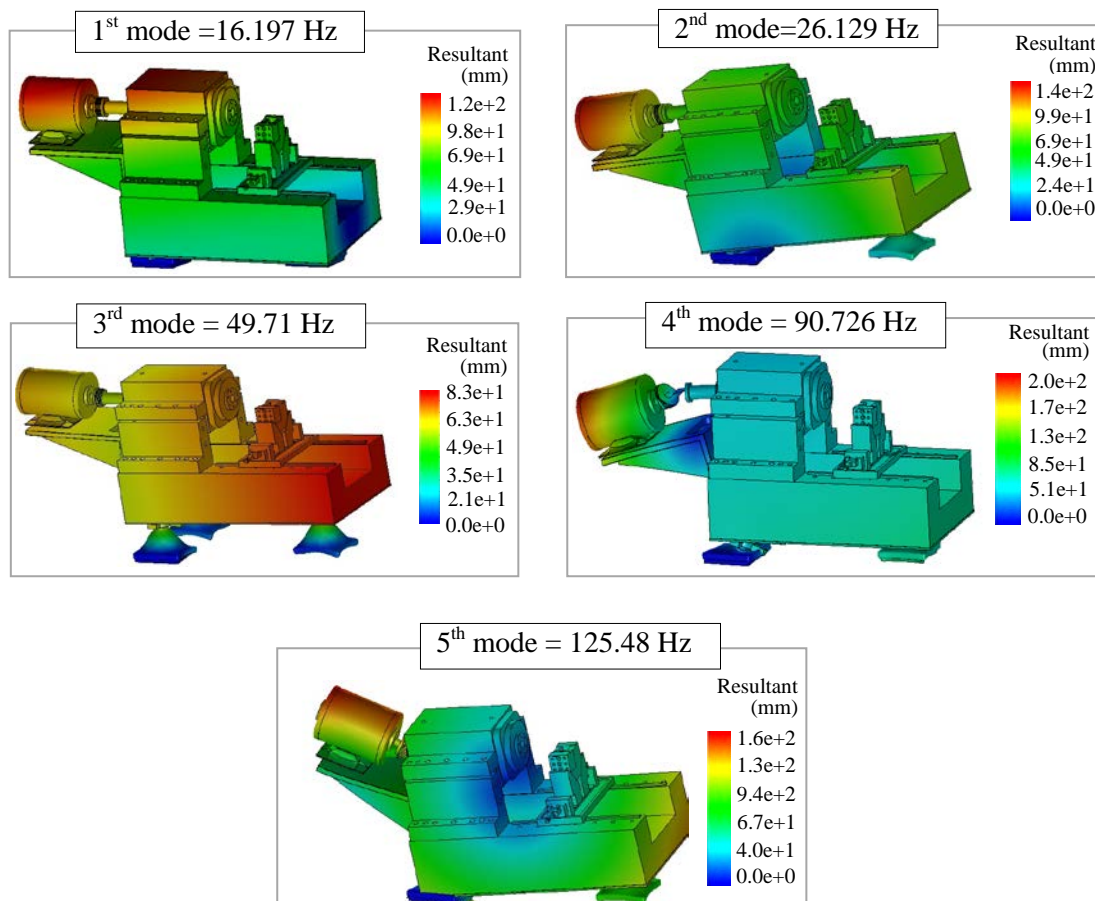


Fig.3.1 Resonance modes from preliminary results of free vibration analysis

The resonant frequencies of the calculated result are 16.197 Hz, 26.129 Hz, 49.71Hz, 90.726 Hz and 125.48 Hz, consecutively. The first three modes are the resonances of vibration of bench lathe in X, Z and Y axis, respectively. The 4th and 5th mode are the combination of vibration in Z-X and Z-Y axis, respectively. Based on these results, the research was performed to investigate and establish new control methods for avoiding these resonant frequencies.

3.1.3 Control methods to control density, stiffness and support position

In developing control methods for controlling resonant frequency, various parameters and countermeasures were considered in order to find the most effective one. The consideration of control methods for controlling density, stiffness and support position is shown in Fig.3.2. From the viewpoint of easier and faster approach: (1) Changing the apparent density, (2) Changing overall stiffness, and (3) Changing position of support points are 3 factors that are considered.

Controlling the apparent density of the machine tool as mentioned in (1):

① Change the thickness of machine structure, ② Use the materials with

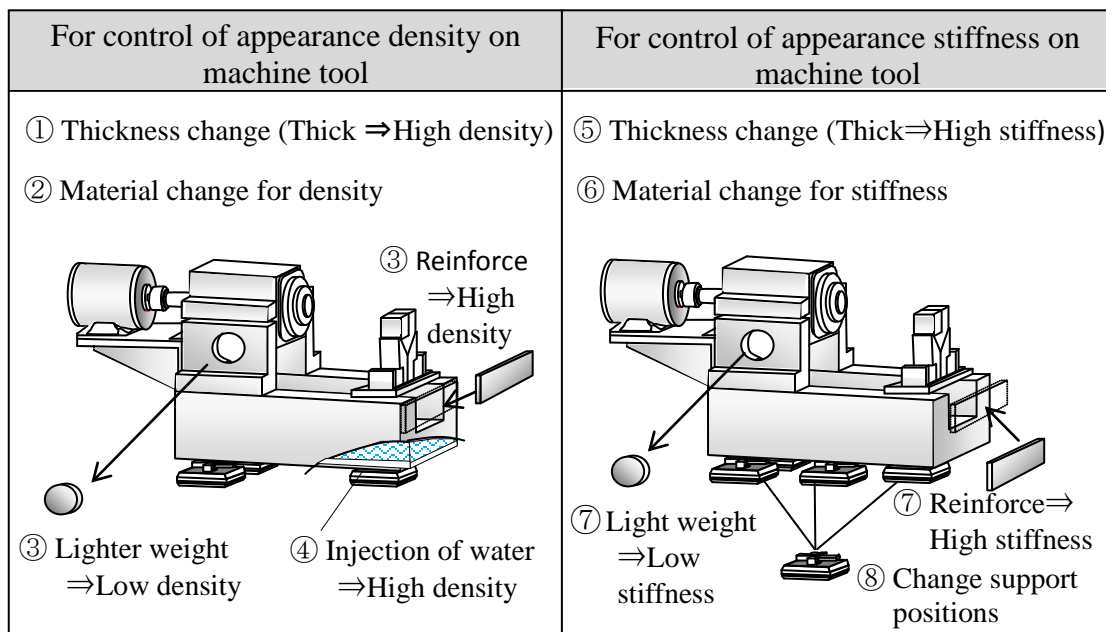


Fig.3.2 Schematic view of several techniques for controls of appearance density and stiffness in a machine tool

different density, ③ Add or remove some parts of machine structure, and ④ Injecting water into machine bed and other space in the machine structure are possibilities of countermeasures that are considered. Since ①, ②, and ③ are not only modify the density, but also affect to the overall rigidity of the machine, the precaution for modification using these countermeasures are required to be taken. Moreover, because ① and ② require major modification of the machine tool, while since the easier controlling is preferred, they are not applicable in this paper. Hence, only ③ and ④ will be applied to control the apparent density of machine tool.

Controlling rigidity of machine tools as mentioned in (2): ⑤ Change the thickness of machine structure, ⑥ Use different young's modulus of different materials, ⑦ Add or remove parts of machine structure are 3 possible ways that are considered. Just like the consideration of changing density, since ⑤ and ⑥ require major modification which is considered unsuitable for simple controlling, hence they are omitted from this study. Therefore, only ⑦ is considered to be applied for changing the overall stiffness of the structure.

Controlling and altering mode shapes of the machine tool by changing support position mentioned in (3): ⑧ the positions of the supporting points of machine tool (position of bolt pocket) were considered to be used for altering machine resonance. Use more support can the change mode shape of the system, hence shift resonant frequency. Moreover, the distance between each support point can also be considered for shifting machine resonant frequency.

3.1.4 Proposed method for controlling resonant frequency

With various considerations had been assumed in section 3.1.3, the proposed method for easy and fast control for controlling resonant frequency was decided. Injecting water into the vessel on the headstock and bed of machine tool, add and remove the part from machine structure, and changing machine support positions were proposed for countermeasures. Table 3.1 shows the explanation of three

parameters to define the proposed method for controlling resonance. Based to the previous Fig.3.2, the countermeasures ③, ④, ⑦, and ⑧ are chosen as countermeasures for control techniques. Countermeasure ③ can be used for the lighter weight of the structure for lowering density and increase the weight of structure for higher density. Since low density was preferable, therefore only countermeasure of lighting machine weight was selected. The countermeasure ④ was selected to be used to control the density by injecting water and by adding some weight to increase the density of machine tool. However, since the light structure is preferable, only injection of water to higher the density on a machine tool was chosen. In the case of higher stiffness, the countermeasure ⑦ was chosen because this countermeasure can be used to increase stiffness by reinforcing machine structure and lower stiffness by removing some of the machine structure. This countermeasure is similar to the countermeasure ③, however since higher stiffness is preferred, the only countermeasure for higher stiffness is chosen. Finally, the countermeasure ⑧ was also chosen because of changing support position and used a different number of support point, the resonant frequency, and its mode shapes can be changed.

Table 3.1 Explanation of three parameters for resonant frequency control

Countermeasures	Contents with more detail	Selected countermeasures
③ (See Fig. 3.3)	Light weight structure for low density & heavyweight structure for high density	Only lightweight structure for low density
④ (See Fig. 3.3)	Injection of water and add weights for high density in a machine tool structure	Only injection of water for high density in a machine tool structure
⑦ (See Fig. 3.3)	High stiffness using reinforce & Low stiffness by removing a structure (This is similar to ③)	Only high stiffness using reinforced
⑧ Supports	Control the position of the support for change of resonance frequency & its mode	Control the position of the Support point

Based on these chosen countermeasures, the proposed methods to control resonant frequency are defined with regard to the easy, simple control, and its effectiveness. The explanation of the several parameters and countermeasure as control methods to control resonance frequency in a machine tool is shown in Fig.3.3. The three control methods as control factors are defined for control methods. Control factor I by injection of water, control factor II by reinforce machine structure and control factor III by changing the number of supports and their positions. Specifically, the explanation of parameter setup for controlling resonant frequency is illustrated in Fig.3.3. The proposed method will be explained by applying the methods on the small bench lathe machine used in the experiments. Firstly, as control factor I, adding mass by injecting water into machine structure for reducing resonant frequency (higher density). By this method, the resonant frequency can be reduced. However, since water tends to magnify the vibration because of the low damping ratio, the mixture of polymer with water was also performed to improve the effectiveness of damping. Next, in accordance with the result of the preliminary analysis in Fig.3.1, since the 1st mode and 2nd mode of vibration are large near the motor's base, hence, higher resonant frequency by reinforcing motor's base and reduce weight (low density) to improve rigidity of machine tool are defined as control factor II. Finally, by changing the position and number of supporting points of the machine tool, the resonant frequency and its mode shapes can be changed. This control method is defined as control factor III. These three methods can easily apply to the machine tool, thus consider to greatly contributing to practical applications. Furthermore, these control methods are considered for resonant frequency with a range below 100 Hz ^[3-1], which has a large influence to the processing accuracy.

In the method which using water in control factor I, the viscosity of water is increased for a higher the damping ratio. Here, the mixing of water with polymer

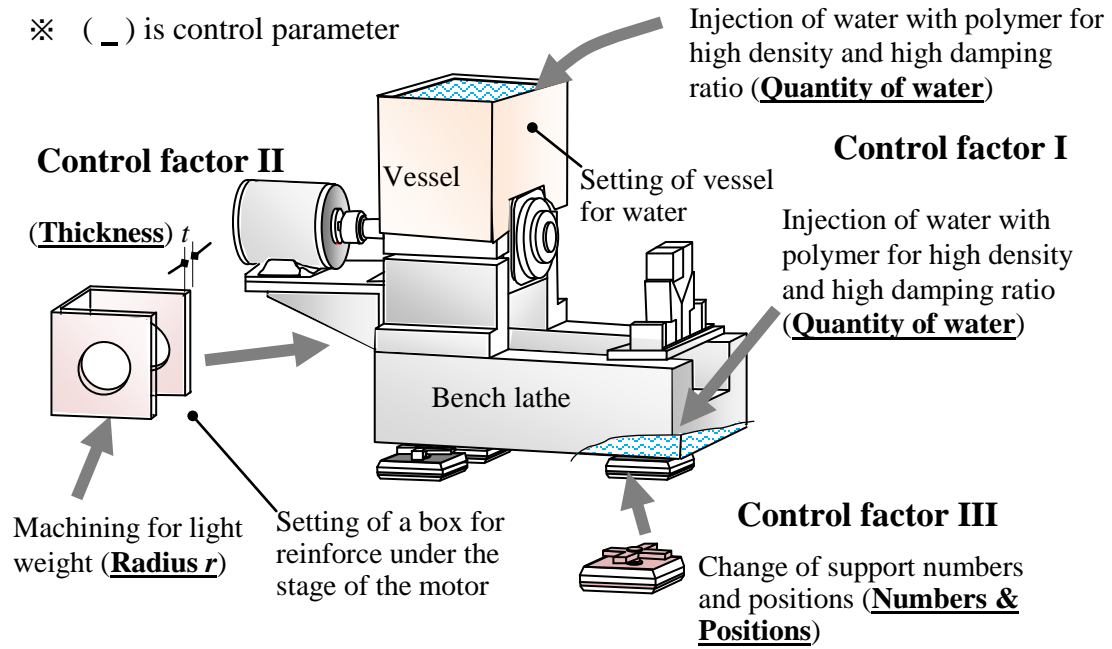


Fig.3.3 Explanation of several parameters and countermeasures for the control of the resonance frequency in a machine tool

PEO (Polyethylene oxide with its properties shown in Table 3.2) was performed and the degree of the improvement in damping ratio was investigated by the experiment. Fig. 3.4 shows the steel pipe with length $\ell = 300$ mm, thickness $t = 2$ mm was filled with water mixed with polymer PEO and hung using wire in $\ell/3$ from both end sides of the pipe. The central part of the pipe was excited with impact hammer, and the vibration was measured by attaching accelerometer on the opposite side of the impact point. Later, the damping ratio was calculated from the logarithmic decrement of excitation response. Since the measured damping ratio from the experiment included damping characteristic of steel pipe, the inverse FEM analysis was done to find the real damping ratio of water with the polymer by curve fitting between experimental and FEM results. The FEM analysis was performed and simulated using SolidWorks. In this simulation, water was modeled by defining its properties such as bulk modulus, density and Poisson's ratio. The value of the Poisson's ratio was changed to obtain the curve of the vibration that fits with experimental curve. The result of curve fitting is shown in Fig. 3.5.

Table 3.2 Properties of the PEO polymer

Chemical name	Polyethylene oxide (PEO-18Z)	Density	Apparent density 0.15-0.35 kg/ℓ True density 1.15 - 1.25 kg/ℓ
Appearance	White powder	Melting point	66 - 70°C
Property	Straight chain/ non-ionic type	Thermal decomposition temperature	423 - 425°C
Molecular weight	5.5 million	Solution ph	6.5 - 7.5

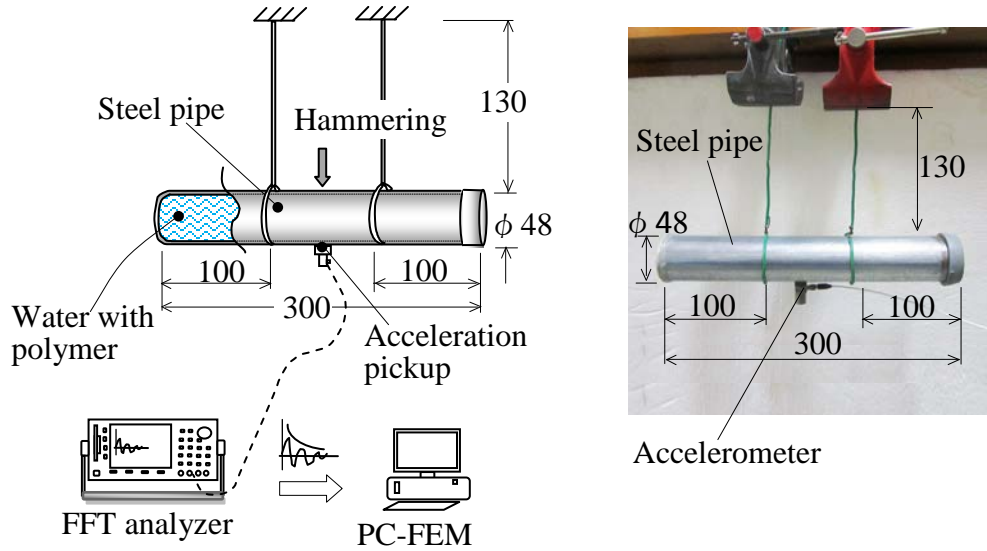


Fig.3.4 Experimental setup and photograph of method to measure damping ratio of water and polymer

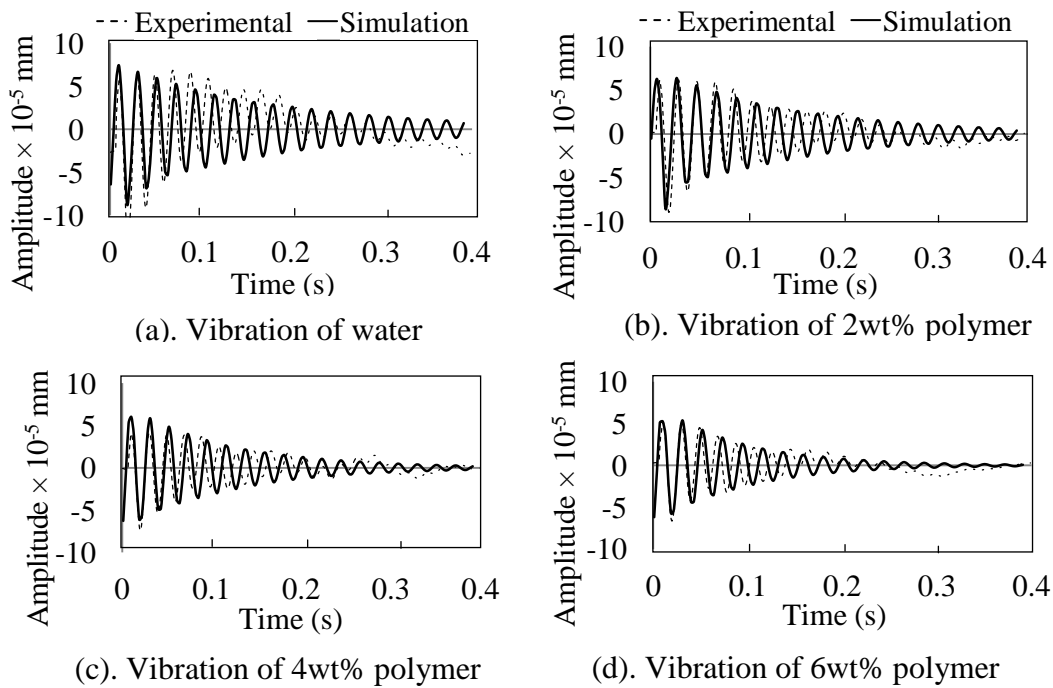


Fig.3.5 Curve fit of damping ratio measurement between experimental and simulation

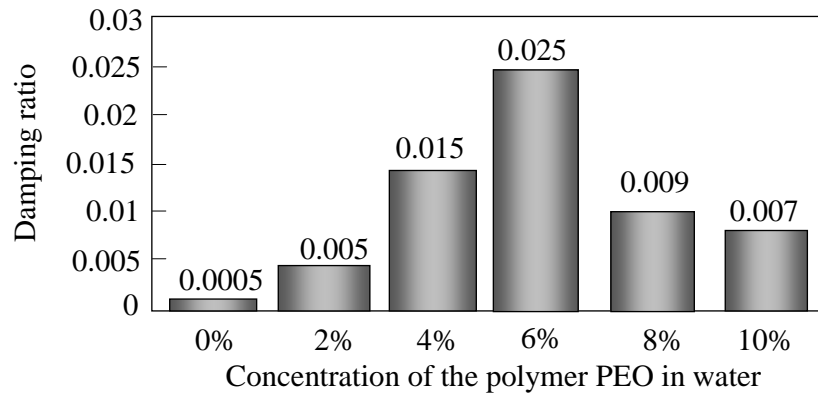


Fig.3.6 The relationship between polymer percentage and damping ratio (Experimental result)

Fig.3.6. shows the relationship between polymer percentage and damping ratio from experiment result. When the apparent density of the water is increased by mixing with polymer, the damping ratio increased. Therefore, it is considered as a sufficient technique to lower resonant frequency and amplitude of vibration. By increasing the polymer concentration, its effectiveness also increases. However, since the viscosity becomes larger when the mixing ratio is larger than 6 wt%, the damping ratio reduces as the jelly become more stiff and rigid. And also, the injection and extraction becomes very difficult when polymer concentration is larger than 6 wt%. Thus, the polymer concentration was decided to be limited to only 6 wt%.

3.2 Investigation using CAE simulation for the control factors (density, stiffness and supports)

The finite element model used in the simulation is shown in Fig. 3.7. This model will be applied in investigation of methods: (1) Reducing the resonant frequency by injecting water into the machine structure for increasing weight (higher density), (2) Increasing the resonant frequency by reducing weight (lower density) and reinforce the structure (increase rigidity), add (3) Changing supporting positions to change resonant frequencies and its mode shapes. In this analysis, the finite element model was built and drawn based the on a real bench

lathe. With this computational model, the analysis can be performed in which can provide new data about the system that are difficult and impossible to find with ordinary instruments. Using this CAE simulation, the model of the bench lathe is built based on the proposed methods that were defined earlier. The analysis was performed for each control method and summarization of the optimum condition was defined from the analysis to be evaluated using experimental evaluation.

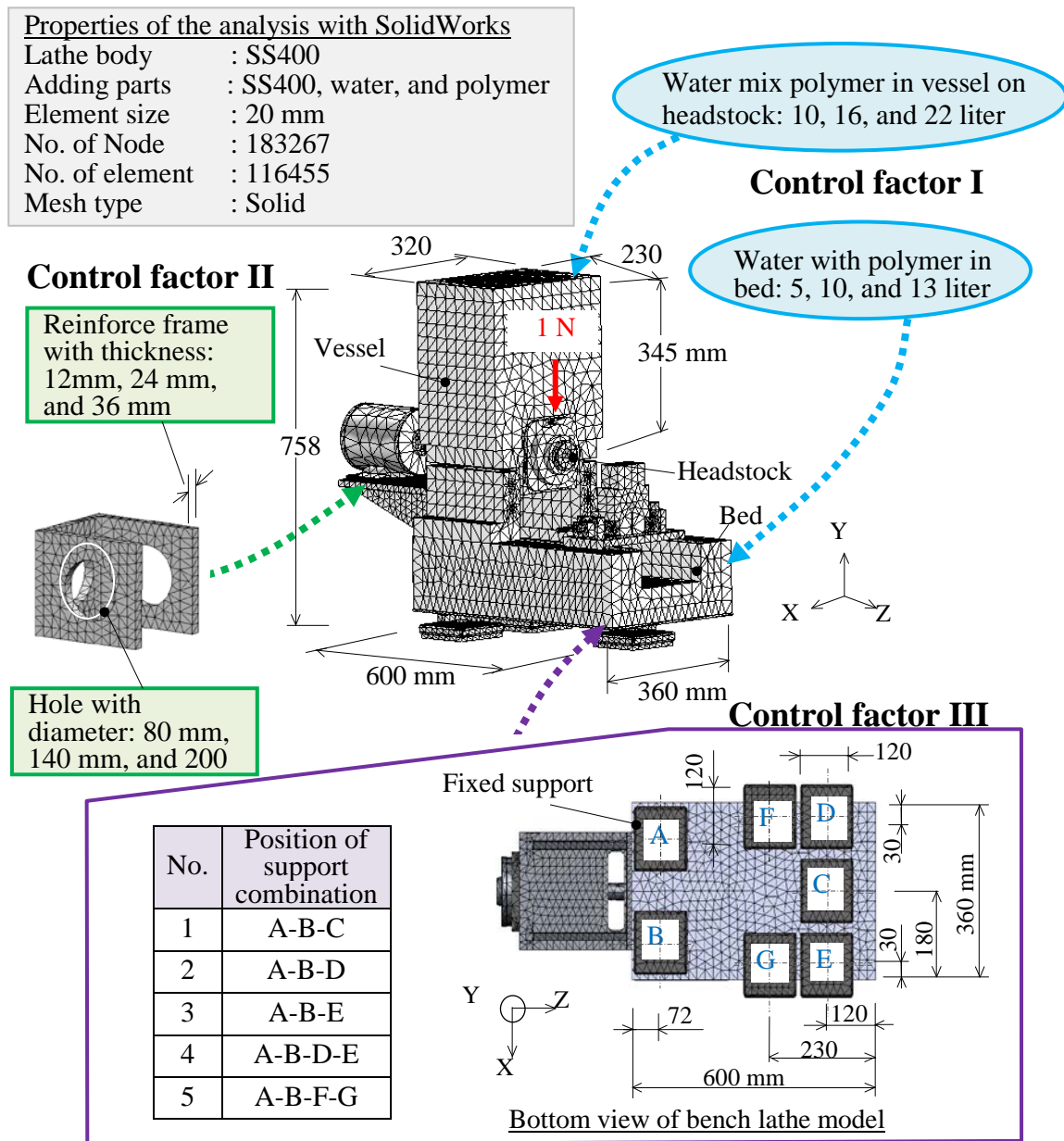


Fig.3.7 FEM model for investigation for influence regarding density, stiffness, and supports

This model was used for the investigation of three control factors such as density, stiffness, and supports. The investigation was done by using:

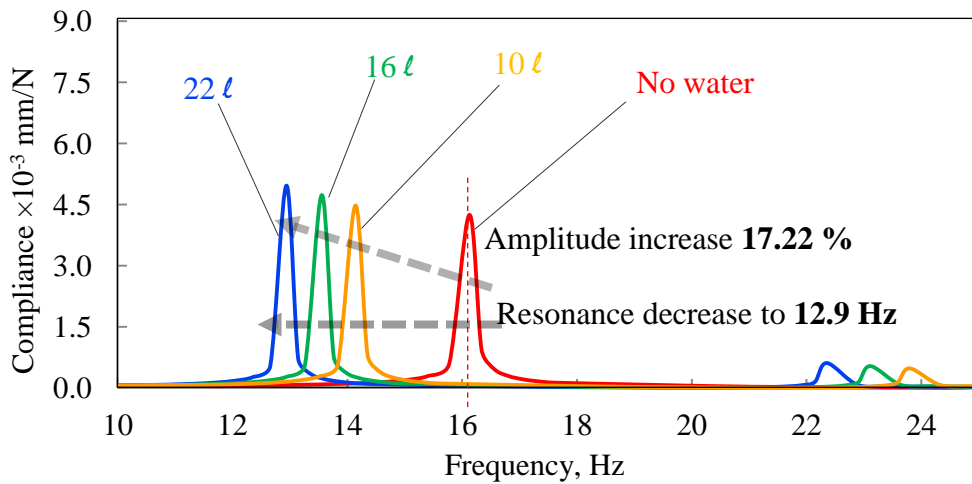
- (1) Control factor I, shift down the resonant frequency by injecting water into the structure of the bench lathe to increase the weight (higher density).
- (2) Control factor II, shift up the resonant frequency by reducing the weight (lower density) and reinforcing the structure (increase rigidity),
- (3) Control factor III, change supporting positions to change resonant frequencies and mode shapes.

3.2.1 Injection of water for reducing resonant frequency

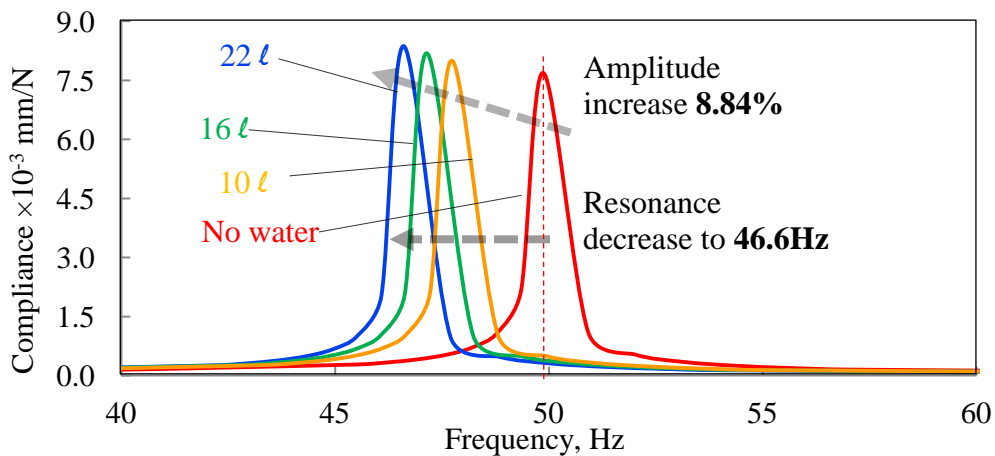
Injection of water into the space in the structure of the machine tool will increase machine weights, which will higher density of the machine. As the density becomes higher, it causes the resonant frequency to shift from its original frequency. In the calculation of resonant frequency by injecting water, the real bench lathe is simplified into the computational model using SolidWorks software. Then, the analysis and calculation of the influence of water on the resonant frequency were performed.

In lowering resonant frequency, water was injected in 2 places: the vessel on the headstock and the bed. The young modulus of water was assumed to be 1×10^{-6} GPa for the small solid element. This value was taken with the assumption that there are very small solid elements in water. For comparison, the others countermeasures by injecting a polymer with concentration 2wt%, 4wt%, 6wt% 8wt%, and 10wt% were considered. The investigation by mixing water with a PEO (Polyethylene-oxide) to obtain jelly-like water for improvement of the damping ratio was also performed. The damping ratio value used for analysis was obtained from the result of the preliminary experiment in previous Fig. 3.6. In this analysis, the position of the supports (A-B-C) shown

in Fig. 3.7 was used. Free vibration analysis was firstly computerized and analyzed, and then the forced vibration analysis was performed by applying impact with 1N force to the upper part of the headstock along Y-axis. The force was applied along Y- axis because Y direction (of the bench lathe) is the cutting direction of the bite. Fig.3.8 shows the analysis result of the frequency response. The vertical axis is compliance of the vibration which is considered to have a very big influence on surface roughness of the workpiece. Large compliance will cause the surface roughness become coarse.

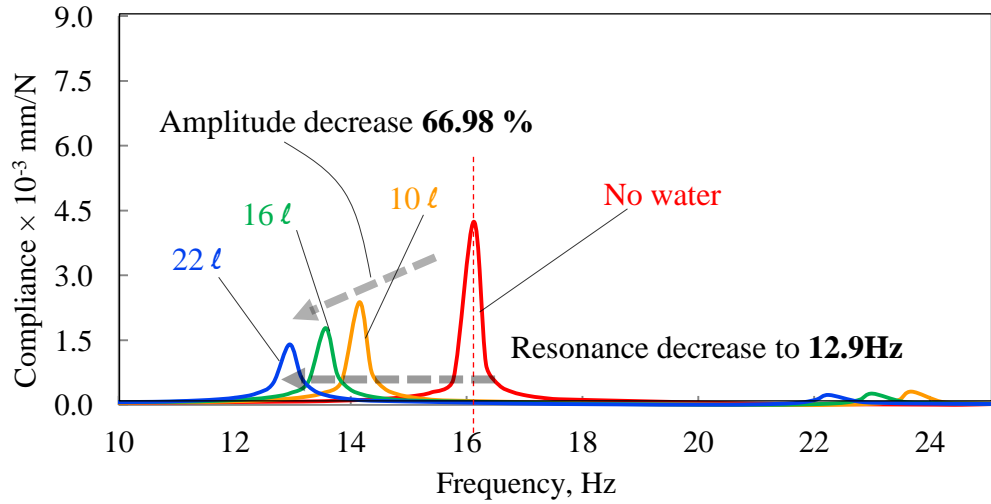


(a) Injection of water to vessel on the headstock (X-axis)

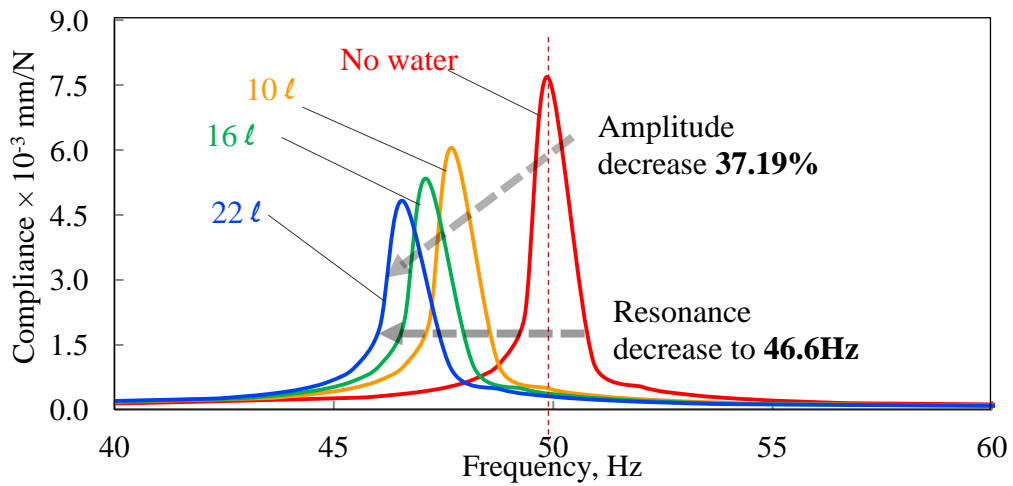


(b) Injection of water to vessel on the headstock (Y-axis)

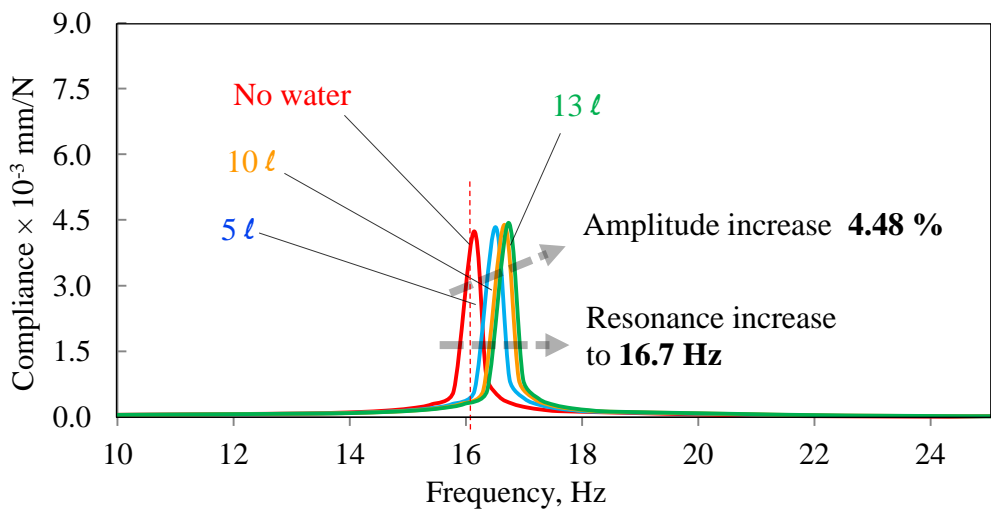
Fig.3.8 Frequency response of the bench lathe with different densities (Calculation using FEM)



(c) Injection of polymer to vessel ion the headstock (X-axis)

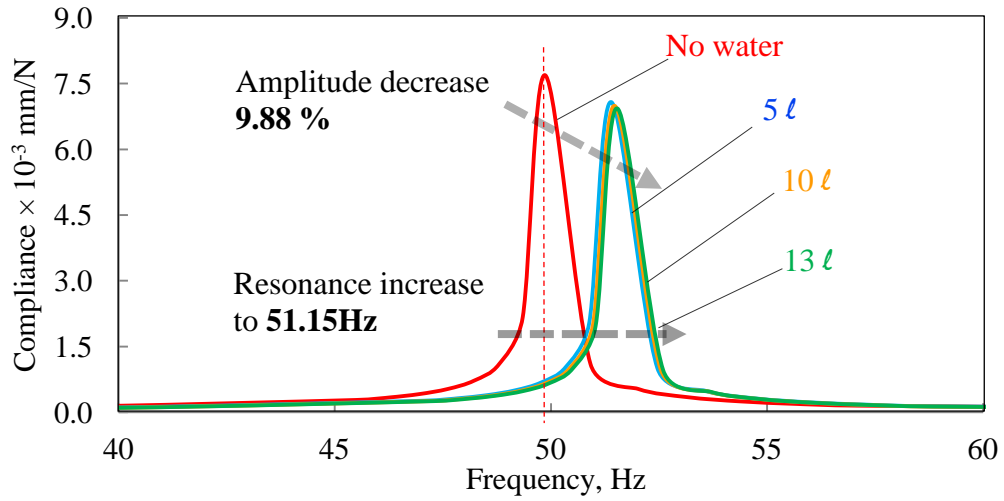


(d) Injection of polymer to vessel on the headstock (Y-axis)

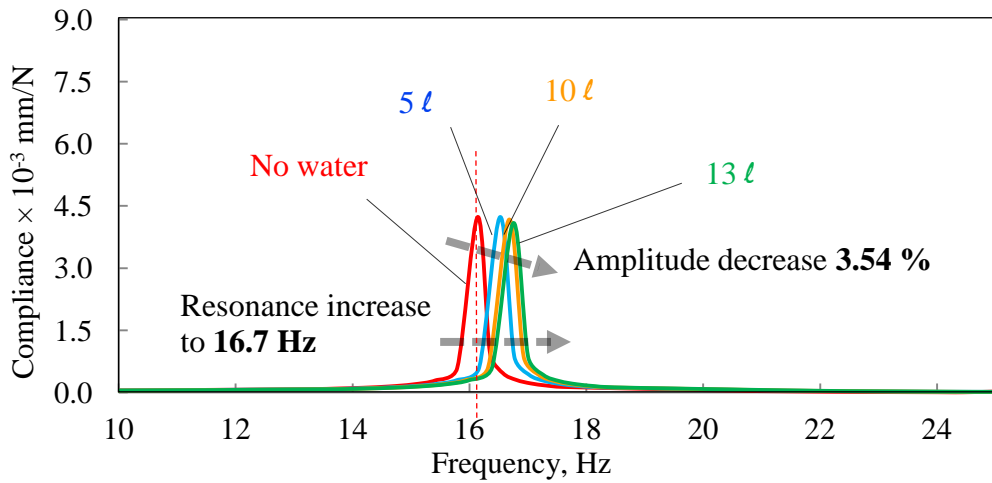


(e) Injection of water to the bed of machine (X-axis)

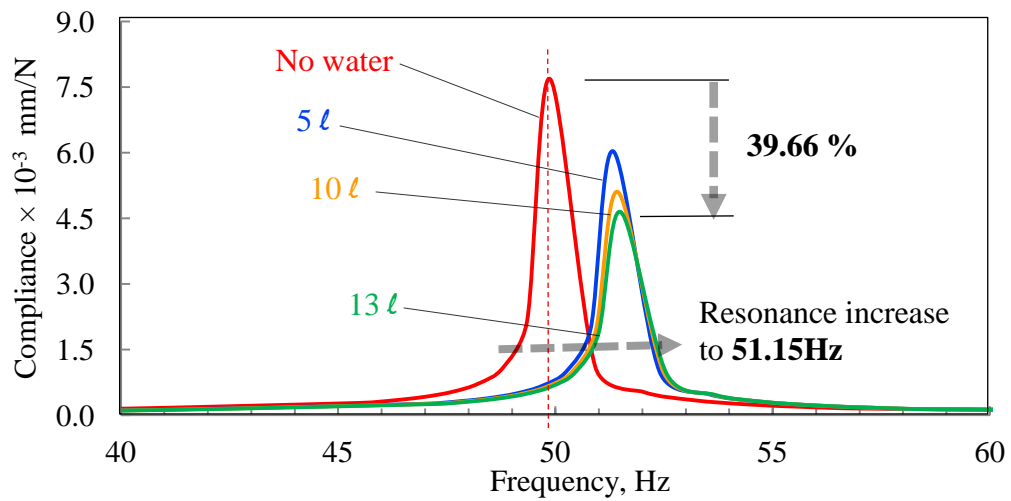
Fig.3.8 Frequency response of the bench lathe with different densities
(Calculation using FEM)



(f) Injection of water to the bed of machine (Y-axis)



(g) Injection of polymer to the bed of machine (X-axis)



(h) Injection of polymer to bed of machine (Y-axis)

Fig. 3.8 Frequency response of the bench lathe with different densities
(Calculation using FEM)

While, small or lower compliance can lead to fine surface roughness. Therefore, the analysis was done to obtain the optimum result with lowest compliance. The result of injecting water with the polymer to the headstock was shown that it is possible to reduce resonant frequency about 10 Hz. Fig. 3.8a), b), c), and d) show the results of the frequency response of the bench lathe computerized model filled with the water mix polymer to the vessel on the headstock while Fig. 3.8e), f), g), and h) represent the results of the frequency response by injecting water with the polymer to the space in the bed. The responses were calculated from the X-axis and Y-axis of the bench lathe. By injecting water into the vessel provided on the headstock of the bench lathe, the resonant frequency decreases to about 12.9 Hz in X-axis (Fig. 3.8a). The result also shows that by filling water up to 22 liters, the resonant frequency can be shifted up to 12.9 Hz in the horizontal direction. In Y-axis (Fig. 3.8b), the resonant frequency decreases to about 46.6 Hz with 22 liters of water. The more water is filled, the more frequencies will be shifted down. However, the more water is used, the amplitude of vibration increases significantly. The results of frequency responses in Fig 3.8(a) and 3.8(b) using 22 liters of water show that the amplitude of vibration increase about 17.22% and 8.84% in X-axis and Y-axis, respectively. From this result, therefore, it can be said that water is effective in controlling resonant frequency, however, less effective in reducing the amplitude of vibration.

The use of water may effective in reducing resonant frequency, however, since water tends to magnify the amplitude of vibration, therefore the method of mixing water with a polymer PEO for reducing amplitude of vibration is considered and analyzed. As explained earlier that water with the 6wt% polymer is very effective damper, therefore the mix of 10 liters, 16 liters, and 22 liters of water with 6wt% polymer concentration were used for

the simulation. The result of the frequency response in X and Y direction by filling with water mix 6wt% polymer concentration is shown in Fig 3.8(c) and 3.8(d), respectively. Fig. 3.8(c) is the frequency response in X-axis by injecting water with the polymer into a vessel on the headstock. The results show that the amplitude of vibration can be decreased about 66.98%. However, the decrement in the resonant frequency is similar to using only water. For vibration in Y-axis (Fig. 3.8d), the amplitude of vibration can be decreased about 37.19% while there is no change in the decrement of resonant frequency.

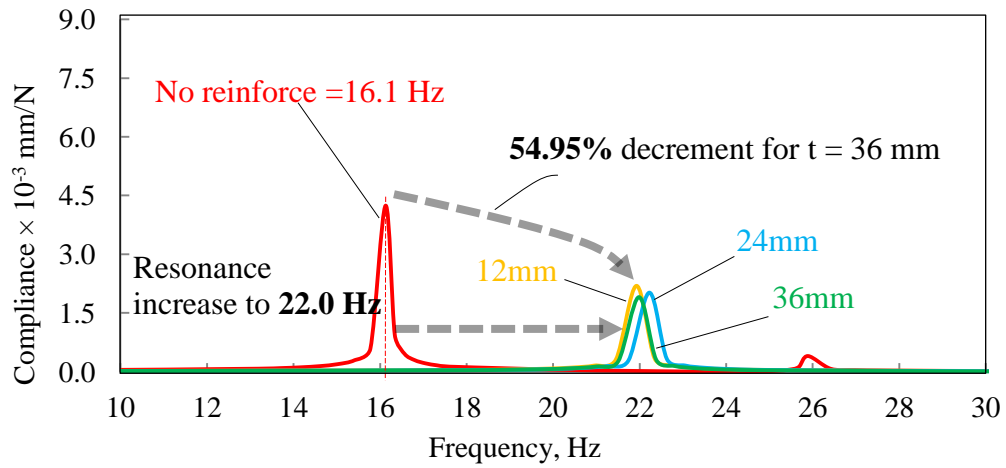
The result of the frequency response by injecting water with the polymer to the bed are shown in Fig. 3.8e), f), g), and h). The amount of water with quantity 5 liters, 10 liters, and 13 liters are used as parameters. The frequency responses calculated in X and Y axes by filling the machine bed with water is shown in Fig.3.8(e) and Fig.3.8(f), respectively. While, the frequency response in X and Y direction by filled the bed with water mixed 6wt% polymer concentration are shown in Fig.3.8(g) and Fig.3.8(h), respectively. The results show that by using only water, the amplitude of vibration in X direction increase about 4.48 % and the resonant frequency also shifts to 16.7 Hz. While in Y direction, the amplitude decreased about 9.88 % and resonant frequency increase to about 51.5 Hz. By mixed water with 6% polymer, the amplitude of vibration decreased about 3.54 % and 39.66 % in X and Y direction respectively while no further change in the resonant frequency.

In summation, by added with water, machine mass increases, thus shifts the resonant frequency. On the other hand, since water tends to magnify the amplitude of vibration, therefore the investigation for reducing vibration by increasing damping ratio of water was performed. The mixing of water with the polymer to become jelly-like water improved damping ratio significantly.

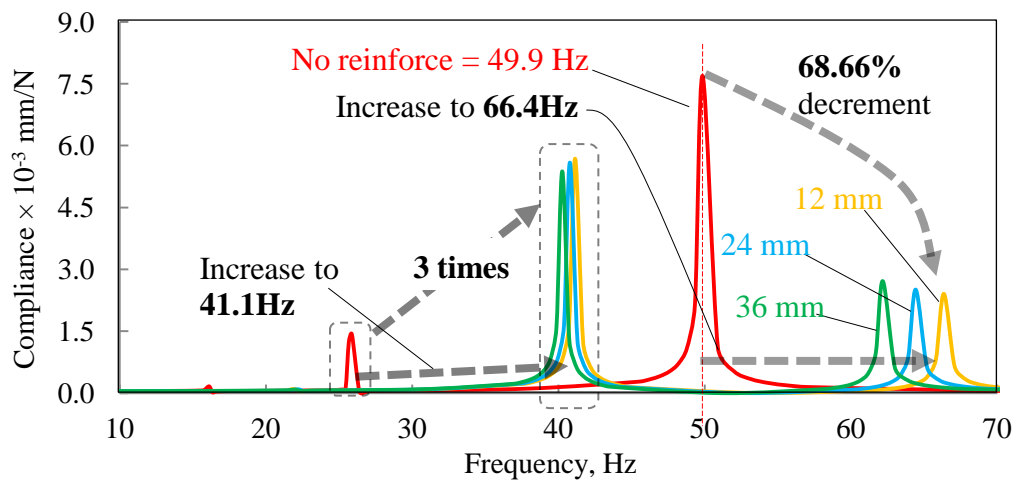
Thus, in this study, we decided to use water mixed with the polymer for optimum controlling resonant frequency. In contrast, by injecting water into machine bed, the resonant frequency only increases 2~3 Hz. This is because of the increment in weight which cause machine base becomes stronger, and therefore increases the structural stiffness and the resonant frequency. Moreover, with the small increment of resonant frequency using an injection of water in the bed, this countermeasure will be omitted in this study. However, we suggest that the injection of water into the machine bed can be very effective if the large space in machines is available to be filled with large amounts of water. By this way, the effect of water on the resonant frequency can be seen.

3.2.2 Reduce weight (lower density) and reinforce the structure (higher rigidity) for increasing resonant frequency

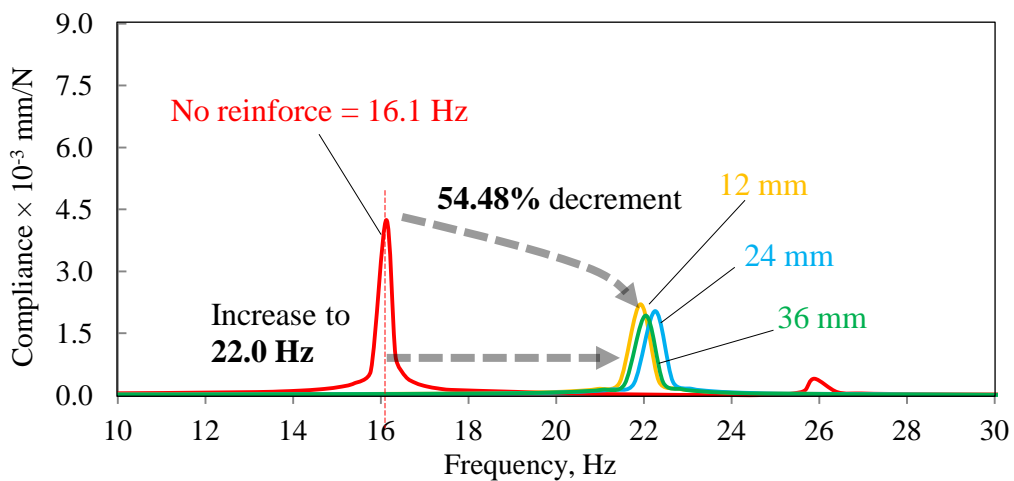
Based on free vibration analysis (Fig. 3.1), since the large vibration occurred on motor's holder, the reinforcement was decided to be applied under motor holder to higher rigidity the holder. By reinforcing the holder and weak parts of the machine, the machine structure will become stiffer, and thus higher resonant frequency. The analysis was performed for the reinforcing frame with thickness such as 12 mm, 24 mm, and 36 mm. To lighter the frame (lower the density), holes with different diameter such as 80 mm, 140 mm, and 200 mm were made on the center of each frame. The analyses were performed using similar condition as in the previous section. The free vibration of bench lathe machine supported at the support point (A-B-C) was firstly calculated. Then, the forced vibration was analyzed by applying 1N impact force to the upper part of the spindle on the headstock, and measured the response of vibration. The calculated results of frequency response are shown in Fig. 3.9.



(a) Reinforce without hole (X-axis)

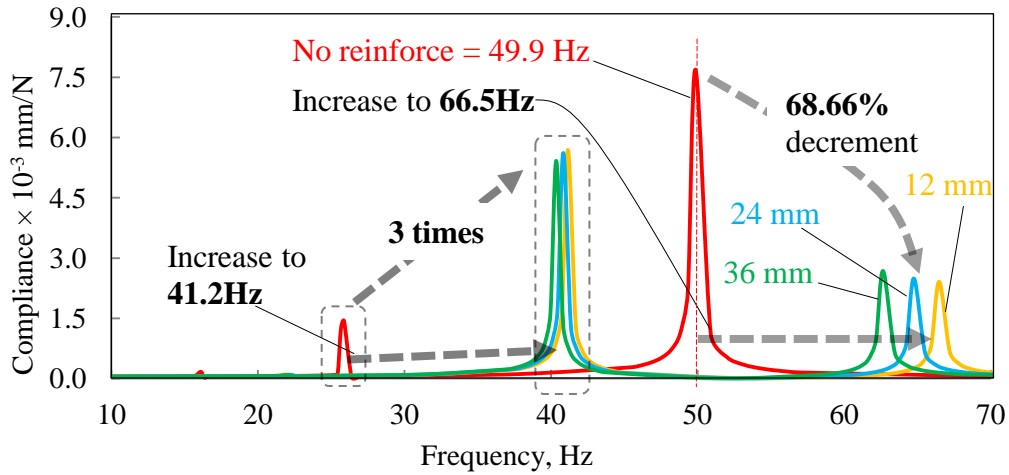


(b) Reinforce without hole (Y-axis)

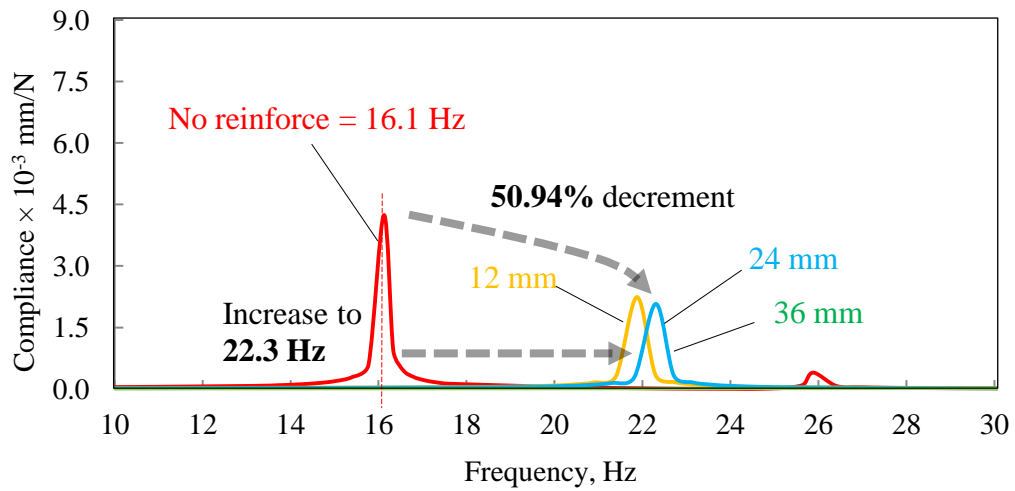


(c) Reinforce with $\varnothing 80$ mm hole (X-axis)

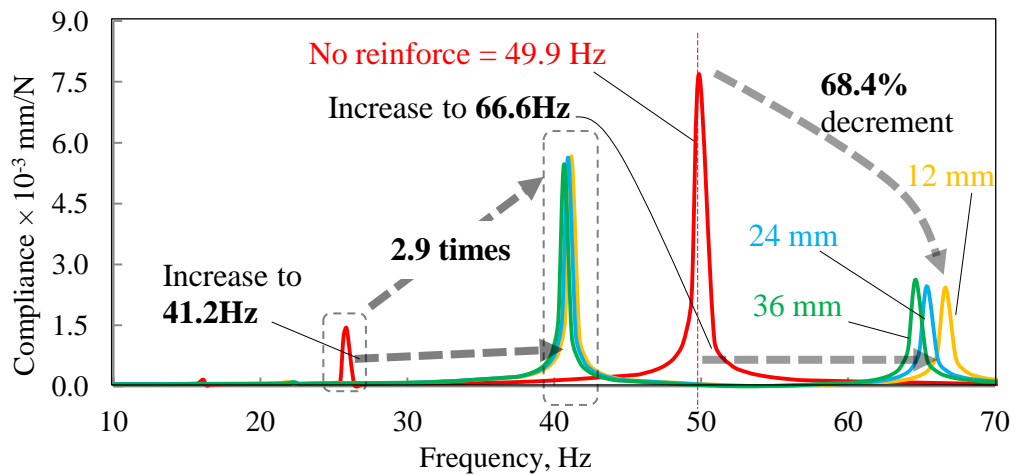
Fig.3.9 Frequency response of the bench lathe with different stiffness
(Calculated using FEM)



(d) Reinforce with Ø 80 mm of hole (Y-axis)

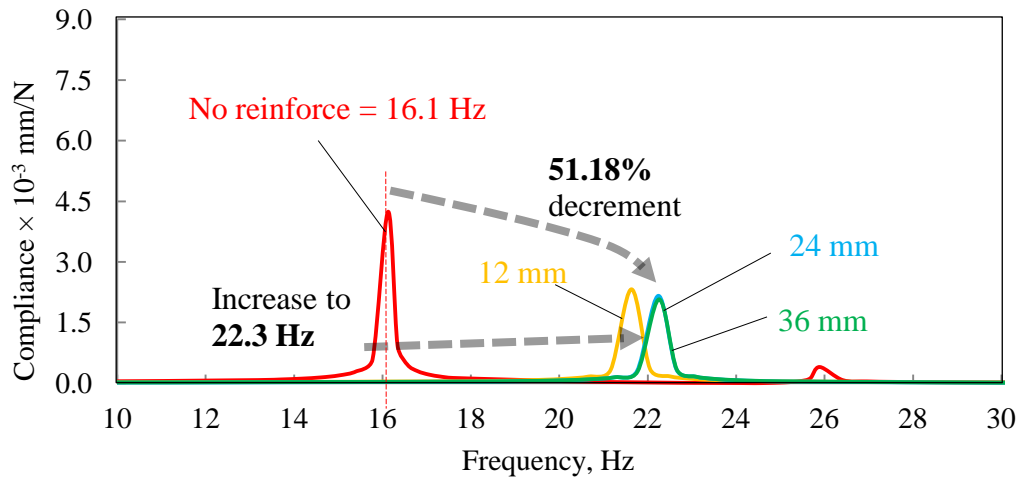


(e) Reinforce with Ø 140 mm of hole (X-axis)

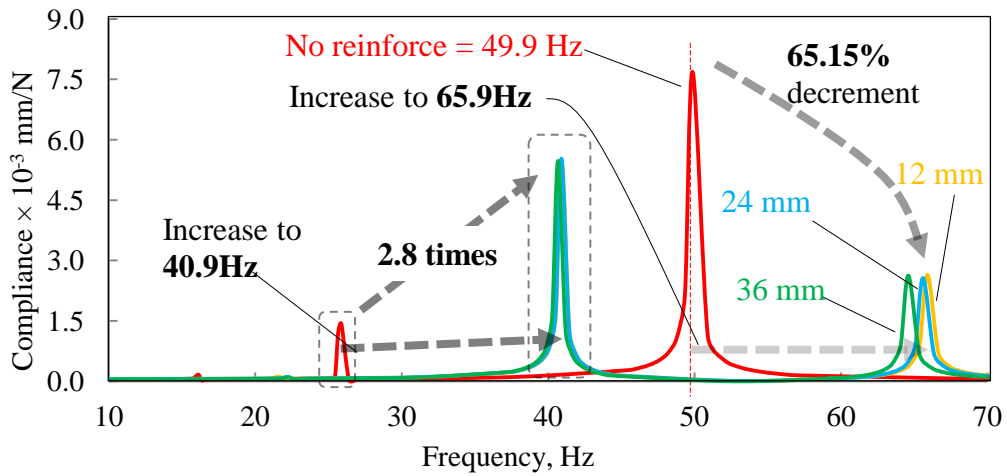


(f) Reinforce with Ø 140 mm of hole (Y-axis)

Fig. 3.9 Frequency response of the bench lathe with different stiffness
(Calculated using FEM)



(g) Reinforce with Ø 200 mm of hole (X-axis)



(h) Reinforce with Ø 200 mm of hole (Y-axis)

Fig. 3.9 Frequency response of the bench lathe with different stiffness
(Calculated using FEM)

Fig. 3.9(a) and (b) are the results of frequency response calculated in X and Y direction respectively using frames without a hole, while Fig. 3.9(c) and (d) are the responses by using the reinforcing frame with 80 mm diameter of the hole. The results of frequency response using the reinforcing frame with other holes measured in X and Y direction are shown in Fig. 3.9(e) and (f) respectively, for the hole with diameter 140 mm and in Fig. 3.9(g) and (h) respectively for the hole with diameter 200 mm. The results show that resonant frequency increases

about 10 Hz to 15 Hz by reinforcing machine structure. Although resonance frequencies increase in the 1st mode, the compliance also increases. We can see that without a hole on the frame, the resonance frequency increased to 22 Hz, and the amplitude of vibration decreased about 54.95 % when using reinforced frame with thickness 36 mm. These are the results from X direction. While, on Y direction, the resonance increased to about 66.4 Hz from its original resonance frequency 49.9 Hz, and the amplitude decreased about 68.8 %. However, by reinforcing the motor base, the other resonant frequency in the 2nd mode (24.5 Hz) increases to 41.1 Hz and its amplitude increases 3 times larger. Since the resonance controller is aimed to shift the frequency away from its original frequency and as long as the 1st, 2nd, or others frequency does not match the next frequency, it is acceptable. Hence, we can conclude that all three frames with different thickness and without a hole can shift frequency to about 22 Hz in X direction. However, only the 36 mm frame can reduce vibration to about 54.95 % compared to the others. While, frame with 12 mm thickness is better in shifting resonant frequency and reducing the amplitude of vibration in Y direction.

By using the reinforcing frame with Ø80 mm hole, the resonant frequencies increase up to 22 Hz and 66.5 Hz in X and Y direction, respectively (Fig. 3.9c and d). At the same time, the amplitude of vibration decreases about 54.48% in X direction and 68.66% in Y direction. It is revealed that the first resonant frequency in Y direction increases to about 41.2 Hz, but magnifies the amplitude 3 times larger. As explained earlier, since the shift of first resonant frequency in Y direction does not match the next resonant frequency, therefore it is acceptable. This parameter is also considered for evaluating the reinforcing frame with Ø140 mm and Ø 200 mm of a hole.

By using the reinforcing frame with Ø140 mm hole, amplitudes of vibration reduce about 50.94 % in the X direction and 68.4 % in Y direction while, resonant frequencies increase to 22.3 Hz and 66.6 Hz in X and Y direction

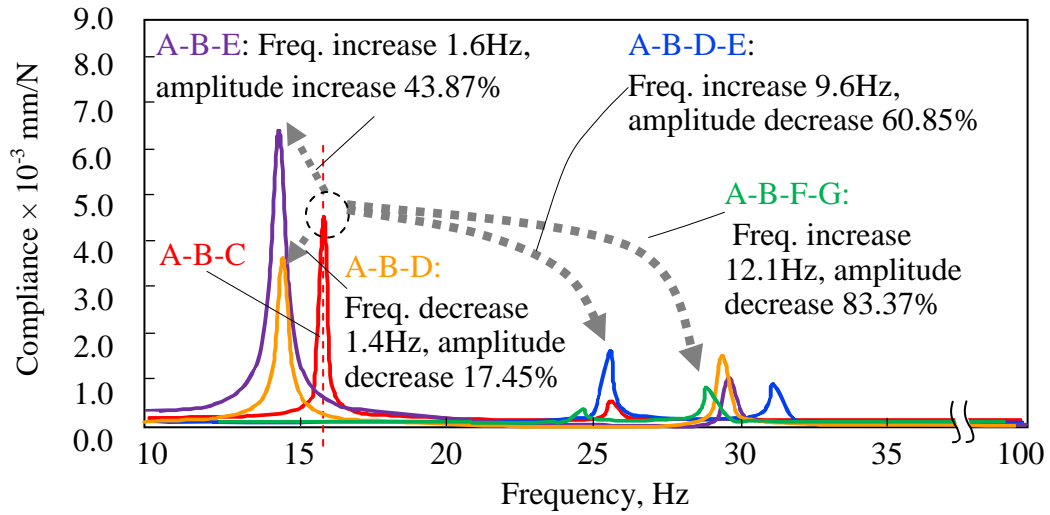
respectively. On the other hand, the use of reinforce frame with Ø200 mm hole shifts the frequency to about 22.4 Hz in X direction and 65.9 Hz in Y direction, while, the amplitude of vibration decreases about 51.18% and 65.15% in X and Y direction, consecutively. Based on the all results of using reinforce frame with different thickness holes, we can conclude by comparing the increment in resonant frequency between each result that reinforcing using Ø140 mm and Ø200 mm of hole can shift the frequency better than without using hole and using Ø80 mm of hole in X direction. However, in Y direction, the use of reinforcing frame without hole and with Ø80 mm hole are better. In case of reduction in amplitude of vibration, reinforce without hole reduce vibration much better than others in X direction, while frame without a hole and with Ø80 mm of the hole can reduce the amplitude of vibration better in Y direction. Because reinforcement without a hole can decrease the amplitude of vibration better than others in the X and Y direction, therefore this reinforcing method is considered to be used throughout this experiment. In case of the frame thickness, 36 mm frame thickness decreases vibration better in X direction while the 12 mm frame reduces the amplitude of vibration better in Y direction. Since the cutting during the experiment will be done from Y direction, therefore the 12 mm frame is decided to be used. For other machine tools that perform the cutting from X direction, the 36 mm frame is the best choice for controlling resonance and amplitude of vibration.

In summary, the calculated results show that resonant frequencies can be increased about 10 Hz to 15 Hz by reinforcement. Although the resonance frequency increases in the 1st mode, the compliance also increases. At the same time, the compliance decreases in 2nd modes. However, it is considered acceptable when the shifted frequency of the 1st resonance does not match the large resonance source that occurs at 50 Hz. Thus, although it is a very effective control for shifting up resonant frequency, consideration is required in case of

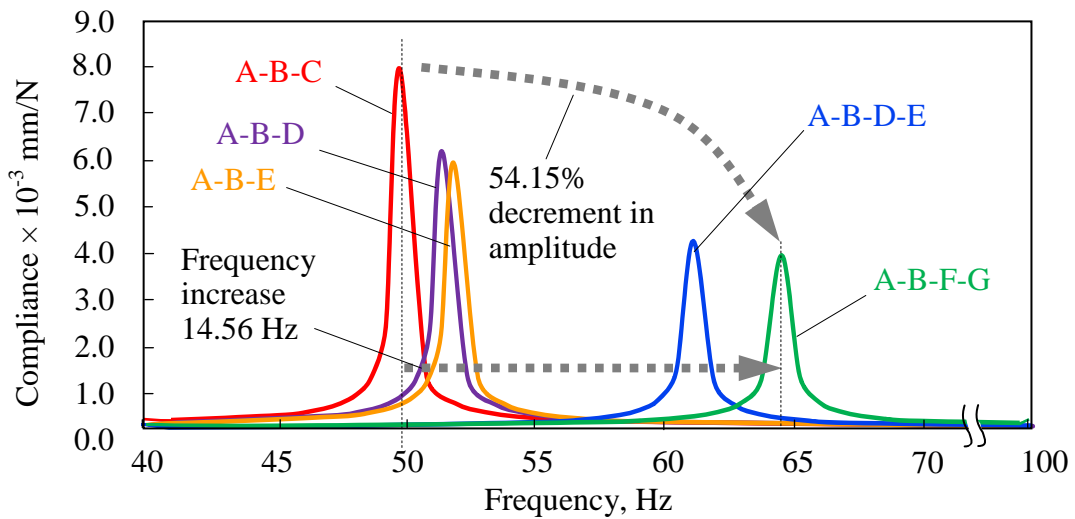
multiple resonant frequencies rise up simultaneously when attempting to avoid one resonance frequency, which the next resonant mode may become a problem. Thus, based on the analyzed results, frame with thickness 12 mm is sufficient for changing the resonant frequency. Moreover, installation of reinforcement frame under motor base can be done in short time with an easy installation using steel plates. However, applying hole to reduce weight is not much effective, hence omits from the application in the further experiment.

3.2.3 Changing support positions for changing resonant frequency and its mode shapes

Changing supports position is considered as third parameter for controlling resonant frequency. In this simulation, the positions of the support points that used for supporting machine tool were shown in the previous simulation model (Fig.3.7 for control factor III). The simplified computational model of the bench lathe machine was built for easy and fast calculation. The analysis condition for simulation uses in this section is using similar condition as 2 previous methods. The free vibration was firstly performed, and then the force vibration was measured by applying 1 N force to the headstock. The calculated results were obtained from the accelerometers placed on the headstock to detect vibration in the X and Y direction. The free vibration analysis was performed to observe changes in the bench lathe structure before analyzed forced vibration. In this simulation, the 5 different combinations of support positions are considered to be used as countermeasures. The frequency response of each countermeasure was firstly analyzed, and then their analysis results will be compared. The best response of the countermeasures will further be used for experimental evaluation. Fig.3.10 shows the calculated result of the frequency response using different support position. The result shows that,



(a) Resonance frequency in X-axis



(b) Resonance frequency in Y-axis

Fig.3.10 Frequency response of bench lathe with different supports (FEM calculation)

the resonant frequency can be shifted by using a different position of support points. Without applying any countermeasure (using main support of A-B-C), the resonant frequency of the bench lathe is 16.1 Hz and 49.9 Hz in X and Y-axis, respectively. When applying countermeasure by change support point to a different position, the resonance frequency of also shifts. Supporting positions A-B-D and A-B-E shift resonant frequency down in X-axis, while shift few hertz up in Y-axis. Although the support positions A-B-D and A-B-E shifted all resonance frequencies down in X direction, in the case of amplitude of the vibration, the

support position of A-B-E tends to magnify the amplitude about 43.87%, while the support position of A-B-D reduces amplitude of vibration about 17.45%. When the A-B-E support combination is used, the large magnification of amplitude occurs because the rotation of spindle forces the unsupported side of bench lathe to magnify in large oscillation. Opposite to the support positions A-B-D and A-B-E, the support positions A-B-D-E and A-B-F-G increase the resonant frequency up to 12.1 Hz in X direction and 14.56 Hz in Y direction. Not only the increment in resonant frequency, but the amplitude of vibration also decreases to about 83.37% and 54.15 % in X and Y direction, respectively. From these results, it can be said that support combination A-B-F-G is better in shifting the resonant frequency and at the same time lowering the amplitude of resonance.

In summary, by using the different combinations of the support points, the resonant frequency can be shifted about 10 Hz to 20 Hz. As the resonant frequency shifted when using proposed supporting method, the compliance values also change to some extent. Hence, this method considered effective.

3.3 Experimental evaluation for control method using bench lathe

The experimental for the evaluation of control methods for controlling resonant frequency were conducted using the bench lathe machine. The main support point used for supporting bench lathe machine is support combination A-B-C as shown in the photograph of the experimental setup in Fig.3.11. The bench lathe is driven by an electric motor which directly rotates the machine spindle. In this setup, we used the inverter for controlling the motor of the bench lathe for changing spindle speed during vibration measurement. The specification of the bench lathe for the experiment can be seen in Table 3.2. The electric motor directly rotates the spindle of the bench lathe. The maximum speed of the spindle of the bench lathe is 3600 min^{-1} . For vibration measurement, two

accelerometers (●) were placed on the top of the headstock in X and Y direction to pick accelerations of vibration up from the bench lathe and analyzes them using FFT analyzer. By using this main setup, the setting for evaluation of proposed control methods for each control factor was established and evaluated.

Table 3.3 Specification of the bench lathe for experiment

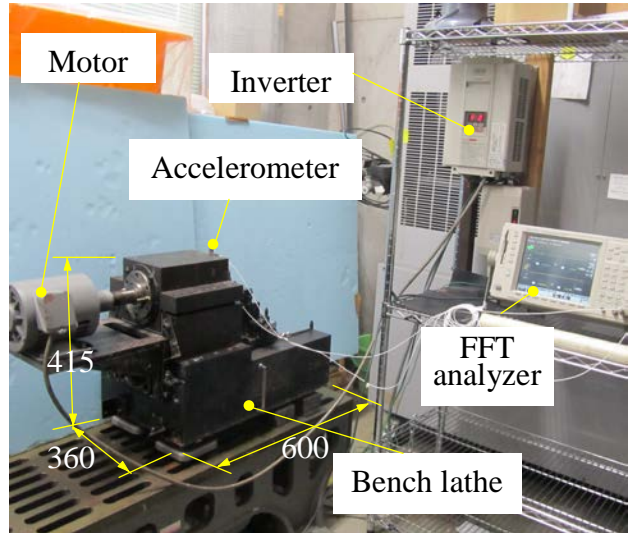


Fig.3.11 Photograph of experimental setup

Head stock	Height of center from bed	177 mm
	Height of center from floor	337 mm
	Spindle speed	Max.3600 min ⁻¹
	Front bearing	50BNC10TY DBB
	Rear bearing	45BN10TYD B
Bed	Size	600×360×160 mm
Tool post	Stroke of Y axis	30 mm
Table	Stroke of Z axis	200 mm
Motor	Power	0.75 kW
	Speed	Inverter control
Weight		200 N

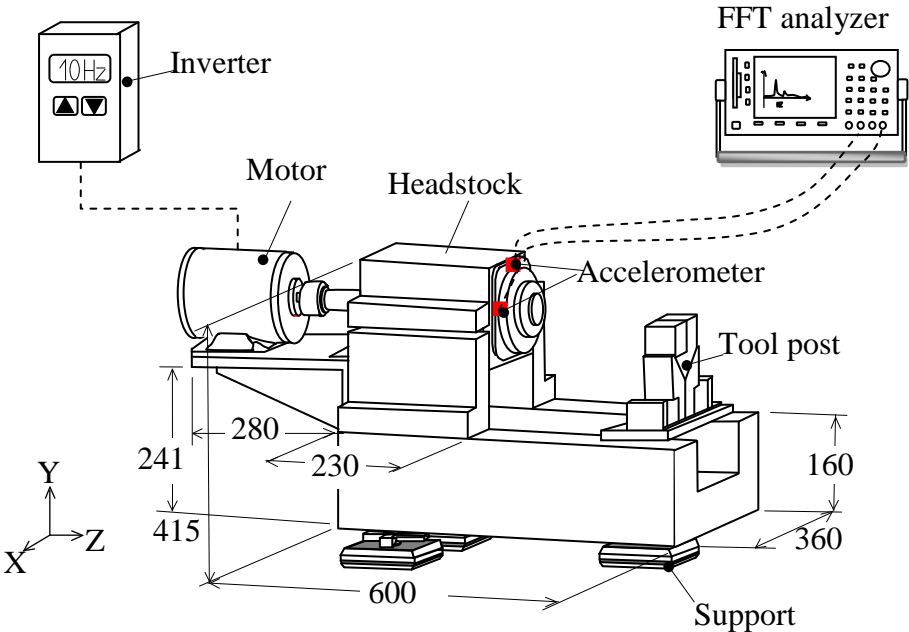


Fig.3.12 Experimental setup and the model of the bench lathe machine

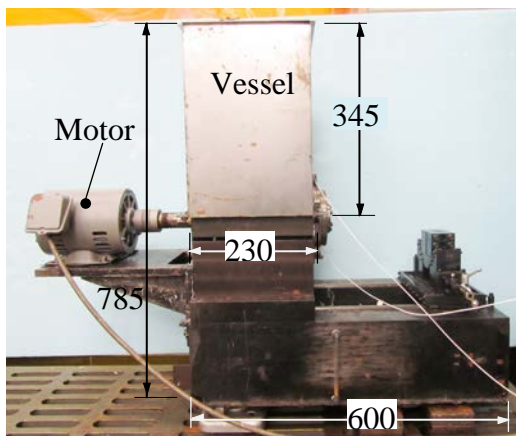
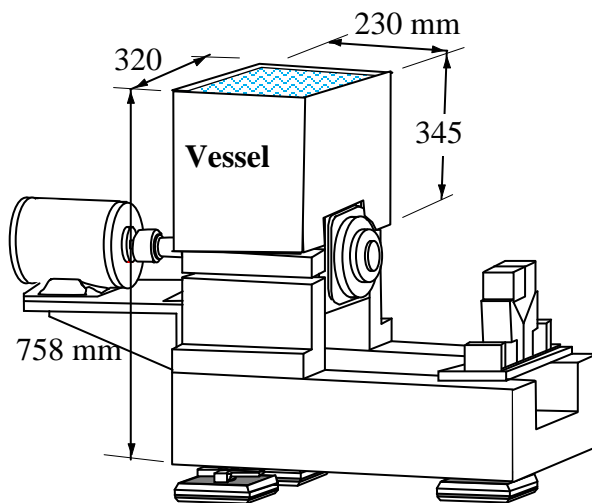
3.3.1 Experimental evaluation for control method using bench lathe machine

3.3.1.1 Control factor I

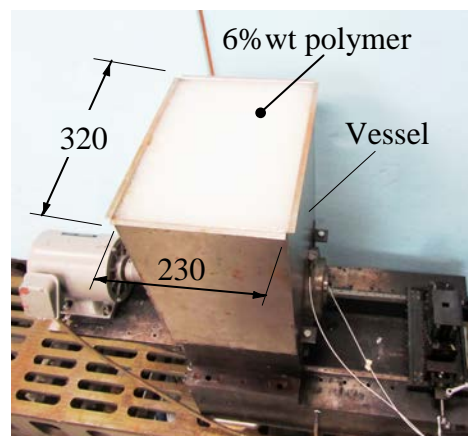
The experimental evaluation to increase density for lower resonant frequency was conducted. Based on the simulation results in the previous section, the injection of water into the bed of the bench lathe was not effective in changing the resonant frequency, therefore, omitted from the experiment. The only countermeasure used in control factor I is an injection of water mixed with polymer into the vessel provided on the machine's headstock.

Table 3.4 Parameter for control factor

Parameter for control I	
Amount of water	Polymer concentration
0	0
10	6wt%
16	6wt%
22	6wt%



Front view

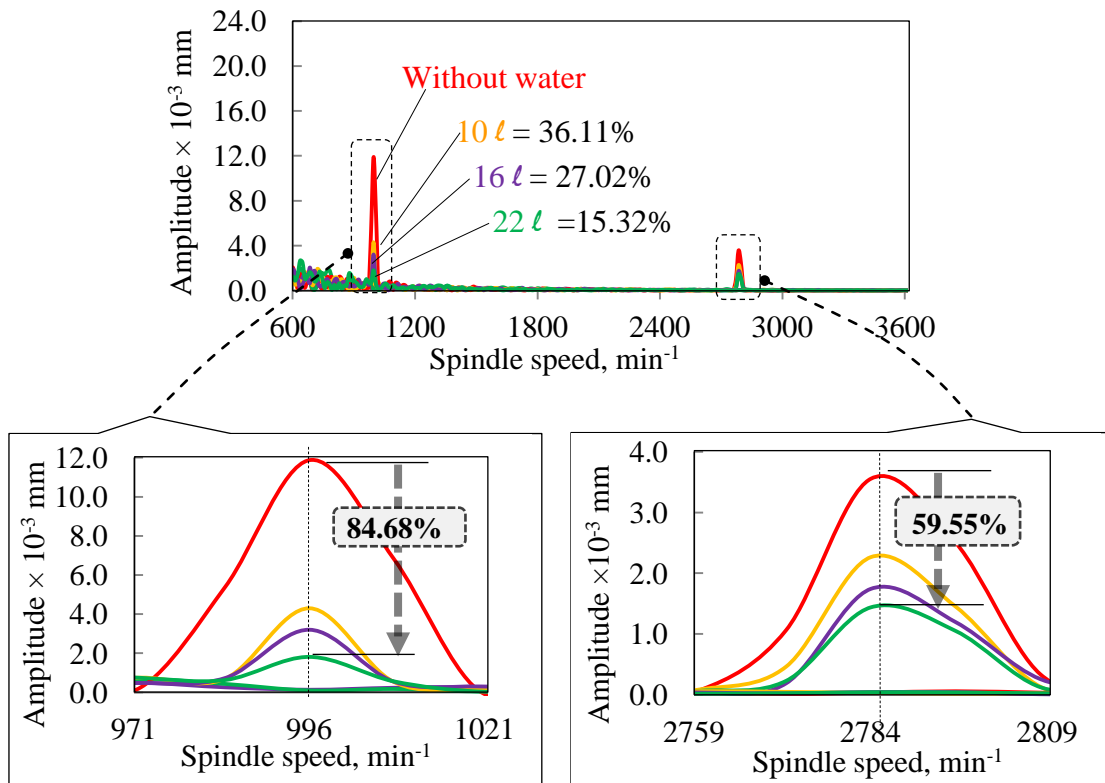


Top view

Fig.3.13 Model and photograph of the experimental setup for control factor I

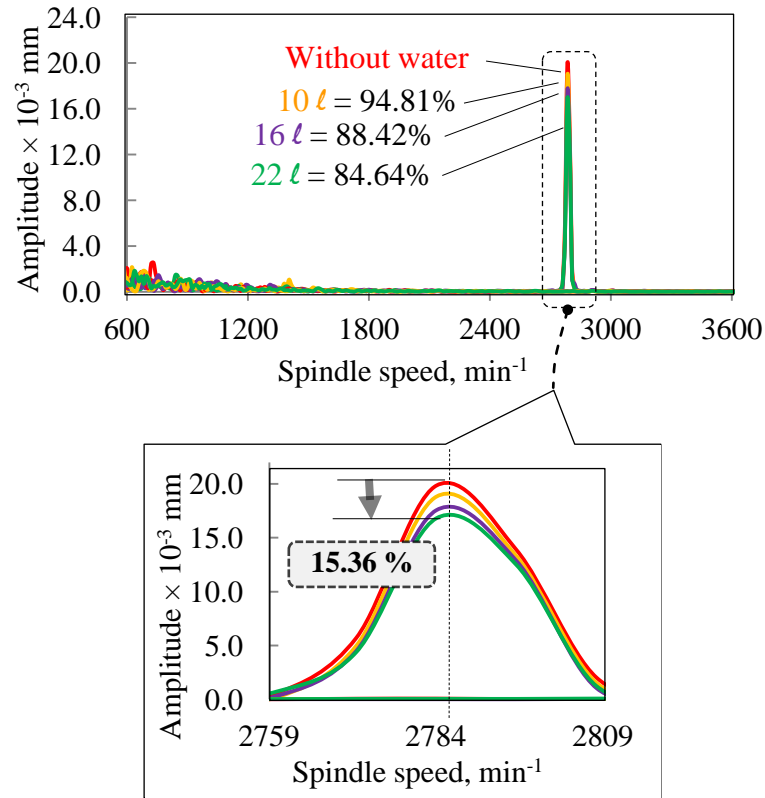
The experimental setup for control factor I is shown in Fig.3.13. In this experiment, we made a simple vessel for injection of water with polymer. The vessel was placed and tied by bolts on the headstock of the bench lathe similar to the simulation model from previous Fig. 3.3. The evaluation was done by evaluating the machine's vibration using parameters such as: without water, with 10 liters, 16 liters, and 22 liters mixed with polymer PEO with concentration 6 wt%.

The vibration measurement was conducted by operating the machine at the spindle speed of 996 min^{-1} and 2784 min^{-1} . These two spindle speed represent the resonant frequency of the bench lathe in X and Y direction respectively without applying any control. The spindle speeds were chosen because we want to evaluate the effectiveness control method (control factor I) by operating bench lathe machine coincided with its resonant frequency. Using these operating conditions,



(a) Vibration at X direction

Fig.3.14 Relationship between spindle speed (in resonance) and the amplitude of vibration by control of density (Experimental results)



(b) Vibration at Y direction

Fig. 3.14 Relationship between spindle speed (in resonance) and the amplitude of vibration by control of density (Experimental results)

the relationship between the amplitude of vibration in the headstock and the spindle speed was evaluated from X and Y direction of the bench lathe. The results of the experimental evaluation by injection of water mixed polymer are shown in Fig. 3.14. The horizontal axis represents spindle speed and the vertical axis represents the amplitude of vibration of the bench lathe. The results show that, amplitudes of vibrations without applying any countermeasure are very large in X direction for 996 min^{-1} and Y direction for 2784 min^{-1} . However, using the method by adding water mixed polymer to machine vessel, the amplitude of vibration decreases drastically. Vibration in X direction in Fig. 3.14(a) shows that by injecting water mixed 6wt% polymer, the amplitude of vibration is suppressed to very small when using 22 liters of water. The amplitude of vibration at the spindle speed

996 min^{-1} reduces about 85.68%, and 59.55% at the spindle speed 2784 min^{-1} . Meanwhile, vibration in the Y direction in Fig. 3.13(b) shows that there is very low vibration at spindle speed 996 min^{-1} , which is considered as a noise, therefore it is neglected. However, the amplitude of vibration is large at spindle speed 2784 min^{-1} without control. When the proposed method is applied, the amplitude of vibration can be reduced up to 15.36%, thus considered effective.

3.3.1.2 Control factor II

In this section, the experimental evaluation was conducted for control factor II. Based on the simulation results from the previous section, a SS40 steel plate was used to reinforce the motor stage. From the simulation results, some parameters such as, without reinforced and reinforce machine using the frame with thickness 12 mm and 36 mm were used. The result of this experiment will be compared with each other.

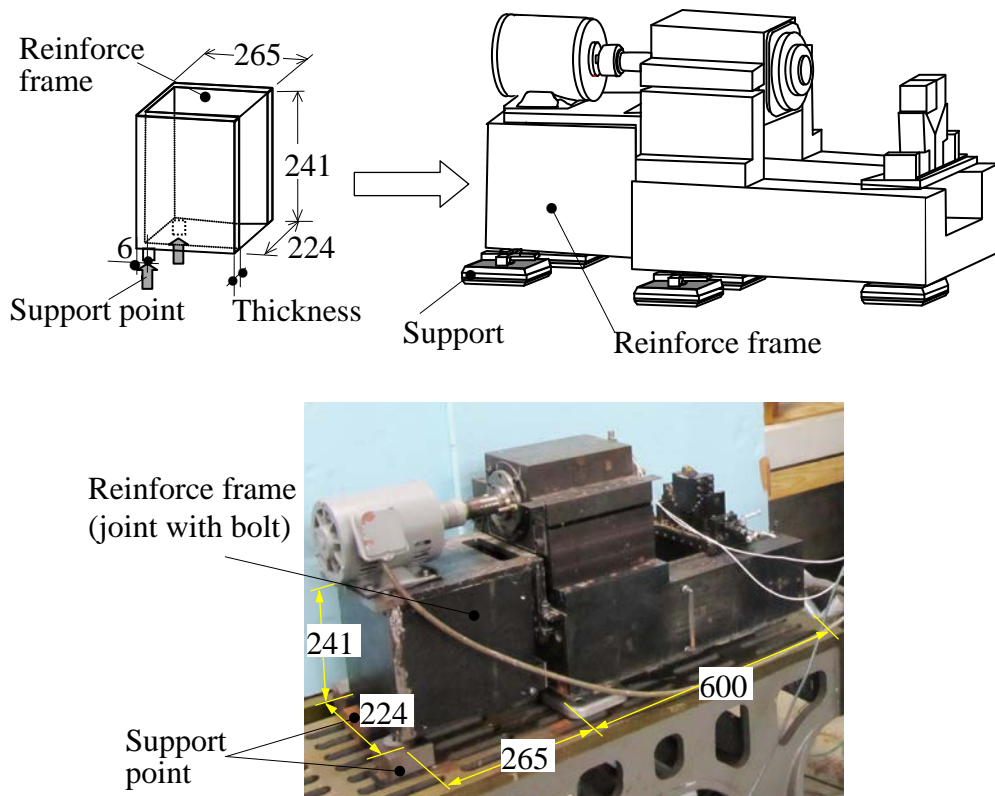


Fig.3.15 Model and photograph of the experimental setup for control factor II

Moreover, because the simulation result shows that making a hole on the frame was not very effective in changing resonant frequency and reducing the amplitude of vibration, therefore it was omitted from this study.

The experimental setup for evaluation of control factor II is shown in Fig. 3.15. The main support point used in this setup is A-B-C support combination. The main thickness of steel frame used in this experiment is 12 mm. To increase the thickness of frame for higher the stiffness, another 12 mm steel plate will be attached to each of three sides of the main frame by bolts. By joining the plate and frame with bolts, we can easily increase and decrease the frame thickness by add and remove the steel plate. Therefore, to increase the thickness of frame plate 36 mm, 2 pieces of 12 mm plate need to be attached on each side of the frame. When the thickness of the frame becomes bigger, the weight increases, which can

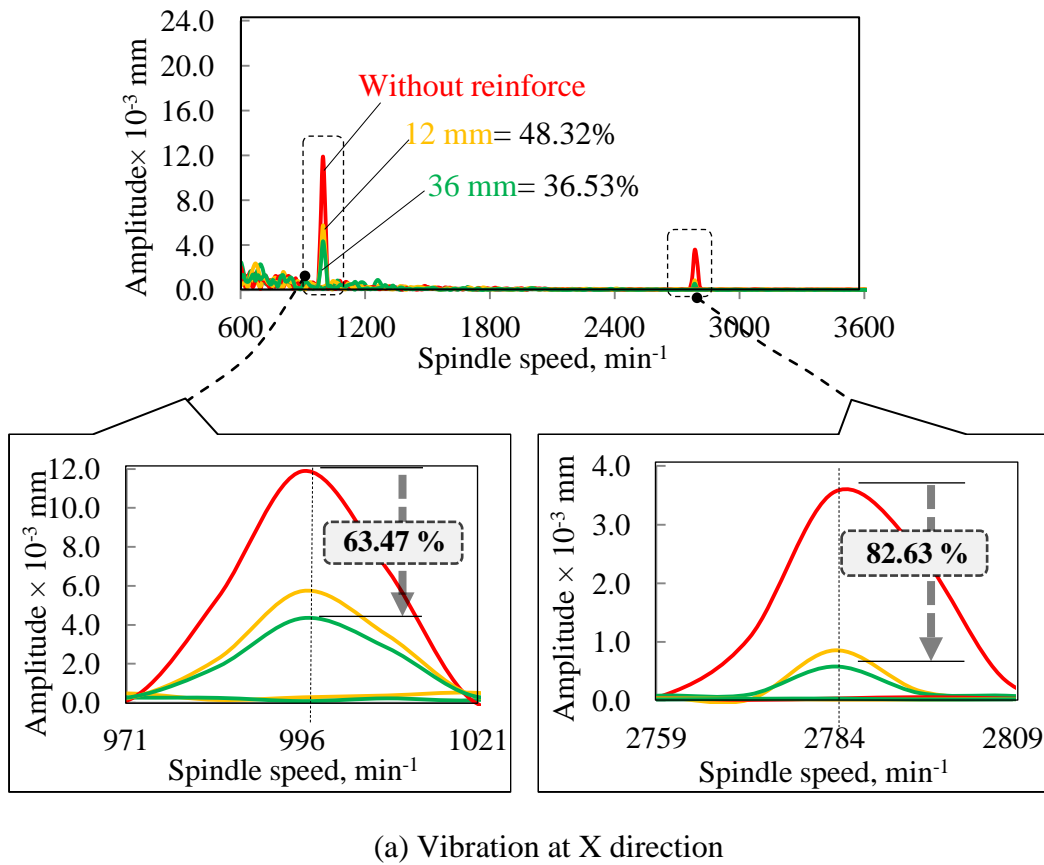
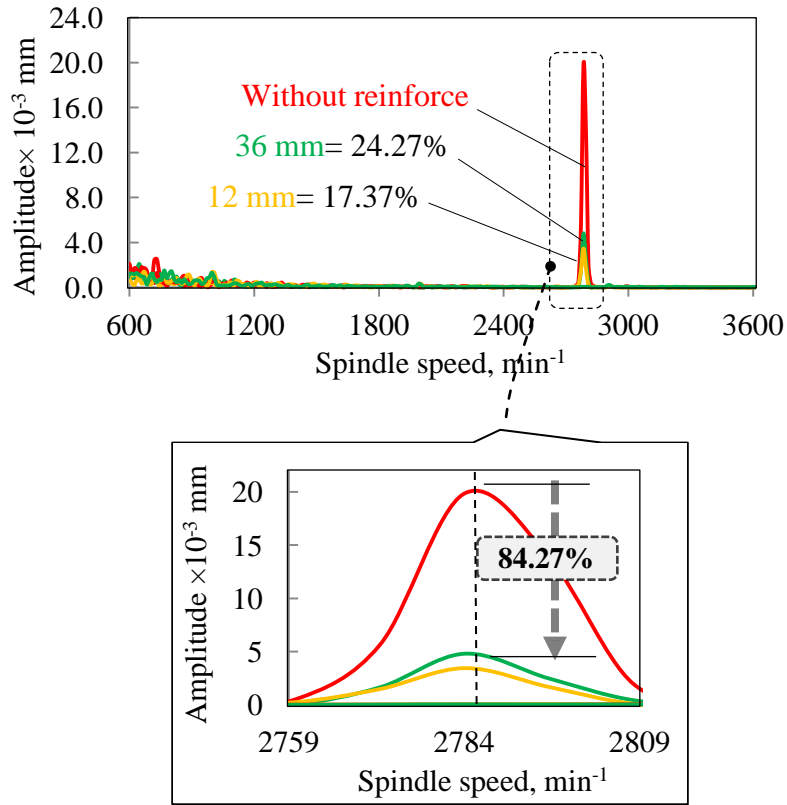


Fig.3.16 Relationship between spindle speed and the amplitude of vibration by control of stiffness and light weight (Experimental results)



(b) Vibration at Y direction

Fig. 3.16 Relationship between spindle speed and the amplitude of vibration by control of stiffness and light weight (Experimental results)

cause machine's headstock becomes heavier and resulting instability in the placement of the machine in case only main support (A-B-C) is used. Therefore, to prevent the occurrence this unstable condition, two support points were used for supporting the reinforcing frame. By using this apparatus setup and parameters, the experiment evaluation is conducted. The results of the experimental evaluation are shown in Fig. 3.16. The horizontal axis represents spindle speed and the vertical axis represents the amplitude of vibration of the bench lathe. In this experiment, the spindle speed was selected at 996 min^{-1} and 2784 min^{-1} . As we can see from the results that without applying reinforce, the amplitude of vibration when operating the bench lathe coincides with the resonant frequency of bench lathe in X-direction and Y-direction are very large. However, by using reinforce frame with thickness 12 mm and 36 mm, the amplitude of vibration reduced about

48.32% and 36.53 %, respectively in X-direction, and 24.27 % and 17.3 %, respectively in Y-direction. Moreover, by using reinforcing frame, the amplitude of vibration can be reduced to about 63.47 % for spindle speed 996 min^{-1} , and about 82.63% and 84.27% for spindle speed 2784 min^{-1} in X-direction and Y-direction, respectively. Thus, by using this method, installation and detaching are easy to be performed. In addition, simple control to higher stiffness can be easily done, and more importantly the resonant frequency can be shifted, which at the same time suppress the amplitude of vibration to become extremely low.

3.3.1.3 Control factor III

The experimental evaluation of control factor III by changing supporting positions was performed and evaluated. Based on simulation results in previous section, the resonant frequency can be effectively changed by using control factor III,

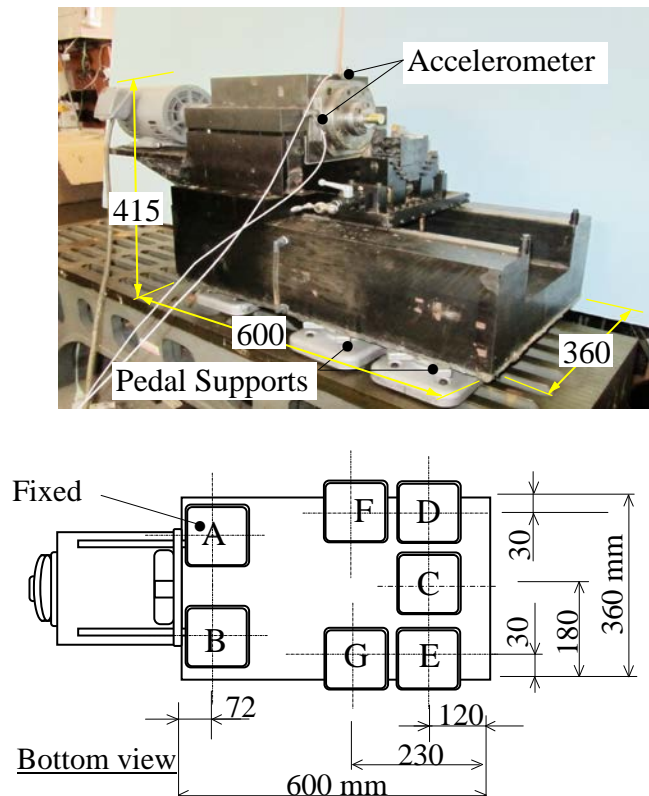
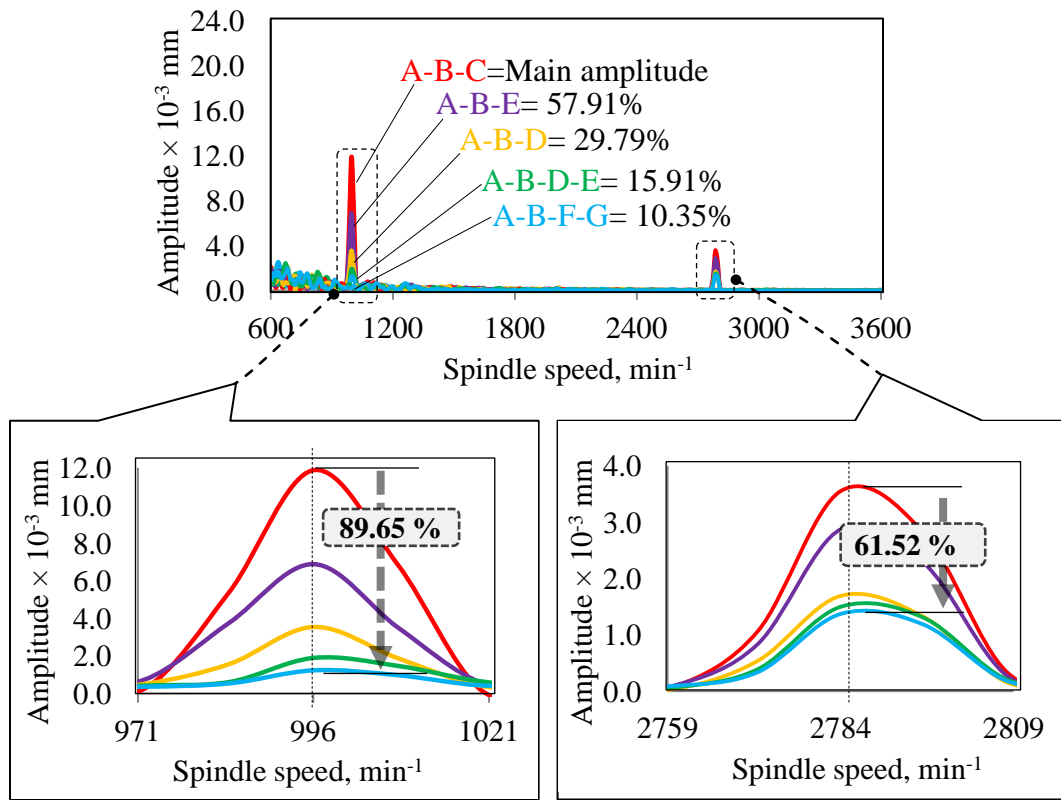


Table 3.5 Parameter for control factor III

Parameter for Control III	
No	Support combination
1	A-B-C
2	A-B-D
3	A-B-E
4	A-B-D-E
5	A-B-F-G

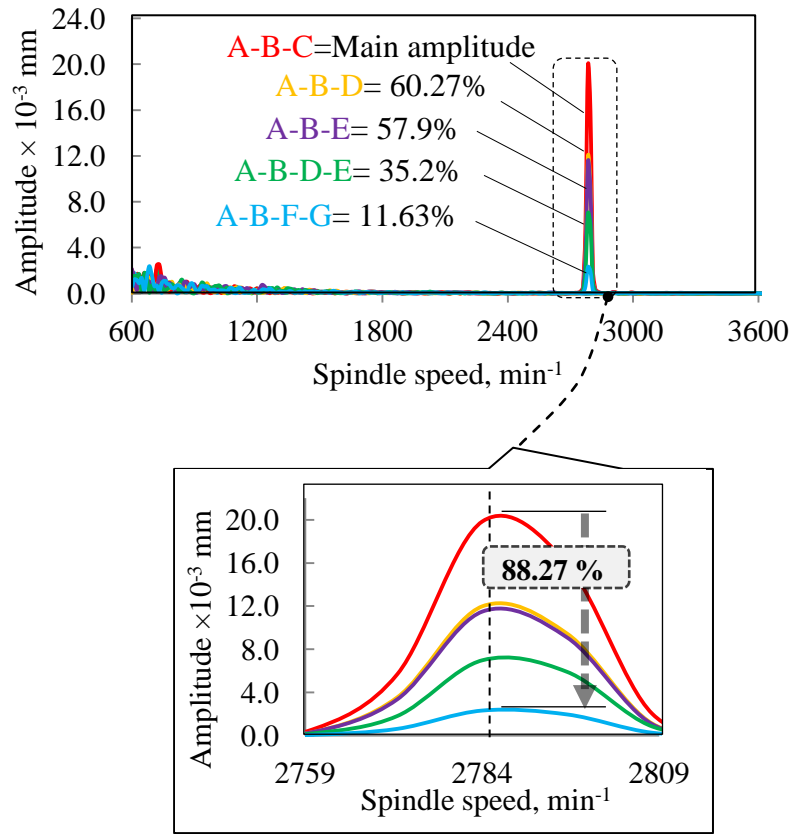
Fig.3.17 Model and figure of the experimental set up for control factor III and the model of bench lathe

therefore, the combinations of supporting point in the different position were used in this experiment to evaluate the effectiveness of the method in reducing the amplitude of the vibration. The experimental setup of bench lathe for the evaluation of control factor III is shown in Fig. 3.17. The bottom view model of the bench lathe was sketched to show the position of the support points. As we are viewing from the bottom of bench lathe, the seven supports point (A, B, C, D, E, F, and G) with the different position are used. With these support points, five different support combinations were used for the evaluation of the vibration. These five combinations are A-B-C, A-B-D, A-B-E, A-B-D-E, and A-B-F-G. The combined support of A-B-C is used as main support. These support points are equipped with bolt pockets for easy changing and adjusting.



(a) Vibration at X direction

Fig.3.18 Relationship between spindle speed (in resonance) and the amplitude of vibration by control of support (Experimental results)



(b) Vibration at Y direction

Fig. 3.18 Relationship between spindle speed (in resonance) and the amplitude of vibration by control of support (Experimental results)

When the A-B-C combination was used, support D, E, F and G are all loosed. The same setting when the A-B-D combination was used, the others supports (C, E, F and G) were loosed and so on. The amplitude of vibration of the bench lathe was measured and compared between the support combinations. The results of experiment evaluation using control factor III are shown in Fig.3.18. The measurement was done by using the same spindle speed as used in control factor I and II, which are 996 min^{-1} and 2784 min^{-1} . The result shows that the amplitude vibration at X-direction in Fig.3.18(a) reduces significantly when control method was applied by using support combination of A-B-E, A-B-D, A-B-D-E, and A-B-F-G. However, for the amplitude of vibration in Y-direction as shown in

Fig. 3.18(b), the support combination of A-B-E reduces the amplitude better than the A-B-D. Thus, the amplitude of vibration can be reduced using support combination of A-B-D, A-B-E, A-B-D-E, and A-B-F-G. The results show that using our control methods by changing support position, the amplitude of vibration can be decreased when the machine operated coincide with machine resonance. Moreover, with this control method, the amplitude of vibration can be reduced up to 89.65 % and 61.52 % at 996 min^{-1} and 2784 min^{-1} , respectively in X- direction, and also can be reduced up to 88.27 % for 2784 min^{-1} in Y-direction. Thus, it can be said that this control factor is effective in controlling the machine tool resonance.

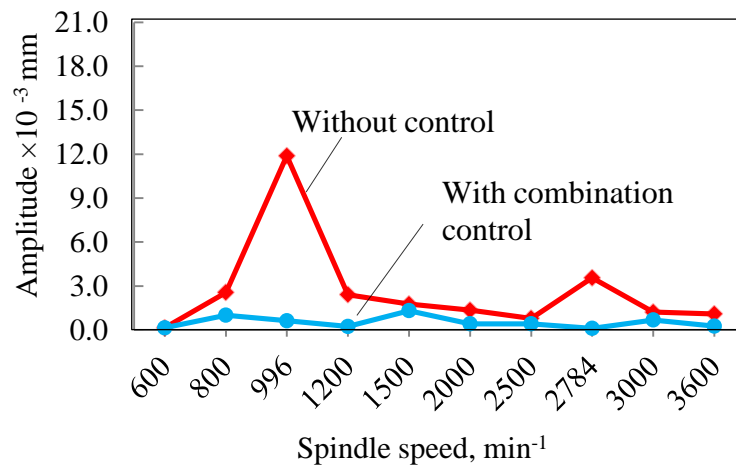
3.3.2 Optimum combination for three countermeasures of control factors

After evaluating the effectiveness of reducing the amplitude of vibration for each control factor, the optimum combination of three countermeasures (control factor I, II, and III) were conducted and evaluated. The combination between

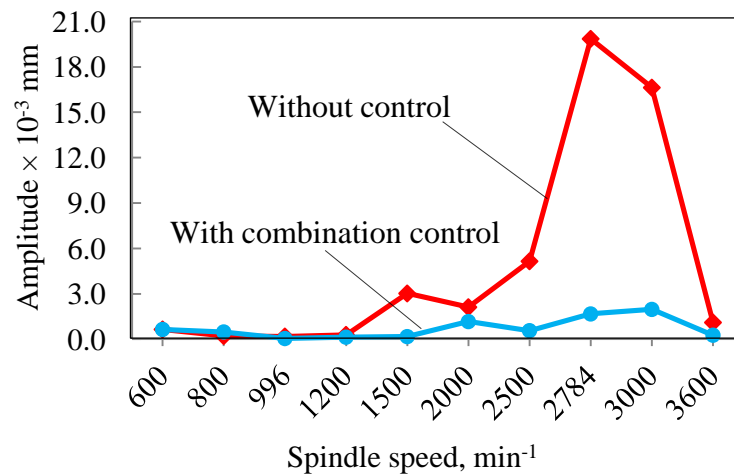
Table 3.6 Optimum combination for three countermeasures

Spindle speed (min^{-1})	Control factor I (Density)	Control factor II (Stiffness)	Control factor III (Support)
600	-	-	A-B-C
800	-	12 mm	A-B-F-G
996	22 liter	-	A-B-C
1200	10 liter	-	A-B-D
1500	-	12 mm	A-B-E
2000	10 liter	-	A-B-E
2500	22 liter	-	A-B-F-G
2784	16 liter	-	A-B-F-G
3000	-	12 mm	A-B-D-E
3600	10 liter	-	A-B-C

control factor I and control factor III was used to optimize the decrement in density of the bench lathe, while the combination of control factor II and control factor III were used to optimize the increment of stiffness of the bench lathe. Various spindle speeds of the bench lathe were selected in this experiment to evaluate the optimum combination control in each spindle speed. In this experiment, the frequency of inverter was used to control spindle speed. Table 3.5 shows the result of the optimum combination for three countermeasures.



(a) Vibration in X direction



(b) Vibration in Y direction

Fig.3.19 Amplitude of vibration at optimum density, stiffness and support (Experimental results)

The optimum combination of the three control factor at the spindle speeds from 600 min^{-1} to 3600 min^{-1} are proposed. The vibrations responses of control using these combinations are shown in Fig. 3.19 with the horizontal axis represent spindle speed and the vertical axis represents the amplitude of vibration. The results show that the amplitude of vibration is large without control and even larger when the bench lathe operated coincide with resonant frequency at spindle speed 996 min^{-1} and 2784 min^{-1} . However, the amplitudes of vibration were reduced to extremely small when the combination control was applied. And also, the vibration resulting from the operating machine coincide with resonant frequency is decreased to only 10%, which is 1/10 smaller compared to without using combination control. Thus, to perform optimum control in controlling the resonant frequency and reducing the amplitude of vibration, combinations that are shown in Table 3.5 are suggested to be used.

3.4 Evaluation by real cutting

Finally, the real cutting experiment is conducted using bench lathe and the effectiveness of the proposed method was evaluated. Based on the result of optimum combination using the three control methods, the cutting application is performed using an ordinary bench lathe machine with cutting condition used in the experiment is shown in Table 3.6. The machine resonance was controlled based on the results of optimum combination control (Table 3.5). The cutting was performed on round bar 3603 alloy brass with diameter $\varnothing 18 \text{ mm}$ and length 40 mm. By using brass $\varnothing 18 \text{ mm}$ as a workpiece, the calculated optimum spindle speed for the cutting is 2784 min^{-1} . However, the measurement result of resonance of bench lathe shows that large vibration occurs at spindle speed 2784 min^{-1} in Y-direction (Fig. 3.19b, without control), the use of this spindle speed will resulting in poor cutting result. Therefore, to achieve the optimum

cutting result for using optimum cutting condition, our proposed control method was applied. Based on the result of the optimum combination control shown in Table 3.5, the optimum control method at the spindle speed of 2784 min^{-1} is the combination of the 16 liters water mixed 6wt% polymer concentration and the A-B-F-G support combination. In addition, for comparison, the same experiment was also performed using the conventional without any countermeasure.

Table 3.7 Cutting condition for evaluation of this method

Cutting speed		158 m/min
Feed speed		0.1 mm/rev
Spindle speed		2784 min^{-1}
Cutting depth		0.2 mm
Tool	Material	Carbide, T725X
	Type	Round
	Nose radius	6 mm
Workpiece		Brass, C3603 $\text{Ø}18 \times 40 \text{ mm}$
Control of resonance frequency	Density	16 liter
	Stiffness	-
	Support	A-B-F-G

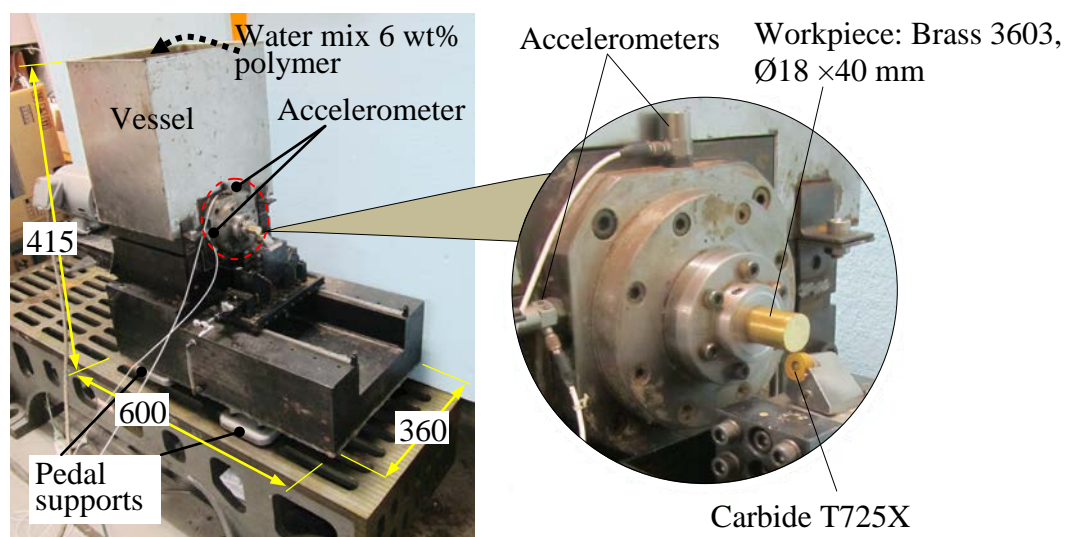


Fig.3.20 The photograph of bench lathe machine with combination control

The results of the frequency response of the bench lathe without control and with our method are shown in Fig. 3.21. It can be seen that the forced vibration frequency of the machine during operation that coincide with the machine resonance can be avoided by controlling resonant frequency. In the results, the amplitude of vibration becomes smaller and dynamic stiffness of machine structure in regard to vibration is also improved.

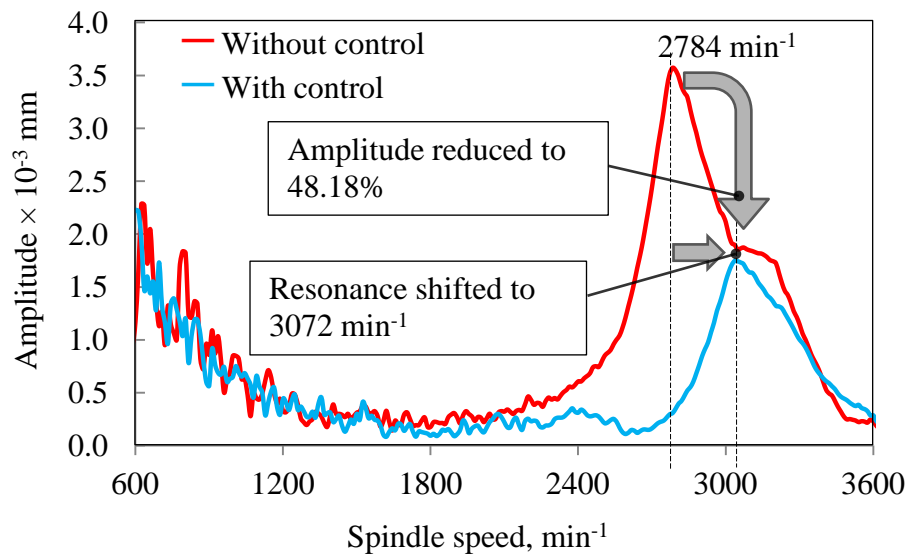


Fig.3.21 Frequency response of the bench lathe with control of resonance frequency (Experimental results)

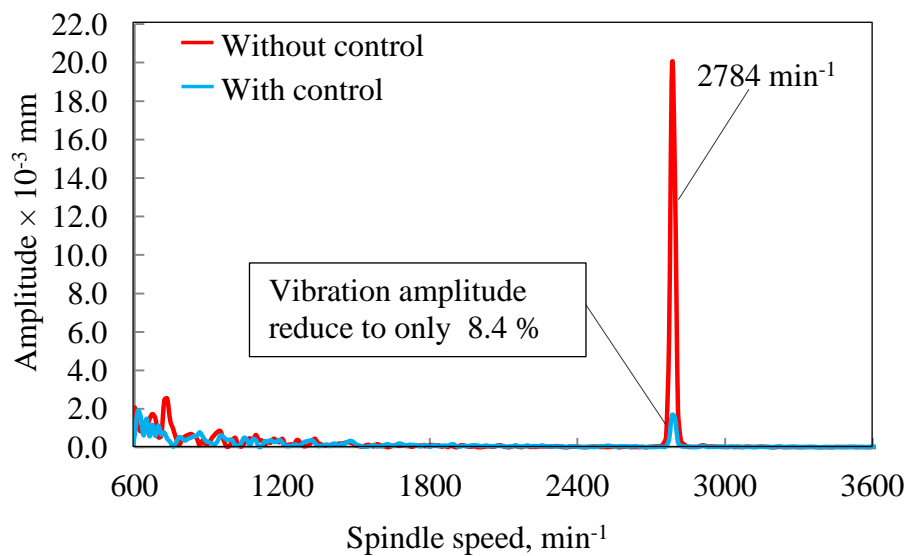


Fig.3.22 Amplitude of vibration when operating machine at 2784 min⁻¹

Fig. 3.23 shows the oscillation during the cutting. There is an extremely large difference between oscillation amplitude with and without applying control. Normally, when the resonance frequency coincides with optimum spindle speed, operation with this optimum cutting condition is difficult to be used for machining. Therefore, by controlling resonant frequency, resonance phenomenon can be avoided and vibration of the workpiece during cutting can be suppressed.

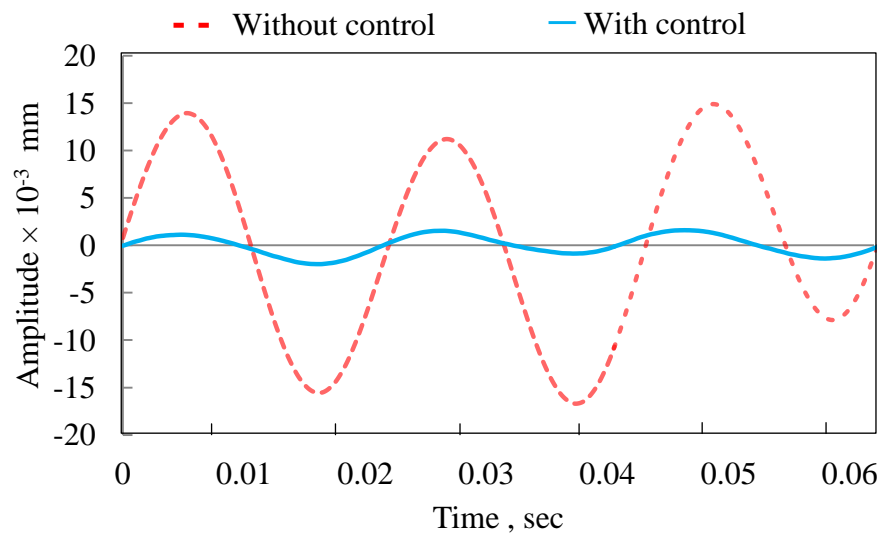


Fig.3.23 Result of vibration oscillation of bench lathe during cutting from Y direction (Experimental results)

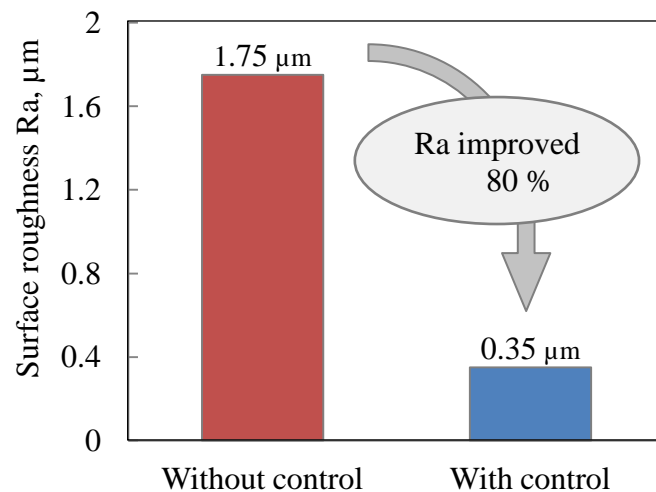


Fig.3.24 Surface roughness of the work piece using control resonant frequency (Experimental result)

Fig. 3.24 shows the comparison result of surface roughness of the workpiece after the cutting. By cutting using the conventional method, surface roughness is $1.75\text{ }\mu\text{m}$ and by control resonant frequency, surface roughness improves to only $0.35\text{ }\mu\text{m}$. Although a normal small bench lathe was used, the surface roughness was improved and the smooth surface likes grinding process can possibly be obtained. This result is well related with the previous result of vibration oscillation in Fig. 3.23.

In summation, the proposed control techniques for controlling resonant frequency make it possible to perform cutting at the optimum cutting condition, and high processing accuracy also becomes much easier to be achieved. Thus, improve surface roughness and final cutting result, reduce processing time, and minimize processing cost which is important in the manufacturing and industries.

3.5 Summary

From the above results, it is confirmed that the developed technique regarding changing machine tool resonance is capable to maintain and optimize the used of cutting condition during machining in resonance zone. The result of this study can be concluded as follows:

- (1) The method of controlling the resonant frequency of machine tool was developed by; changing density of machine structure, stiffness and support positions.
- (2) By filling water mixed with 6wt% polymer to the machine's structure, can reduce the resonant frequency and achieved higher damping ratio simultaneously.
- (3) The real cutting by applying this method was evaluated, the resonance was successfully avoided, and surface roughness of the final cut was also improved.

Chapter (4)

DEVELOPMENT OF FORCED COOLING TECHNOLOGY ON DRILLING USING ALKALINE WATER WITH MICROBUBBLE

4.1 Introduction

Generally, drill bit becomes extremely hot and easy to wear out as it drills deeper into the workpiece which is considered severe for continuous drilling during the drilling process. The deeper drilling is, the heat caused by friction between the drill bit and workpiece build-up in the drill bit, which can cause failure and breakage, that shorter tool's life. For this reason, cermet drills have been introduced besides conventional high-speed steel and cement carbide drills for the great toughness and heat resistance ^[4-1]. Various cooling and lubricating system have also been used to dissipate heat from the tip of the drill bit and prolonging drill life ^{[4-2], [4-3]}. However, although the technique ^[4-4] of supplying high-pressure cutting fluid has been used, the cooling effect is still insufficient, and also from the viewpoint of environmental protection, it is not preferable. Moreover, to reduce the coefficient of friction of tool surface and cutting heat generation, a solid lubricant of the surface coating of DLC ^[4-5] and TiAlN^[4-6] are frequently being used in manufacturing. However, these solid lubricants are also not perfect yet from the viewpoint of their strength and durability. Thus, in this study, the forced cooling by using the phenomenon of evaporation effect ^[4-7] of water to achieve force cooling by supplying water to the through-hole drill was developed. Microbubbles were added to strong alkaline water (pH 12.5) in order to accelerate the effect evaporation cooling. In this study, firstly, the optimal specification of strong alkaline water was clarified by experiments. Then, the

heat load of the drill was reduced by supplying strong alkaline water with microbubbles through the through-hole drill and evaluated by an experiment. Moreover, the effectiveness of this method for the industrial application was evaluated by performing drills experiment.

4.2 The characteristic of the strong alkaline water added with microbubbles

4.2.1 The characteristic of strong alkaline water

Water is a very good conductor of heat nevertheless has drawbacks as a cutting fluid. Since the beginning of the 20th century, when F.W. Taylor used water for the first time to cool the machining process and concluded it increased tool life, a large variety of cutting fluids has been used for this and other purposes^{[1-7],[4-8]}. Although the effectiveness of water evaporative cooling is very large compared with the use of cutting fluid, there are still only few applications being used in industries because it corrodes any steel material around it. Therefore, the mixing of water with another solvent as water-miscible cutting fluid for cooling has been widely used in processing and manufacturing^[4-9]. However, in the last decade a lot has been done aiming to restrict usage of cutting fluids in the production and manufacturing due to the costs related issue, ecological issues, human health and other related problems to the environment and surroundings. With these reasons, the use of strong alkaline water as cutting fluid was introduced in this paper.

As mention earlier that water enhances corrosion, but oppositely the use of strong alkaline water is best as cutting fluid because it did not corrode most of the metals. The corrosion by water can be inhibited by higher pH of water to pH 12.5 (Alkaline water) to be able to use for cooling during machining. Therefore, in this research, the corrosion proof inside the strong alkaline water

for the most materials which are being used well in industries is clarified by experiment. The specification of the strong alkaline water generation equipment for generation of strong alkaline water with pH 12.5 used in the experiment is shown in Table 4.1. The strong alkaline water was firstly measured to define the change of pH over 2 months by leaving in the ambient condition of $20^{\circ}\text{C}\pm 1$, $40^{\circ}\text{C}\pm 1$ and $12^{\circ}\text{C}\pm 1$ as shown in Table 4.2. It is confirmed from the result shown in Fig. 4.1 that the pH only decreases 0.2 at $12^{\circ}\text{C}\pm 1$, 0.3 at $20^{\circ}\text{C}\pm 1$ and 0.5 at $45^{\circ}\text{C}\pm 1$, therefore it is considered can be used for a long period of time.

Table 4.1 The specification of strong alkaline water device


	Method of generation	Closed generation type
	POCA (K_2CO_3)	2.18 g/ℓ
	Value of pH	pH 12.5
	Quantity of generation	10 ℓ/h
	Voltage & Power	100 V & 300W
	Size	495W×430D×1100H

Table 4.2 Test condition for changes of alkaline water pH

Medium in container	Strong alkaline water
Ambient condition	$20\pm 1^{\circ}\text{C}$, $40^{\circ}\text{C}\pm 1$ and $12^{\circ}\text{C}\pm 1$ Humidity: 60%
Quantity of water	10 ℓ
Size	Ø 250×230 mm

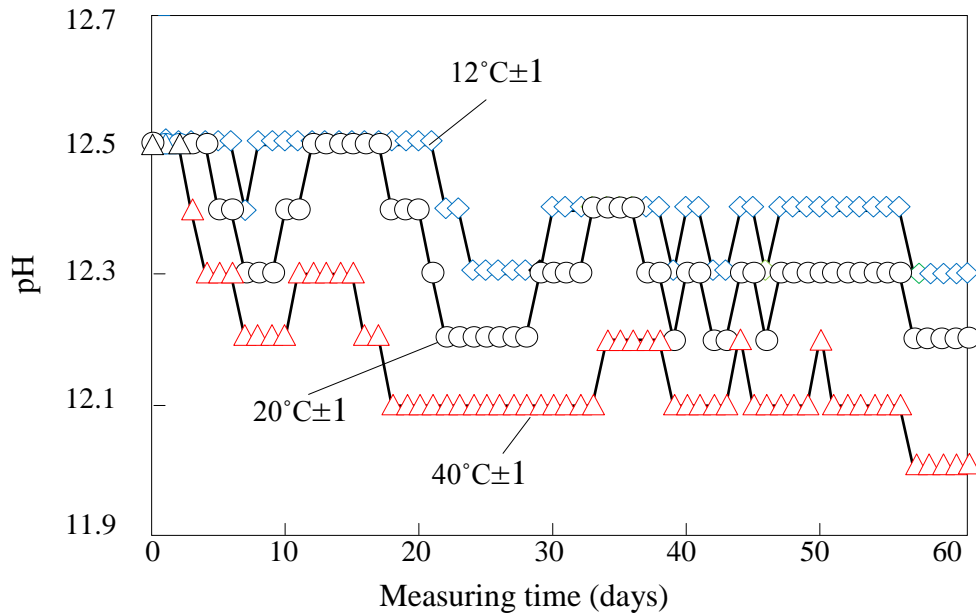


Fig.4.1 Variation of pH values at different temperatures





As explained in previous chapter 2, based on the corrosion properties of strong alkaline water ^[2-29] in the case of steel, the corrosion will not occur when the pH of strong alkaline water is more than 10.0, while nickel base alloys in the range of pH 8.5 ~ pH 13.0. In addition, in the case of titanium alloys, its chemically passivity range is below pH 13.0. From these facts, it is considered that cutting titanium alloy and nickel base alloy materials by submerging them in the strong alkaline water and forced cooling by water evaporation can reduce the heat effect on the tool. Therefore, the pH value of strong alkaline water between pH 10.0 ~ pH 13.0 is considered appropriate for this application. Moreover, for corrosion proof, the workpiece materials are tested in the strong alkaline water with condition shown in Table 4.3 at constant room temperature of $20 \pm 1^\circ\text{C}$ and 60 % humidity for two months. The alkaline water was replaced once a week to maintain its pH value. The experimental results of the corrosion resistance of materials in strong alkaline water are shown in Table 4.4. Few workpiece

materials tested in the experiment are: pure titanium, titanium alloy, nickel-based alloys, common industrial product materials such as; steel (S45C), aluminium, brass, copper, cutting tool materials such as; high-speed steel tool,

Table 4.3 Condition for corrosion test

Medium in the vessel	Strong alkaline water (pH 12.5)
Ambient conditions	Room temperature: 20±1 °C, Humidity: 60%
Period	Two months

Table 4.4 Results of the materials tested in strong alkaline water with pH12.5 (for two month)

Workpiece materials	Condition in the strong alkaline water			Tool materials	Condition in the strong alkaline water
Inconel 718	○			Carbide (S30T, T725X)	○
				High speed tool	○
Ti6Al4V	○			Ceramics (LX11)	○
				Cermet (NS530)	○
Ti (pure)	○			CBN (KBN525)	○
				Diamond (DA2200)	○
Steel (S45C)	○			Coating materials of tool	
Aluminum	×			TiC	○
Copper		Changed to dark brown		TiN	○
				DLC	○
Brass		Changed to dark green		TiAlCr	×
				TiAlN	×

Symbol: ○ = No Corrosion, × = Corroded

carbide, cermets, ceramics (alumina) CBN, diamond, and coating materials such as; TiN, TiC, DLC, TiAlN, TiAlCr. The results were achieved through experimentation by putting these materials into the tube filled with strong alkaline water of pH 12.5 using condition in Table 4.3. The results show that most types of materials show no corrosion after kept in strong alkaline water for two months except aluminium and aluminium alloys. Therefore, it is considered possible to perform cutting of steel, titanium alloy, and nickel alloy by immerse completely in strong alkaline water. However, for the case of cutting aluminium, the use of alkaline water exhibits corrosion, and thus cautions are required to be taken. In addition, it should also be noted that the surface of copper and brass are decolorized.

4.2.2 The characteristic of the microbubbles

In this research, we considered that large cooling efficiency can be achieved by supplying strong alkaline water with microbubble via through-holes on the drill to the cutting point. The photograph and the specification of microbubble device used to generate microbubble are shown in Fig.4.2 and Table 4.5, respectively.



Fig.4.2 Photograph of microbubble device

Table 4.5 Specification of microbubbles device

Microbubble device		
Model		A-01
Power consumption	kW	0.56
Water quantity	ℓ/min	8~11
Pressure	MPa	0.35~0.45

This device generates thousand of air bubbles with the distribution of bubble sizes in microbubbles shown in Fig.4.3. The large amount of the generated bubble size is 10 μm bubbles. As air bubbles disappear in short time, therefore, in order to supply microbubble to the cutting point, the lifetime of microbubble in the water was measured by released microbubbles into the strong alkaline water. Fig.4.4 shows the experiment setup for measuring bubble life in alkaline water. In this experiment, 30 ℓ of strong alkaline water was filled in a vessel, and then microbubble was supplied for 10 minutes with flow rate 8 ℓ/min . The time taken for strong alkaline water (pH 12.5) to become transparent again was measured. The measurement was also performed for the bubble sizes 1~2 mm and 3~5 mm, that were supplied to the strong alkaline water with flow rate 32 ℓ/min .

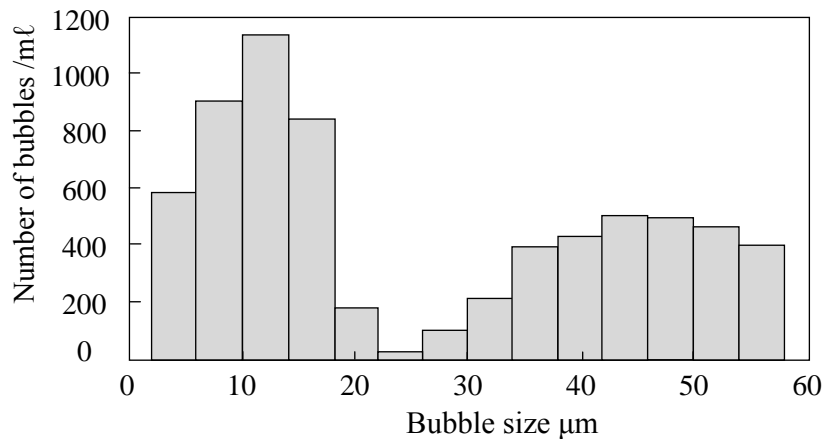


Fig.4.3 Distribution of bubble size in microbubbles ^[4-10]

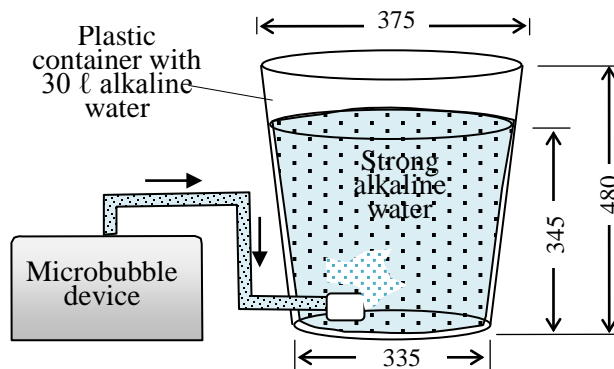


Fig.4.4 Experiment setup for measurement of the lifetime of air bubbles in alkaline water

The appearance of the different bubble sizes can be seen in Fig.4.5. Water becomes milk-like color when microbubbles were generated in strong alkaline water. The measurement result of bubbles life is shown in Fig.4.6. It is observed that microbubbles were retained for about 5 minutes in strong alkaline water,

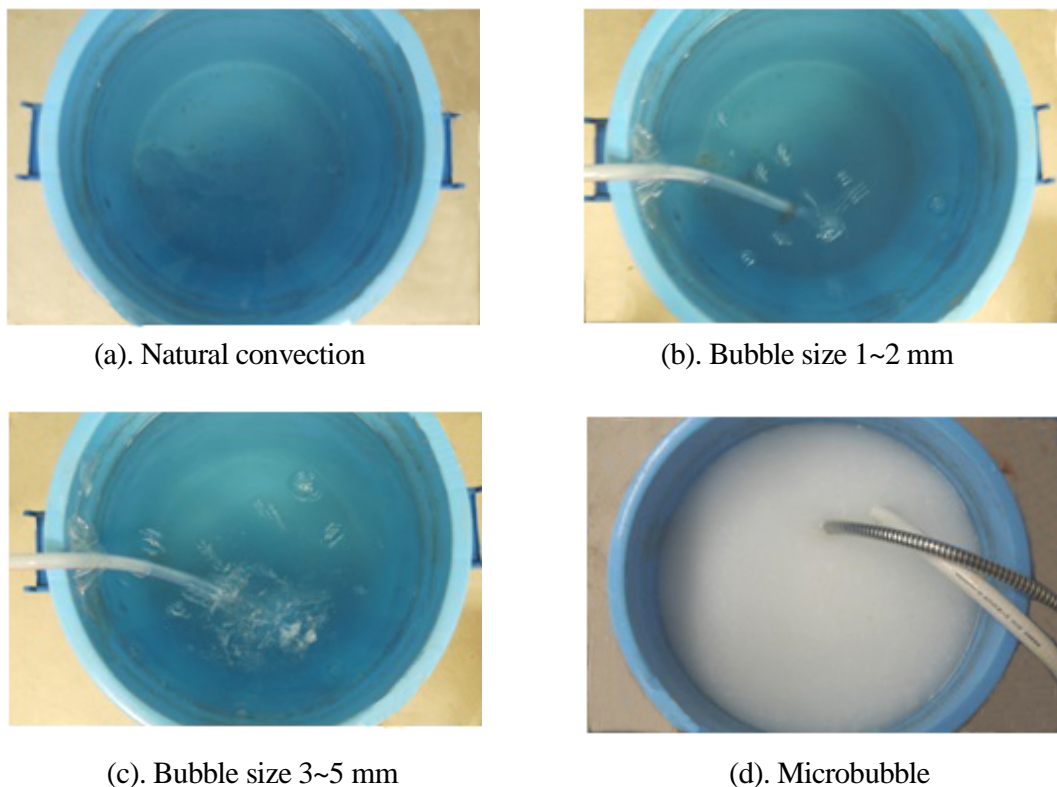


Fig.4.5 Appearance of different bubble sizes in strong alkaline water inside vessel

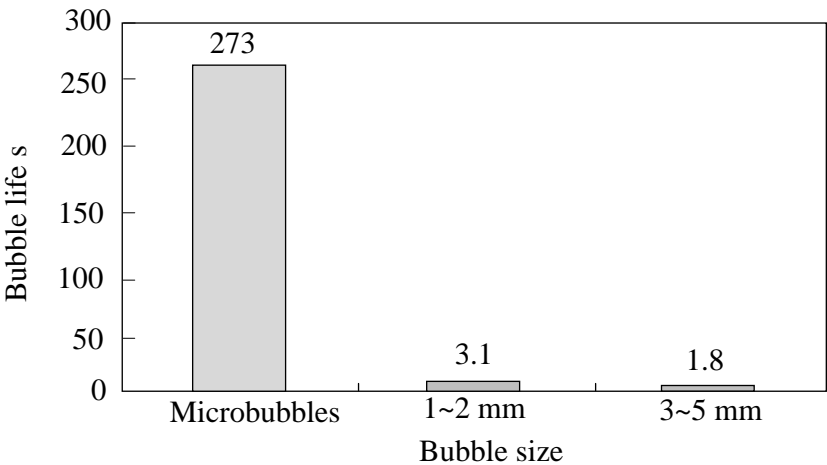


Fig.4.6 Relation between bubble size and its life in strong alkaline water

and thus, it is considered that, microbubbles can be transported through pipes until reach to the cutting point, and hence forced cooling is applicable. However, when the size of the bubbles in strong alkaline water are 1~2 mm or 3~5 mm, they only retain for a few second inside strong alkaline water. In addition, large bubbles only reach a few mm near to the cutting point. Consequently, supplying strong alkaline of those sizes of air bubbles is considered very difficult. Therefore, in this paper, it is decided to supply only microbubble to the strong alkaline water throughout the experiments.

In order to improve cooling capacity, the simple experiment on achieving optimum flow rate contain a large amount of air bubble in strong alkaline water was conducted. The experimental setup for the measurement of air amount is shown in Fig.4.7. In this experiment, strong alkaline water was firstly pumped from the vessel and mixed with microbubble inside the microbubble device. The water mixed with microbubble then passed through flow meter 'A' and filled into the Messzyylinder to measure the amount of the water. After strong alkaline water becomes transparent, its amount was measured again. The amount of air carried by microbubble in 1ℓ of strong alkaline water was calculated from the difference of the reading. The measurement result of the amount of air carried by bubbles is shown in Fig.4.8. The result shows that the maximum amount of microbubbles generated from a micro

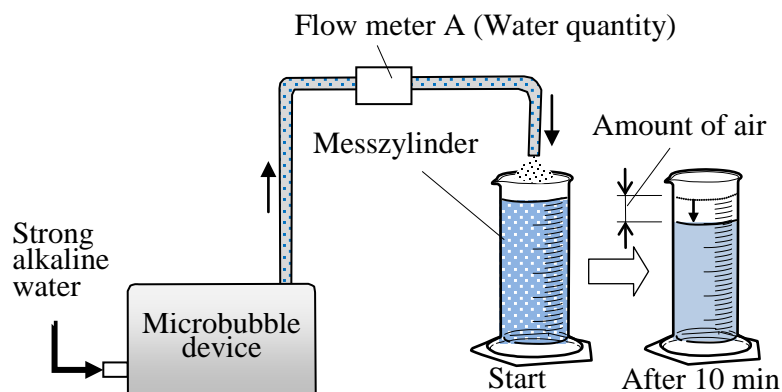


Fig.4.7 Experimental setup for measuring amount of microbubble in alkaline water

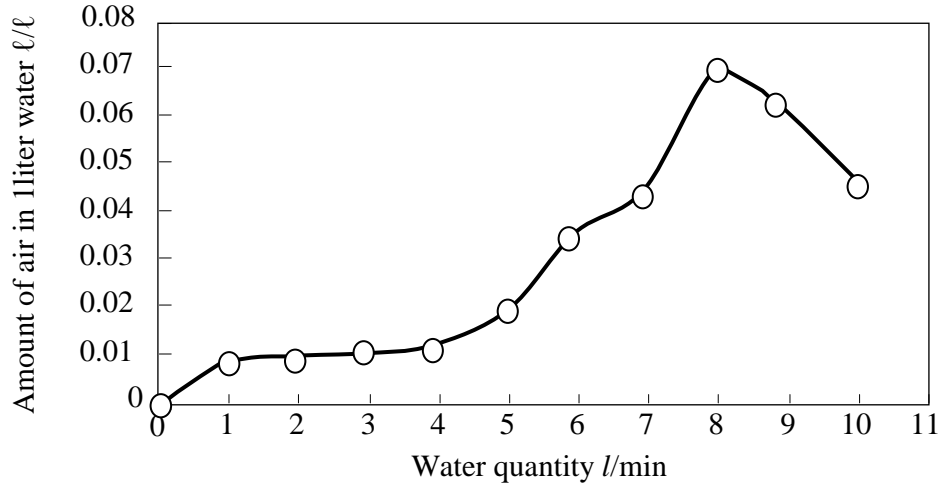


Fig.4.8 Experimental results for amount of air in alkaline water

bubble device was obtained at flow 8 l/min. Thus, this flow rate will be used throughout this experiment. This flow rate can also be obtained by setting the pressure of microbubble device to 0.4 Pa. However, when the pressure is less or larger than 0.4 Pa, the amount of microbubble in the strong alkaline water decreases. In order to know the effectiveness of the force cooling capacity of strong alkali water with microbubble, the experiment for measurement of the heat transfer coefficient was conducted. As shown in Fig. 4.9, rubber heater with the specification showed in Fig. 4.10 was sandwiched between two steel plates (SPCC, 100×100×1 mm) and hung in the center of a vessel filled with strong alkaline water. The steel plates were measured at 10 points (One side 5 point×2) using thermocouples till the steady condition was reached. The heat transfer coefficient was calculated from the average temperature results of steel plate surfaces and strong alkaline water by equation (4-1).

$$h = \frac{Q}{A(T_a - T_w)} \quad (4-1)$$

Where: h = convective heat transfer coefficient of the process (W/(m²K))

Q = heat transferred per unit time (W)

A = Heat transfer area of the surface (m²)

T_w = Temperature of strong alkaline water (°K)

T_a = Temperature of the metal surface (°K)

• Thermocouples

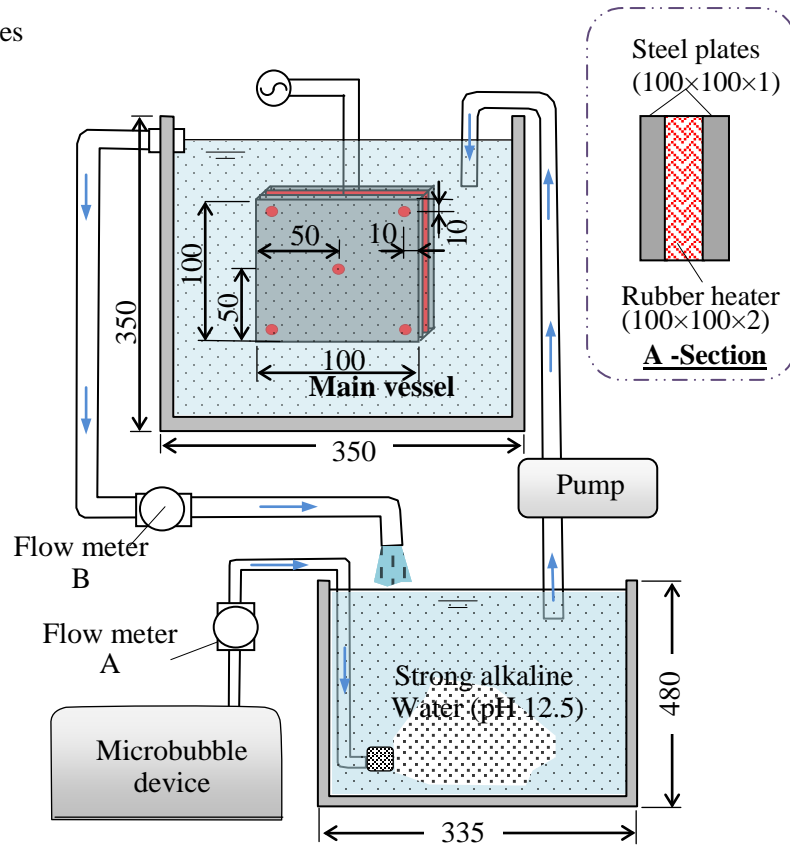
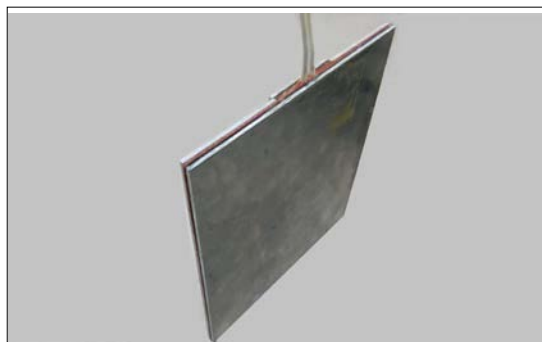


Fig.4.9 Experimental setup for measuring heat transfer coefficient of alkaline water with bubbles



Specification of the rubber heater	
Input voltage (V)	96.7 V
Input power (W)	50
Max operating temp. (°C)	600
Size (mm)	100×100×2

Fig.4.11 Photograph of the rubber heater



Specification of the pump	
Output power (kW)	0.4
Water quantity (ℓ/min)	8~11
Pressure (MPa)	2.1
Size (mm)	580×440×740

Fig.4.11 Photograph of the pump

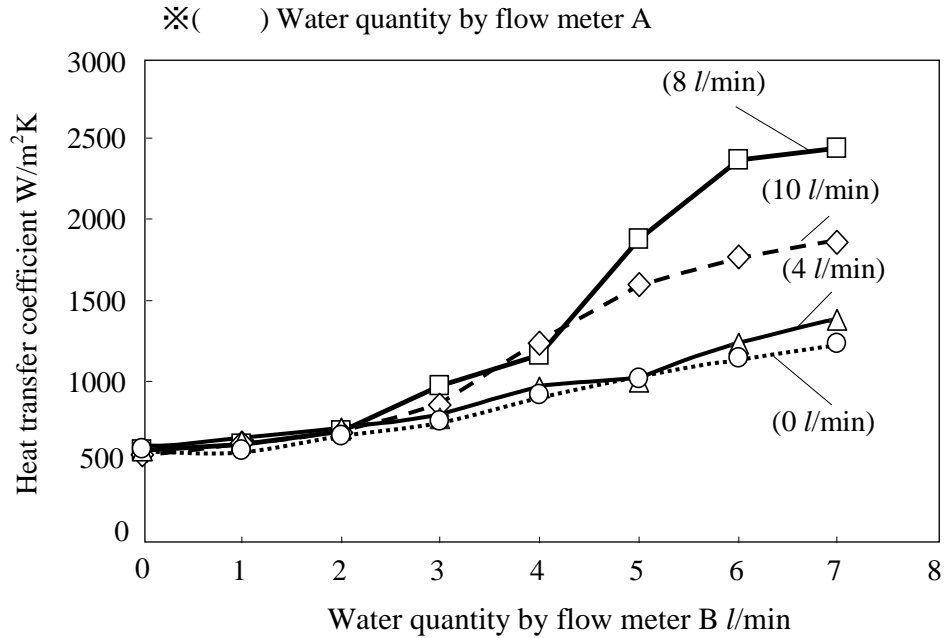


Fig.4.12 Relationship between the water quantity and the heat transfer coefficient

The strong alkaline water mixed with microbubble was supplied to the main vessel by using a pump with a maximum discharge pressure 2.1 MPa and maximum flow rate 10 ℓ/min . The difference in convection of heat transfer was measured. In order to obtain the optimum water flow rate pumped out by a pump, the different flow rate that flow through flow meter 'B' were also measured for heat transfer measurement. The photograph of pump machine used in this experiment is shown in Fig.4.11. As the amount of microbubble that was generated depend on the flow rate, in this case, the parameters for the experiment were taken by varying the amount of microbubble supplied into the strong alkaline water. By these, a main vessel with a through-hole drill was selected, and the relative evaluation was made on forced cooling effect by supplying strong alkaline water mixed with microbubbles. Fig.4.12 shows the measurement result of heat transfer coefficient. In the case of without using a pump (The natural convection state of strong alkaline water), heat transfer coefficient is about 500 $\text{W}/\text{m}^2\text{K}$, in the case of supplying only strong alkaline water at 7 ℓ/min , the cooling capacity is improved to 1200 $\text{W}/\text{m}^2\text{K}$ and improves more to 2500 $\text{W}/\text{m}^2\text{K}$ when

using strong alkaline water of 7ℓ/min containing with microbubbles (at 8 ℓ/min). As large amounts of microbubbles containing in the strong alkaline water, heat transfer coefficient improved and the effectiveness of cooling by water evaporation was also improved by supplying air. From this result, it is confirmed that large cooling effect can be generated by circulating the strong alkaline water with microbubbles.

4.3. Drilling processing by supplying strong alkaline water mixed with microbubble on the through-hole drill

4.3.1 Tool Temperature

The drill tip temperature at the time of supplying strong alkaline water mixed with microbubbles was investigated by experiment. The experimental setup for measuring drill tip temperature is shown in Fig.4.13. In this experiment, instead of using real cutting, two small ceramic heaters were bonded to the tip of cutting

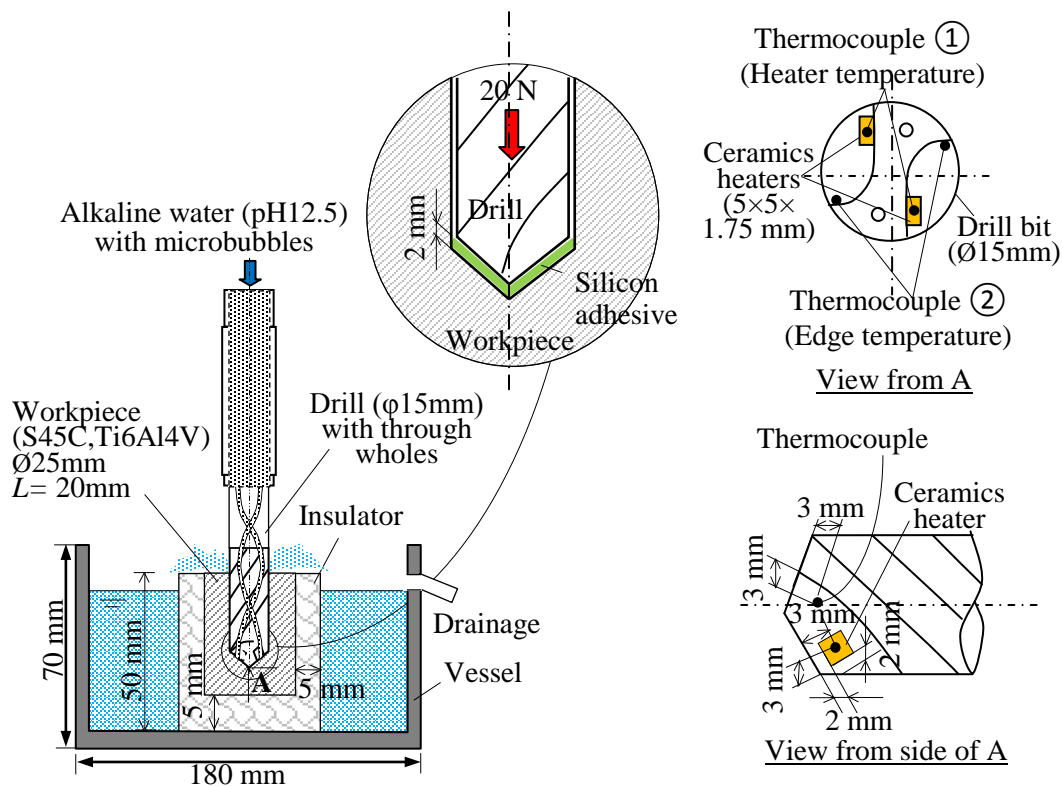


Fig.4.13 Experimental setup and position of thermocouples for measuring temperature on the edge of the drill

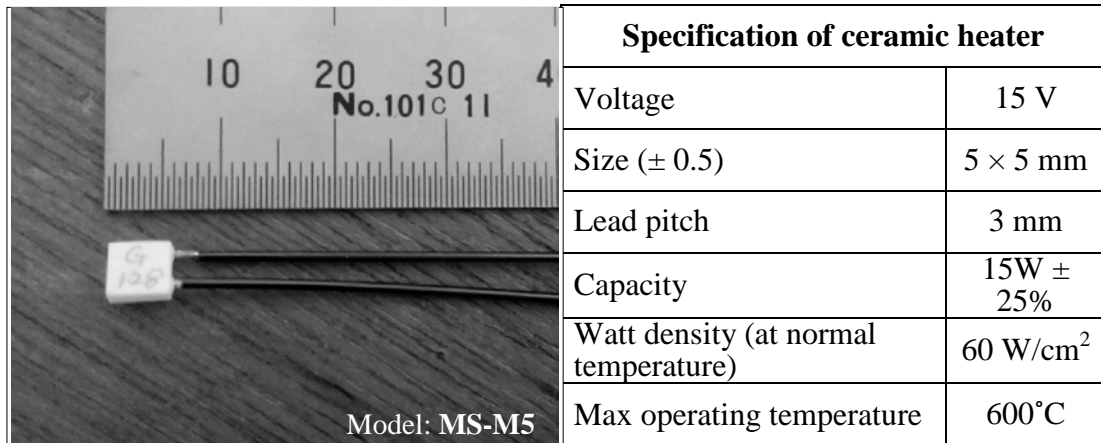


Fig.4.14 Photograph and the specification of ceramic heater

edges of the drill ($\varnothing 15$ mm, with through hole) and two T-type thermocouple were also fitted in the groove (5 mm from the cutting edge) in 2 places near cutting edge using silicon bond with 2 mm of thickness until solidify. Then a load of 20N was applied in the thrust direction of a drill in the experiment so that the hole in the workpiece and drill tip was contacted tightly together. In this experiment, two types of workpieces (S45C, Ti6Al4V) were used and max $260^\circ C$ was supplied to ceramic heaters with consideration to the measurement limitation of T-type thermocouple and applicable limitation of silicon bond. With the dry condition, the steady state temperature of the cutting edge of drill reached to $260^\circ C$ when supplied 0.12 kW with 29.8 V (for each ceramic heater), therefore those conditions were fixed to be used. The outside surfaces of work piece were insulated with polystyrene foam (thermal conductivity $0.04 W/m.K$) of 5 mm thickness to prevent the influence of cooling from the side surfaces. The experiment was conducted using 3 conditions; dry condition, only strong alkaline water was supplied ($7\ell/min$) via through hole, and by supplying strong alkaline water ($7\ell/min$) mixed with microbubble ($8\ell/min$) in the 20 ℓ container via through-hole. The measurement results of temperature on the edge of the drill for workpiece S45C and

Ti6Al4V are shown in Fig.4.15. Regarding to the result of S45C, the cooling effect of the strong alkaline water, is 3.5 times larger compared with the dry test and for strong alkaline water mixed with microbubble was also nearly above 3.5 times of dry-type. Although the forced cooling effect is slightly better than strong alkaline water, there was no large effect observed. By considering the measurement limitation of T-type thermocouple, the applicable limitation of silicon bond and ceramic heater, the temperature cannot set to a higher degree and thus the evaporation effect of forced cooling effect did not remarkable appear. However, it can be considered that the effect of the cooling from strong alkaline water is sufficient to maintain the strength and hardness of the drill. Particularly, for the case of work piece of Ti6Al4V, material with low thermal conductivity, the thermal load on the tool become much larger. Hence, for the processing of the deep hole drilling on this material, it is considered that the proposed method is very effective when applying forced cooling to drill tip.

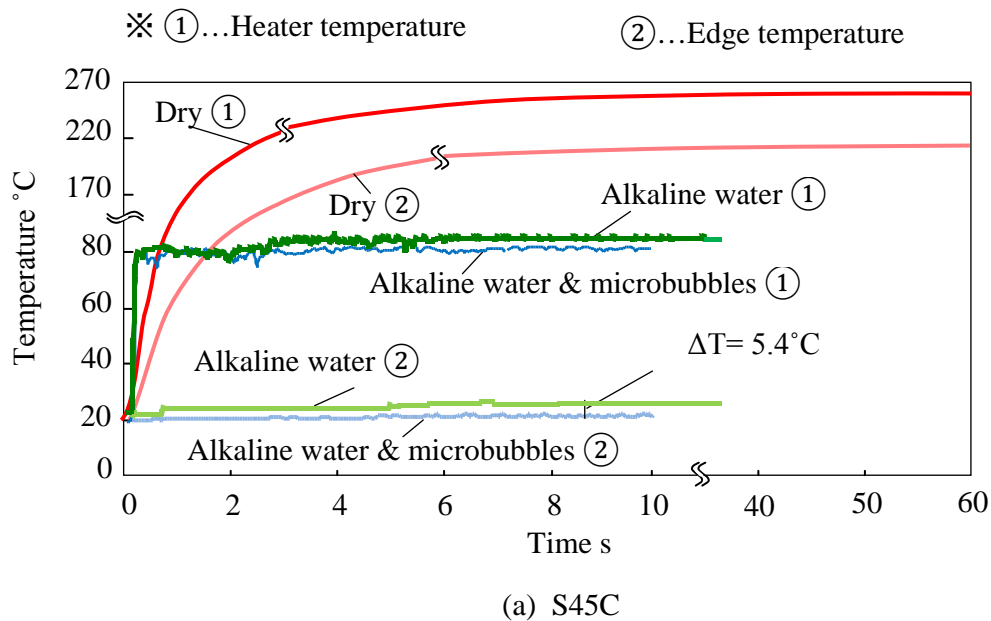


Fig.4.15 Temperatures on the edge of the drill for different cooling conditions

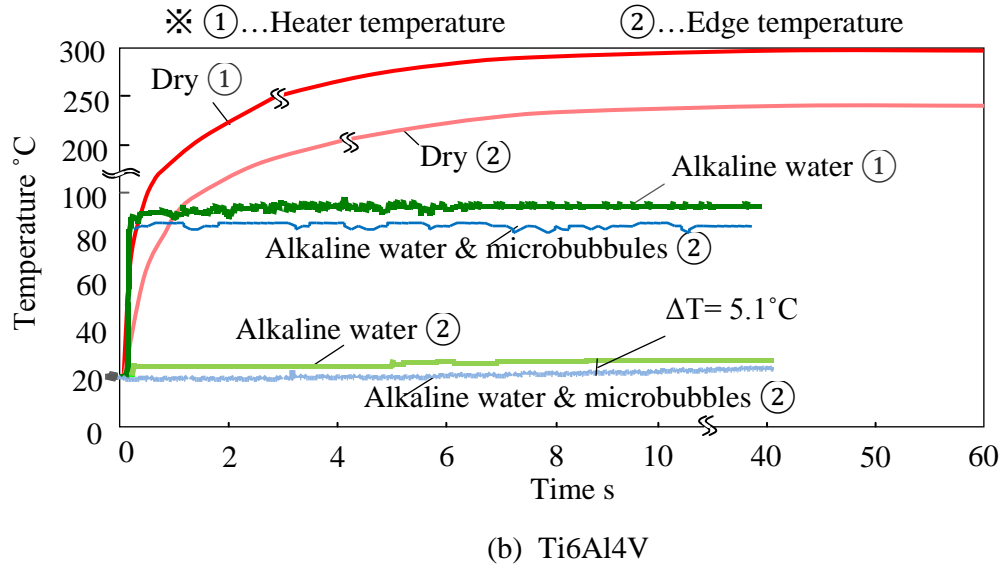


Fig. 4.15 Temperatures on the edge of the drill for different cooling conditions

4.3.2 Surface roughness

In this section, the real cutting experiment was performed and effectiveness of the forced cooling method using strong alkaline water mixed with microbubble was evaluated by measuring the surface roughness of the cut surface. NC milling machine with specification shows Table 4.6 and the appearance shows in Fig.4.16 was used for cutting evaluation. The conventional drilling condition shown in Table 4.7 is used for drilling carbon steel S45C and Ti6Al4V material using a Ø15 mm drill bit. In the experiment, the surface roughness of workpiece was measured at surfaces on starting time of the processing and on the time just before drill life was reached. The measurement was done by taking the average value of 9 points in the positions of three places with depth of the holes are 5 mm, 15 mm and 25 mm. However, for the case without reaching 25 mm depth, the surface cut by the drill shoulder on the top of the drill is measured by taking the average value. Fig.4.17 shows the experiment setup for evaluation by drilling. In this experiment, 4 conditions; the dry cutting, the conventional wet cutting, cutting by only supplying strong alkaline water (7 l/min),

Table 4.6 Specification of NC milling machine used in the experiment

Table working surface	mm	610×381
Table loading weight	kg	250
Table movement stroke X-axis	mm	510
Table movement stroke Y-axis	mm	381
Table movement stroke Z-axis	mm	460
Distance from the table top face to the surface of the spindle nose	mm	100~560
Spindle speed	min ⁻¹	130~5000
Feed speed	mm/min	0~5000
Power of motor for spindle	kW	5
Machine weight	kg	2600

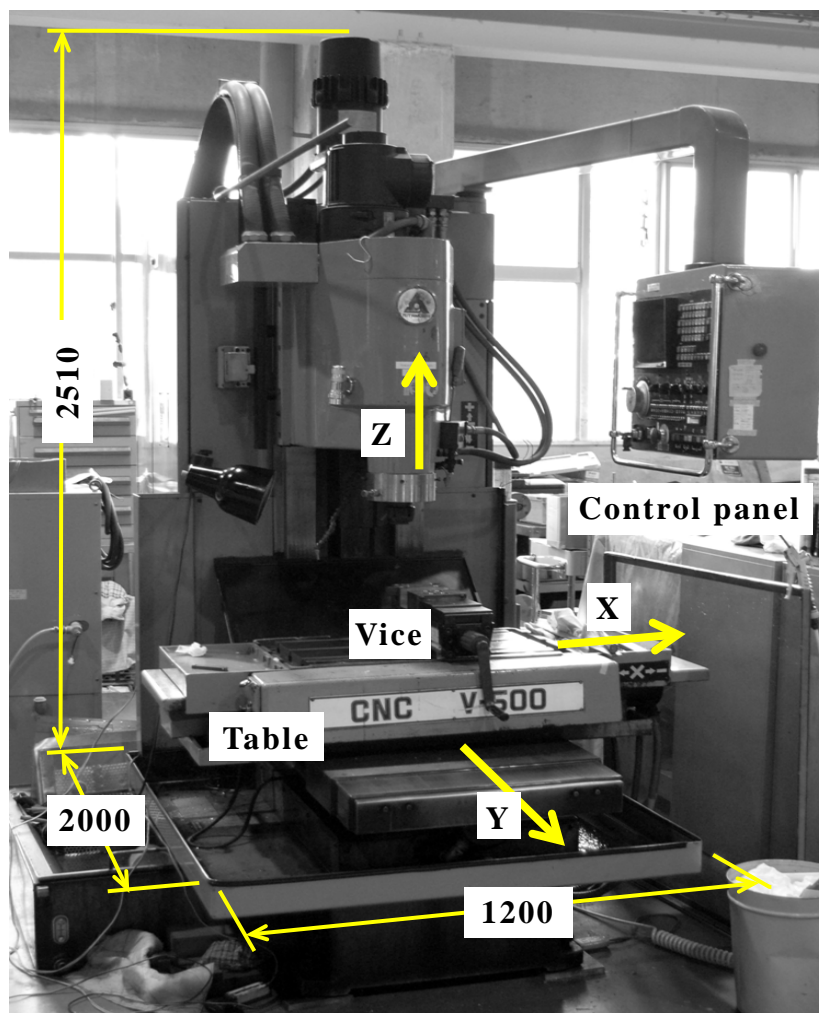


Fig.4.16 NC milling machine used in the experiment (Unit: mm)

Table 4.7 Drilling condition for evaluation of forced cooling of alkali water with microbubbles

Specification of the drill bit	
Diameter	Ø 15 mm
Length	150 mm
Material	Carbide with TiN
Through hole	Ø 5mm× 2 holes
Specification of the cooling medium	
Medium	Strong alkali water (pH12.5)
Microbubbles	8 ℓ/min in 40 ℓ alkaline water
Drilling condition	
Spindle speed	500 min ⁻¹
Cutting speed	24 m/min
Feed speed	40 mm/min
Depth of drilling	From 0 to 25 mm
Workpieces	S45C and Ti6Al4V

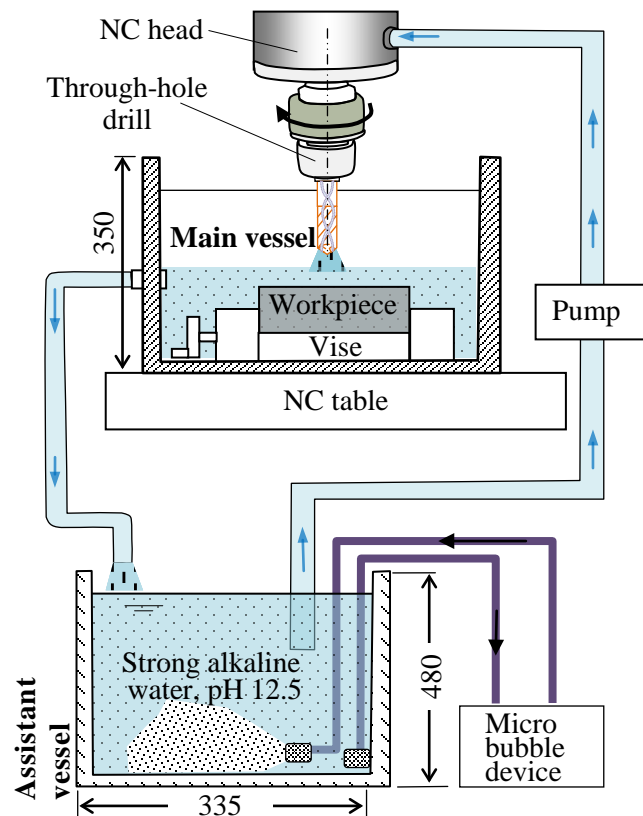
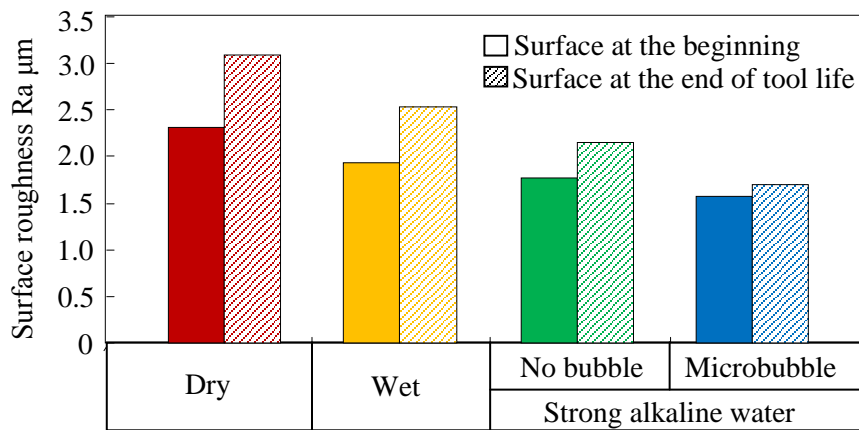


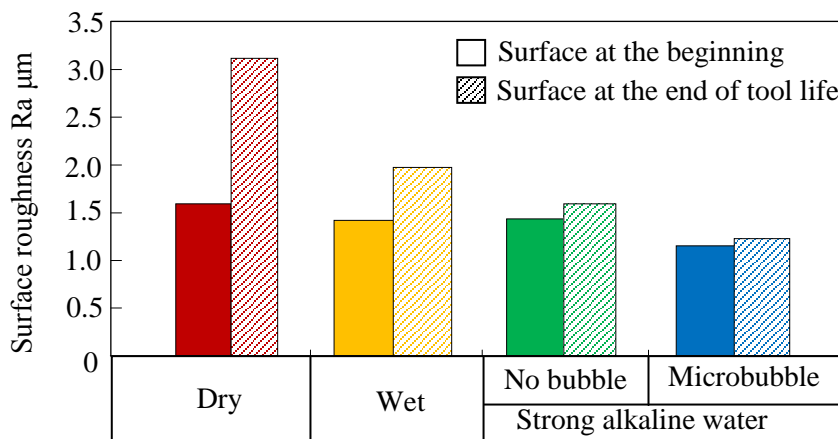
Fig.4.17 Experimental setup of evaluation by drilling

and the cutting in 40ℓ of strong alkaline water vessel supplying with 8 ℓ/min of microbubble via through-hole of the drill were performed. There exists some obstruction at tiny through-hole by some cut pieces however the high-pressure pump with discharge pressure of 2.1 MPa can flushes out the cut pieces easily.

The measurement results of surface roughness (arithmetic average roughness Ra) for S45C and Ti6Al4V are shown in Fig.4.18. The result shows that by using force cooling of strong alkaline water mixed with microbubble on drilling S45C (Fig.4.18a), surface roughness was improved about 30.5% compared



(a) S45C



(b) Ti6Al4V

Fig.4.18 Surface roughness of the hole of the drilling using the forced cooling of strong alkaline water with microbubble

with dry cutting and about 17.2% compared with wet cutting. When drilling Ti6Al4V (Fig.4.18b), surface roughness was improved about 27.2% compared with dry cutting and about 18% compared with wet cutting. Since the cooling effect of evaporation of strong alkaline water mixed with microbubble is large enough to suppress the thermal deformation of the drill, the loss in hardness and strength of the drill is lower, the loss of drill sharpness is lesser, and also the reduction in rigidity of drill is lower resulting the small vibration amplitude and smooth surface roughness.

4.3.3 Tool life

The tool life for drilling with supplying strong alkaline water mixed with microbubble was measured and evaluated. The previous drilling condition (Table 4.7) was used for processing. Again, in this experiment, 4 conditions such as the dry cutting, the conventional wet cutting, by supplying strong only alkaline water (7 ℓ/min), and cutting in 40 ℓ of strong alkaline water vessel supplying with microbubble via through hole (7ℓ/min) were performed. For the judgment of the tool life, as shown in Fig.4.19, the tool life is defined to be reached by the time when flank wear of the drill's edge reaches 0.15 mm.

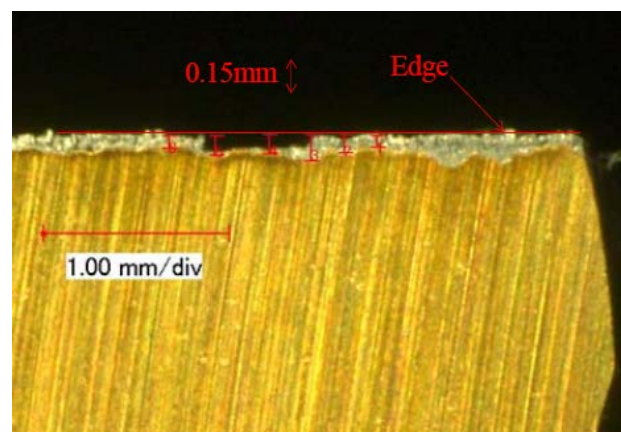


Fig.4.19 Photograph of edge of the drill for the judgment of the tool life

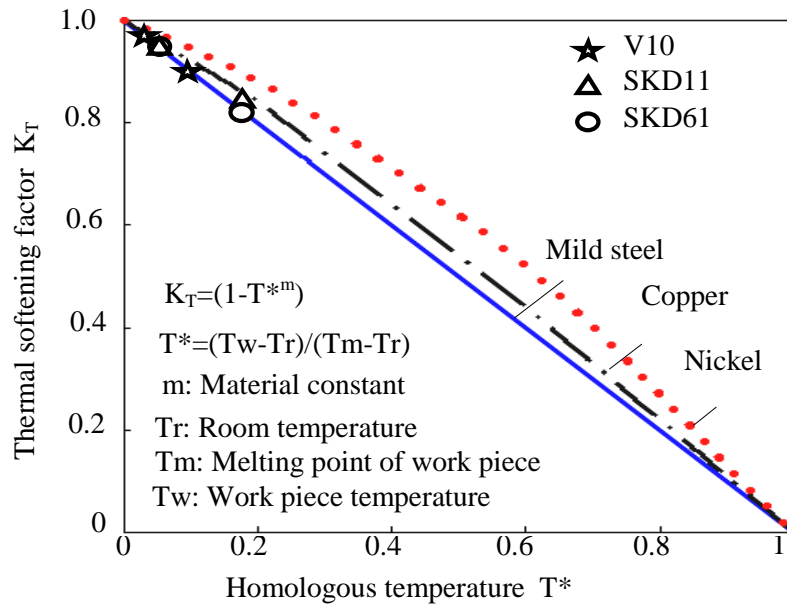
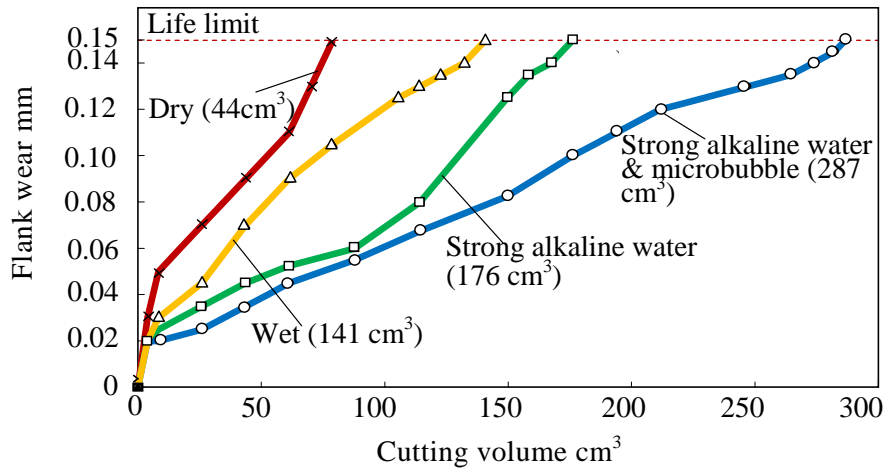
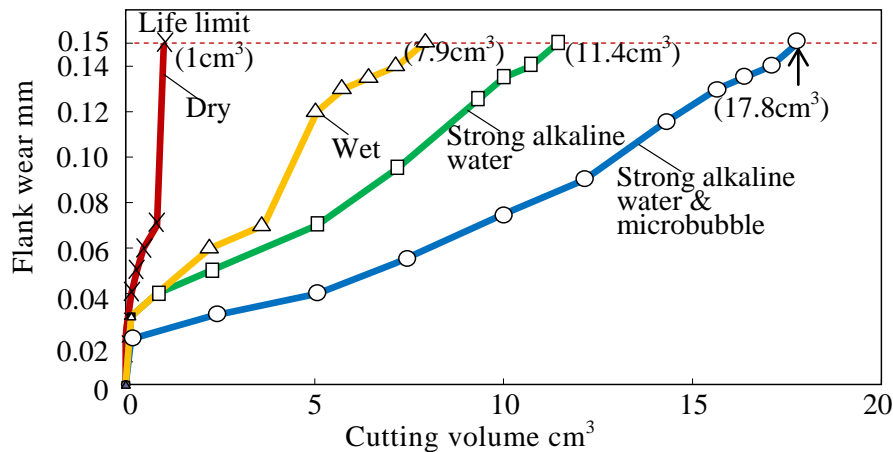


Fig.4.20 Relationship between the softening factor and the temperature ^[4-11]

All metals at normal temperature, thermal softening factor are 1.0. However, at their melting point, thermal softening is zero and the hardness also becomes zero, as shown in Fig.4.20. The relation of the thermal softening factor between those temperatures is almost linear ^[4-11]. For example, for carbide material with melting point 2500°C, exhibit hardness HRC 92 at room temperature, HRC 62.5 at 800°C ($92 \times (1.0 - 800 \div 2500)$), and HRC 46 at 1250°C, ($92 \times (1.0 - 1250 \div 2500)$). The hardness HRC 62.5 at 800°C can be used as a tool, however, using hardness HRC 46 at 1250°C is too soft to cut steel materials. Thus, the temperatures of the tools significantly affect their hardness and cutting using soften tool also greatly influence on tool life. Therefore, we proposed our forced cooling method to prevent softening of drill and keep tool life last longer. The measurement result of a tool life is shown in Fig.4.21. For the workpiece S45C as shown in Fig.4.21(a), the tool life using forced cooling by strong alkaline water mixed with microbubble was 6.5 times compared to dry cutting, 2 times compared to wet cutting using cutting oil and about 1.6 times using only strong alkaline water respectively. By using forced cooling effect of strong alkaline



(a) S45C



(b) Ti6Al4V

Fig.4.21 Results of tool life regarding the drill using the forced cooling of alkaline water with microbubble

water mixed with microbubble, the drill is effectively cooled and the reduction in the hardness of the drill became lesser. For the workpiece Ti6Al4V (lower thermal conductivity material) in Fig.4.21(b), the effect of forced cooling of the strong alkaline water added with microbubble was more remarkable compared with dry cutting and wet cutting using cutting oil. The tool life using forced cooling by strong alkaline water mixed with microbubble is 17.8 times larger compared to dry cutting, 2.2 times compared to wet cutting using cutting oil and about 1.6 times using only strong alkaline water. Since the thermal

conductivity of Ti6Al4V workpiece and chip are lower, the generated cutting heat is intensively conducted to the drill, therefore, the drill temperature becomes higher and the hardness of the drill has also become lower. From these results, it can be considered that drilling processing of difficult to cut materials with low thermal conductivity is possible to be operated using proposed forced cooling of strong alkaline water mixed with microbubble.

4.4. Summary

From the above results, it is confirmed that forced cooling technology on drilling using alkaline water with microbubble is capable of improving evaporation of the cooling effect. The results of this study are summarized as follow:

- (1) By adding microbubble to the strong alkaline water, it produces extremely large forced cooling effect with higher heat transfer coefficient value about $2500\text{W/m}^2\text{K}$.
- (2) By using the proposed method, supplying strong alkaline water added with microbubble to the drill with through holes, the temperature rise at tool tip could reduced about 70%, the work surface roughness improved about 30% and the tool life also improved 6.5 times, compared with dry cutting.
- (3) The forced cooling method using strong alkaline water added with microbubble is considered effective for environmental conservation.

Chapter (5)

DEVELOPMENT OF IMMERSED MACHINE TOOL AND MACHINING IN THE STRONG ALKALINE WATER FOR REDUCTION OF CO₂

5.1 Introduction

5.1.1 Research background

Since the end of the last century, scientists face serious problems on energy resources and destruction of the natural environment on the global scale. Reducing electric usage, cutting oil usage, and the cooling fluid which are harmful to the environment and human health become the most important factors to be considered in manufacturing and production field. Especially, the major reduction in CO₂ emission is extremely important to prevent the global warming. Since large amounts of lubricating oil have been used for smoothing, while much cutting oil has been used for cooling during machining, they generate pollution by releasing more CO₂ throughout a year, which is considered as large problem for environment conservation. Thus, alternative cutting fluid other than cutting oil is required to minimize the impact on the environment. Hence, eco-friendly manufacturing ^[5-1] has become a common request as a processing technology, as well as high accuracy and productivity of manufacturing with consideration to energy conservation. The various cooling system has been applied during machining to remove heat load for longer tool life and to obtain smooth surface roughness of final cutting results. However, optimum tool, cooling and cutting condition alone do not guarantee the achievement of an optimum final cutting result. The heat load caused by bearing unit that support spindle in lathe machine

also has an influence on the final cutting result. The heat, which is generated by friction on bearing, can cause thermal deformation to take place. When this condition occurs, workpiece displaces from its original position resulting uneven shape and poor surface roughness of the final cutting result. Regarding this problem, many countermeasures have been made to minimize thermal deformation on the machine tool for high precision manufacturing ^{[5-2], [5-3]}. In addition, many forced cooling technologies for releasing heat have been established for high accuracy and productivity improvement ^{[5-4], [5-5]}. Many of those measures have effectively used high capacity refrigerators for forced cooling to eliminate heat and suppress thermal impact on machines and cutting tool. However, in consideration to environmental conservation, additional measures are required to meet those constraints.

5.1.2 Proposed technique

In this study, we propose a new technique to minimize thermal deformation caused by excessive of heat and to reduce the amount of CO₂ emitted during machining. The study was performed by cutting experiment using machine tool which completely submerged into strong alkaline water. The evaporative cooling effect of strong alkaline water is capable of suppressing thermal deformation of machine tool, as well as the cutting heat generation at the cutting point of the tool by immersing condition. Therefore, the immersed cutting processing systems using forced evaporation cooling effect was developed. Concretely, a small bench lathe is immersed completely in strong alkaline water, and then the thermal deformation of the machine structure, processing accuracy, and tool life are evaluated by experiment. Moreover, to satisfy the applicability of proposed cutting technology, corrosion resistance of machine elements in strong alkaline water and the improvement of cooling capacity by the addition of microbubble to strong alkaline water were examined.

5.2 Corrosion resistance of machine elements in strong alkaline water

Although the evaporative cooling effect of water is very large compared with cutting fluid ^[5-6], there is still very low application for cooling machine tool using water in industry. This is because of the water causes the machine tool, workpiece and machine elements corroded. However, it was described in corrosion engineering that, when the logarithmic value of the metal ion concentration (mol/l) is less than -6, metal shows no corrosion. As stated in previous chapter 2 and 4, based on the corrosion properties of strong alkaline water ^[2-29] in the case of steel, the corrosion will not occur when the pH of strong alkaline water is more than 10.0. Therefore, it is considered that the strong alkaline water with pH value over 12.5 does not corrode the steel parts as mentioned above. Similarly, for the workpiece materials other than steel, in the case of nickel and nickel-based alloys, the range of pH 8.5 ~ pH 13.0 is chemically passive range which means no corrosion will occur between these range of pH. Furthermore, in the case of titanium and titanium-based alloys, their chemical passivity range is below pH 13.0. From these facts, the range between pH 10.0 ~ pH 13.0 is considered to be adequate for immersing cutting for most of the machine tool related materials. As a result, cutting process can be performed using strong alkaline water with effective evaporative cooling to reduce the thermal loads on the machine tool. Moreover, strong alkaline water has high permeability, detergence, peeling decomposition capability, emulsification (when the separation property is large, detergency is extremely large), and eradication (with the action of putrefaction prevention, recently has been often used as a cleaner over a wide area). In addition, when the strong alkaline water is kept longer in the ambient air, it will lose its alkalinity and becomes normal water with the range of pH of 7.0 ~ 8.0.

In previous chapter 4, some of the workpieces materials had been investigated for their corrosion resistance in strong alkaline water. However,

since various materials other than workpieces will also be submerged during immersion of machine tool, various types of machine tool related materials need to be investigated for their corrosion resistance in strong alkaline water. Hence, in this study, the characteristic of the common industrial related materials immersed in strong alkaline water is clarified by experiment. The same strong alkaline water generator showed in previous Table 4.1 of chapter 4 is used in this research with its specification is shown in Table 5.1. By using this portable alkaline water generation equipment, the strong alkaline water with pH 12.5 can be easily generated.

Table 5.1 Specification of the strong alkaline water device

Method of generation	Closed generation type
POCA	K_2CO_3
Value of pH	pH 12.5
Quantity of generation	10 ℓ/h
Voltage & Power	100 V & 300W
Size	L 495×W 430× H 1100

Table 5.2 Condition for the corrosion test

Medium in the vessel	Strong alkaline water (pH 12.5)
Ambient conditions	Room temp.: $20\pm 1^\circ\text{C}$, Humidity: 60%
Period	Two months

As stated earlier, since corrosion resistant of some material on the strong alkaline water have studied in chapter 4, the corrosion characteristics in strong alkaline water for various materials such as machine tool structural materials, workpieces, tools, coated tools, machine tool elements, and painted materials were confirmed by experiment using condition shown in Table 5.2. Some of the sample materials showed in Fig. 5.1 were put in containers filled with strong alkaline water with pH 12.5 in the constant room temperature of $20 \pm 1^\circ\text{C}$ and 60% of humidity. The materials were left for two months inside strong alkaline water for observation of corrosion phenomenon in the test materials. Although the pH of strong alkaline water does not degrade much during left for two months at room temperature, however in this test, strong alkaline water still needs to be replaced once a week to maintain its constant pH value. The results of the experiment are shown in Table 5.3. Most of the machine tool related materials, with the exception of aluminum and aluminum alloy,



Fig.5.1 Photograph of the parts in strong alkaline water

show no corrosion after submerged in strong alkaline water for two months. The photograph of the appearance of some materials before and after two months immersed in strong alkaline water is shown in Fig.5.2.



Fig.5.2 Corrosion and discoloration by strong alkaline water

We observed in this test that small thread of bolts and nuts were corroded, however, big thread was not. Copper and copper alloy were decolorized on their surfaces. While, bearing and ball screw show no corrosion. Therefore, immersed machining in strong alkaline water is considered applicable. However, in recent years, since TiAlN and TiAlCr coating materials are widely being used in cutting tools for their high hardness and low frictional coefficient, we observed that the materials corrode faster when more element of Al contains in the materials. Hence, TiAlN and TiAlCr show no corrosion as they are contained with a small amount of Al. Another observation shows the spring inside the oil seal and the wire net of the exhaust cleaner made of aluminum was corroded. Some of the mechanical and electrical components that are used for assembly and packing such as screws and springs that contain aluminum or copper element, the corrosion and discoloration may occur, and therefore caution is required to be taken. Regarding the inclusion of grease in bearing and linear guide, there was no eruption of oil occurs, and also no changes in the driving characteristic before and after submerging into the strong alkaline water. The characteristic of bearing was observed by winding up the outer ring of bearing with a tiny rope and applied a specific load hanging in the end, for measuring its rotational speed. For the linear guide, it was put on an inclined plane and measured its sliding movement. In case of servo motor, its condition was confirmed after fully dries, and then confirmed by setting and running on the NC lathe machine. Coated material with Diamond-like-Carbon (DLC) and Titanium Nitride (TiN) show no corrosion and therefore, they are possible to be used as solid lubricant for the sliding surfaces when the whole machine is submerged in strong alkaline water. Moreover, there were also no corrosion and discoloration occurred on the bench lathe machine after placing inside vessel filled with strong alkaline water with pH 12.5 for two months while the bench lathe machine operates continuously.

Table 5.3 Results of the proof test for two month in alkaline water with pH12.5

Machine tool structure	S45C	○	Changeless condition
	SUS304	○	Changeless condition
	Cast iron	○	Changeless condition
Work piece	Ti	○	Changeless condition
	Ti6Al4V	○	Changeless condition
	Inconel 718	○	Changeless condition
	S45C	○	Changeless condition
	Copper	△	Only discoloration
	Brass	△	Only discoloration
	Aluminum	×	Corrode
Tool	HSS	○	Changeless condition
	Carbide	○	Changeless condition
	Cermet	○	Changeless condition
	Diamond	○	Changeless condition
	CBN	○	Changeless condition
	Ceramic	○	Changeless condition
Coating material of tool	DLC	○	Changeless condition
	Ti AlN	×	Discoloration
	TiAlCr	×	Discoloration
Electrical element	Push-button switch	△	Terminal corroded Screw corroded
	Command switch	△	Terminal corroded Screw corroded
	Optoelectronic switch amplifier	△	Terminal corroded Screw corroded
	Servomotor	△	Only screw corroded
	Box terminal	○	Changeless condition
	Electromagnetic contactor	×	Electromagnet corroded
	Solenoid valve	△	Only discoloration
	Solenoid valve base	△	Only discoloration
	Flat cable	○	Changeless condition
	Cable connector	○	Changeless condition
	Direct acting two port solenoid valve	△	Only corrode and discoloration

○ : Enable △ : Only discoloration or only screw corroded × : Disable

Table 5.3 Results of the proof test for two month in alkaline water with pH12.5 (continue)

Machine element	V-belt	×	Small crack
	Drive belt	○	Changeless condition
	Timing belt	○	Changeless condition
	O-ring	○	Changeless condition
	Bearing	○	Changeless condition
	Linear guide	○	Changeless condition
	Ball screw	○	Changeless condition
	Oil seal	△	Spring corroded
	Oil pump	×	Terminal corroded (Not work)
	Wire hose	○	Changeless condition
	Excel hose	○	Changeless condition
	Cap connector	△	Only screw corroded
	Tube fitting	○	Changeless condition
	Oil level gauge	○	Changeless condition
	Rubber bushing	○	Changeless condition
	Exhaust cleaner	×	Corrode and discoloration
	Check valve	△	Only screw corroded
	Lubricator	○	Changeless condition
	Regulator	△	Only screw corroded
Basic material	Acrylic acid resin	○	Changeless condition
	Vinyl chloride	○	Changeless condition
	Nylon	○	Changeless condition
	Polyurethane	○	Changeless condition
	Polycarbonate	○	Changeless condition
	Nitrile rubber	○	Changeless condition
	Polyurethane rubber	○	Changeless condition
	Fluoro rubber	○	Changeless condition
	Chloroprene rubber	○	Changeless condition
	Chlorosulfonated Polyethylene rubber	○	Changeless condition
	Oilproof vinyl mixture	○	Changeless condition
	Urethane elastomer	○	Changeless condition
Paint	Lacquer paint	○	Changeless condition
	Urethane resin paint	○	Changeless condition
	Epoxy resin paint	○	Changeless condition

○ : Enable △ : Only discoloration or only screw corroded × : Disable

5.3 Improvement of heat transfer coefficient of strong alkaline water by adding microbubbles

In this section, the heat transfer coefficient of strong alkaline water was improved by adding with microbubble and its effectiveness was clarified using an experiment. The life of microbubble in the water was measured by releasing microbubbles in strong alkaline water using the same experiment as performed in Chapter 4-Fig. 4.4. Microbubble was supplied into the 30 ℓ of alkaline water in a container with flow rate 8 ℓ/min (the size distribution of microbubbles are shown in Fig. 5.3) for 10 minutes; the time when until microbubble in strong alkaline water become clear was measured. The similar measurements were also conducted for different bubble sizes (1~2 mm and 3~5 mm) with flow rate 10 ℓ/min. The measurement results are shown in Fig. 5.4. It is observed that the lifetime microbubble in strong alkaline water is last about five minutes. Therefore, it is concluded that the use of our proposed cooling system is possible by supplying microbubbles into the strong alkaline water passing through the pipe until reach the cutting point on the machine tools for the improvement of forced cooling. However, for the bubble sizes of 1~2 mm and 3~5 mm, their lifetime in strong alkaline water is last shortly in a few seconds, which make these sizes of bubbles difficult to reach to the cutting point on the machine tools.

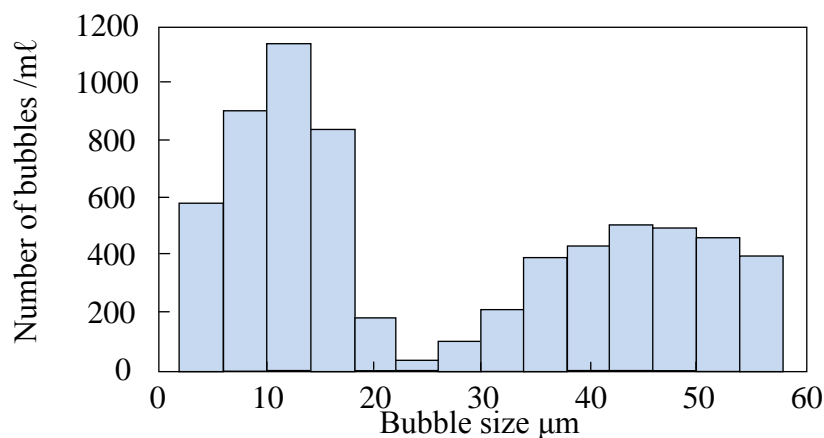


Fig.5.3 Bubble size distribution of micro bubble ^[4-10]

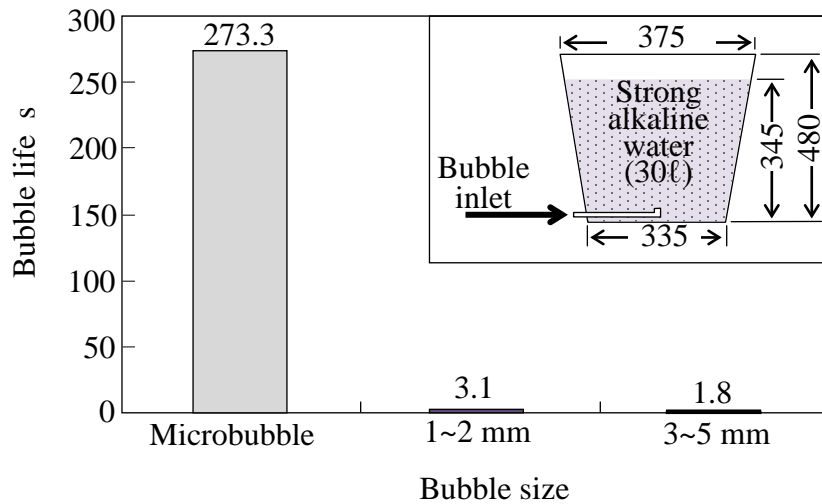


Fig.5.4 Relationship between bubble size and its life in strong alkaline water

Microbubble has been used in various fields as a coolant and waste water treatment [5-7], [5-8], [5-9]. The small bubbles that carry air coated with water can help improve cooling effectiveness. In addition, separation process such as flotation of waste and oil recovery becomes easier by using microbubble. In order to verify the cooling capacity of microbubble supplied to the strong alkaline water, the heat transfer coefficient was measured by experiment using rubber heater. As shown in Fig. 5.5, a rubber heater (100×100×2mm) inserted between two flat steel plates (SPCC, 100×100×1mm), was put into the vessel of strong alkaline water (L1190×W980×H790 mm) together with bench lathe fully in immersing condition. Measurement of the temperature of the bench lathe was performed by hanging rubber heater in the center of the vessel and supplied with 50 W of electricity powers. When the temperature of thermocouples on both sides of the steel surfaces reaches a steady state condition, the temperature values were recorded and the heat transfer coefficient was calculated from the average temperature values on both surfaces and the average temperature of the water. The experiments were done for cooling using natural convection of strong alkaline water and by supplying microbubble (8 ℓ/min) while operating with and without spindle speed at 3600 rpm. The photograph of the experimental setup for immersing bench lathe shows in Fig.5.6.

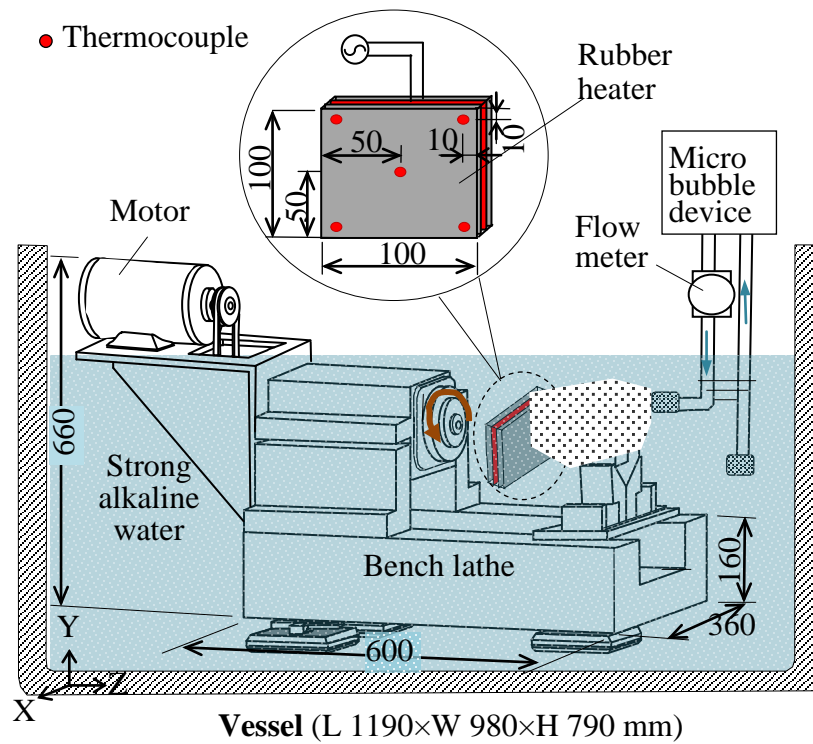


Fig.5.5 Experimental setup for measuring heat transfer coefficient

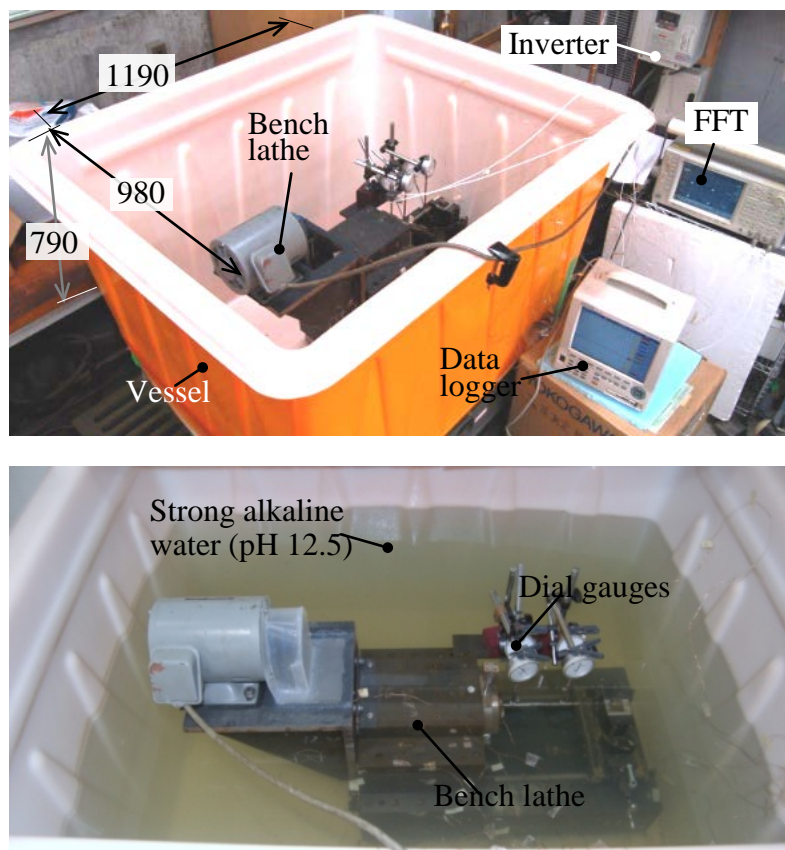


Fig.5.6 Photograph of the experimental setup

Fig.5.7 shows the average temperature for various cooling method measured every five minutes for 50 minutes. It was observed that using strong alkaline water supplied with microbubble together with the operation of spindle speed at 3600 min^{-1} can maintain the temperature of the bench lathe machine around 22°C.

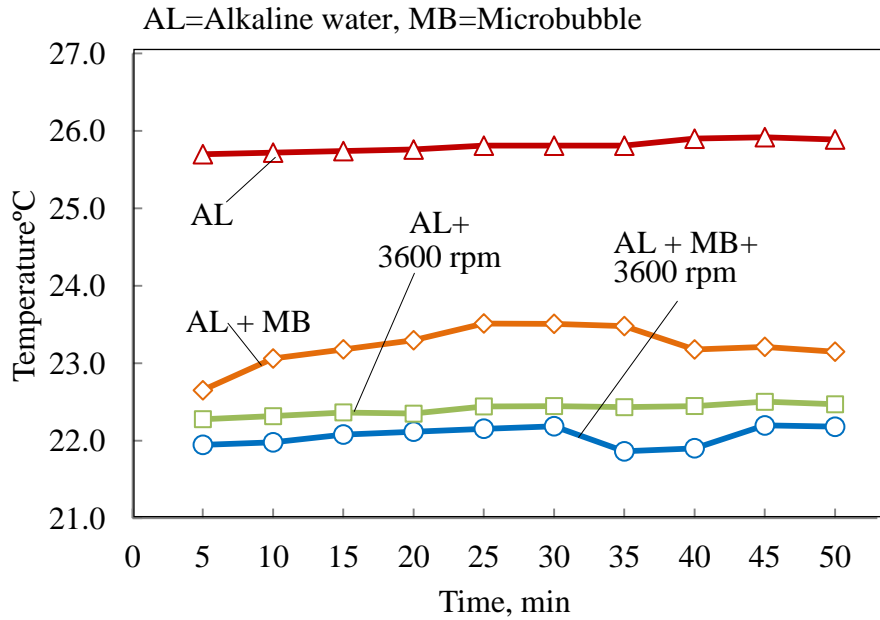


Fig.5.7 Average temperature for various cooling methods

The heat transfer coefficient was calculated from the difference between the temperature of the heater and the temperature of strong alkaline water using the general equation of heat transfer of equation 5.1.

$$h = \frac{Q}{A(T_a - T_w)} \quad (5.1)$$

Where: h = convective heat transfer coefficient of the process ($\text{W}/(\text{m}^2\text{K})$)

Q = heat transferred per unit time (W)

A = Heat transfer area of the surface (m^2)

T_w = Temperature of strong alkaline water ($^{\circ}\text{K}$)

T_a = Temperature of the metal surface ($^{\circ}\text{K}$)

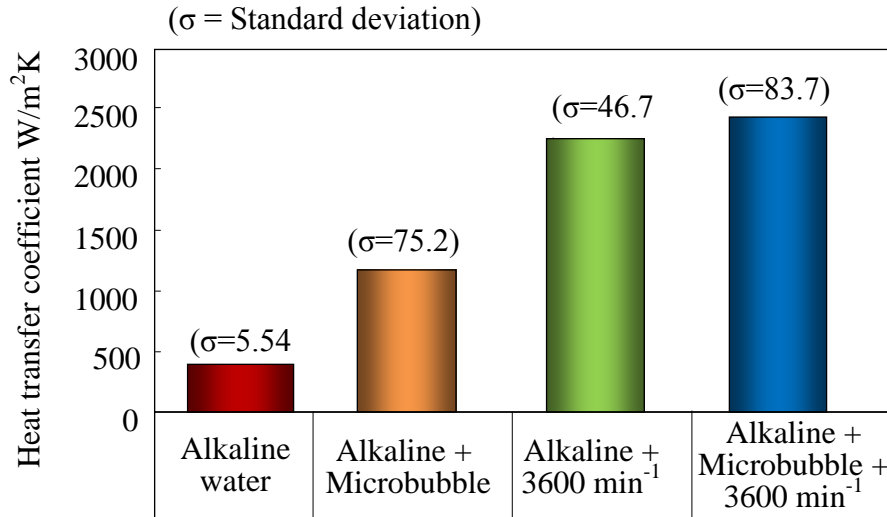


Fig.5.8 Relationship between alkaline, microbubble and 3600 min⁻¹ with the heat transfer coefficient

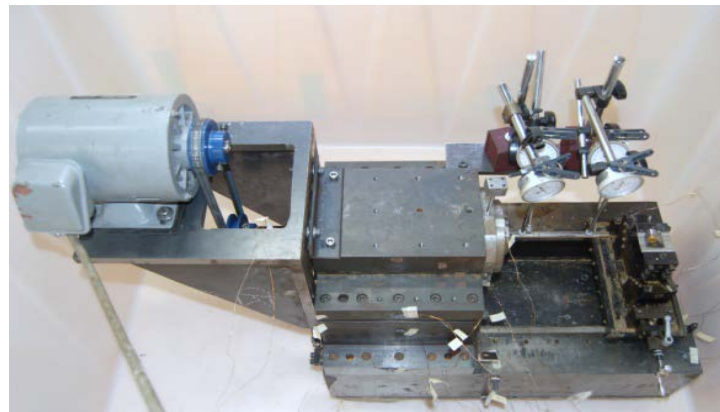
The calculated result of heat transfer coefficient shows in Fig.5.8. The result shows that compared to the natural cooling condition of the strong alkaline water, heat transfer coefficient improve about 5.5 times when operating bench lathe inside strong alkaline water and increase about 6 times when added with microbubble. From these results, it can be clarified that supplying microbubble in the strong alkaline water could achieve a remarkable higher cooling effect.

5.4. Investigation of the vibration, thermal deformation of bench lathe and the processing quality under immersed condition

It was explained in the chapter 3 that water can reduce machine resonant frequency, however, increases the vibration amplitude. In this research, the vibration of bench lathe under immersed conditions in strong alkaline water was investigated and measured. Thermal deformation caused by heat from the friction of bearing unit can affect the surface roughness of final cutting result. Therefore, the influence of immersing condition on the thermal deformation of bench lathe machine inside the strong alkaline water was also investigated.

Table 5.4 Specification of the bench lathe for experiment

Head stock	Height of center from bed	177 mm
	Height of center from floor	337 mm
	Spindle speed	Max. 3600 min ⁻¹
Bed	Size (W×L×H)	600×360×660 mm
Tool post	Stroke of Y axis	30 mm
Table	Stroke of Z axis	200 mm
Motor	Power	0.75 kW
	Speed control	Inverter (Hitachi J300)
Mass		200 kg



(a) Without strong alkaline water



(b) With strong alkaline water

Fig.5.9 Photograph of the experimental setup

The specification of the bench lathe used in the experiment is shown in Table 5.4. The structure of bench lathe was modified by higher motor stand in order to keep the motor outside water. Considering the potential of electric shock and fire hazard that may occur, precaution is required to be taken in case of wiring during installation of the machine. By using the above setup, the vibration of the bench lathe machine, the thermal deformation of the test bar and the processing quality under immersed condition were investigated and conducted. In addition, the experiment conditions without using strong alkaline water (Fig.5.9a) and with strong alkaline water (Fig.5.9b) were done for comparison.

5.4.1 Investigation of the vibration

In this section, the influence of immerse condition to the vibration of the bench lathe machine was investigated. The experiment setup shown Fig.5.10 was used. In this experiment, the bench lathe was immersed in strong alkaline water. Machine vibration was measured by placing two accelerometers at the head of bench lathe machine in X and Y direction. The measurement was done by measuring

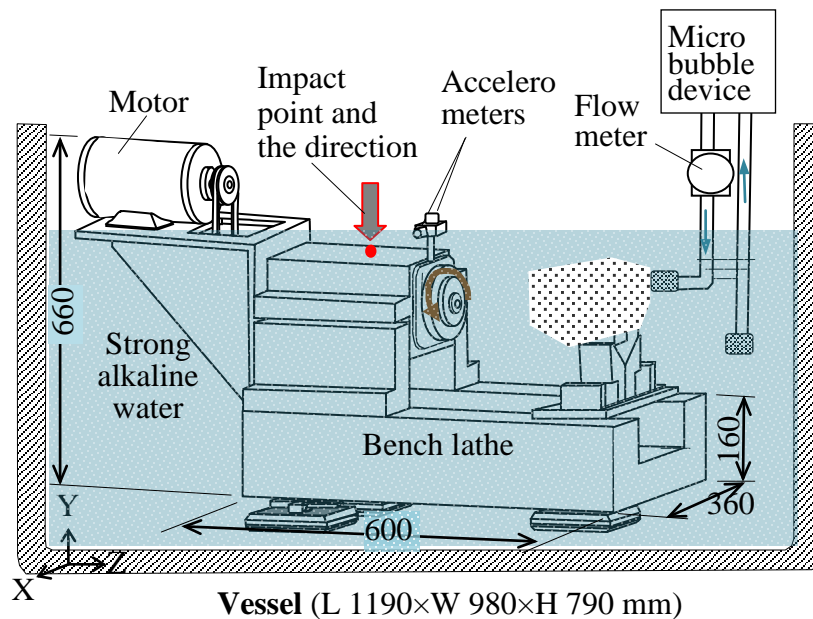
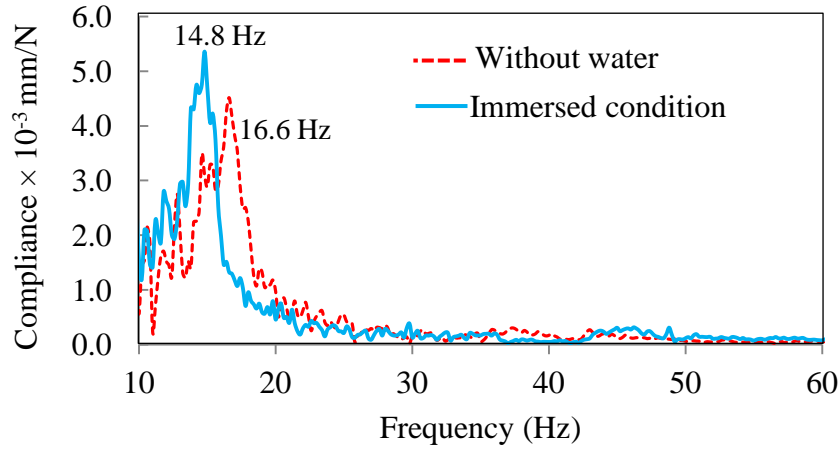
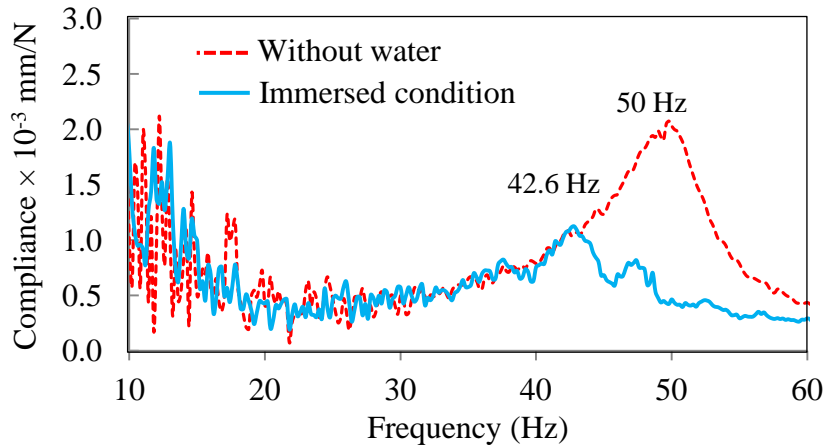


Fig.5.10 Experimental setup for measuring amplitude of the vibration



(a). Resonance of the bench lathe at X-axis



(b). Resonance of the bench lathe at at Y-axis

Fig.5.11 Bench lathe resonant frequency measurement result by impact test

the resonant frequency of dry and under immersed condition by impact test on the head of the bench lathe. The bench lathe was then operated at spindle speed which coincide machine resonant frequency to analyze the effectiveness of immersing condition in suppressing machine vibration. The measurement result of resonance of the bench lathe is shown in Fig.5.11. By applying impact force to the machine head from the vertical direction, the result shows that without immersing condition, large vibration occurred at frequency 16.6 Hz and 50 Hz in the X and Y direction, respectively. When water is added, resonant frequency reduces to 14.8 Hz in the X direction and 42.6 in the Y direction. As frequency shifted, the operation becomes

smoother. The bench lathe machine was then operated at the spindle speed of 996 min^{-1} and 3000 min^{-1} which correspond to the resonant frequency of the machine at 16.6 Hz and 50 Hz respectively and analyzing their amplitude of vibration. The measured result for the spindle speed of 996 min^{-1} and 3000 min^{-1} are shown in Fig. 5.12 and Fig.5.13, respectively. The measurement result shows that the amplitude of vibration reduces about 57% at the spindle speed of 996 rpm and 68% at 3000 min^{-1} when using immersed condition. Therefore, it is considered that immersed machine condition can reduce machine vibration, which is effective in optimizing the final cutting result.

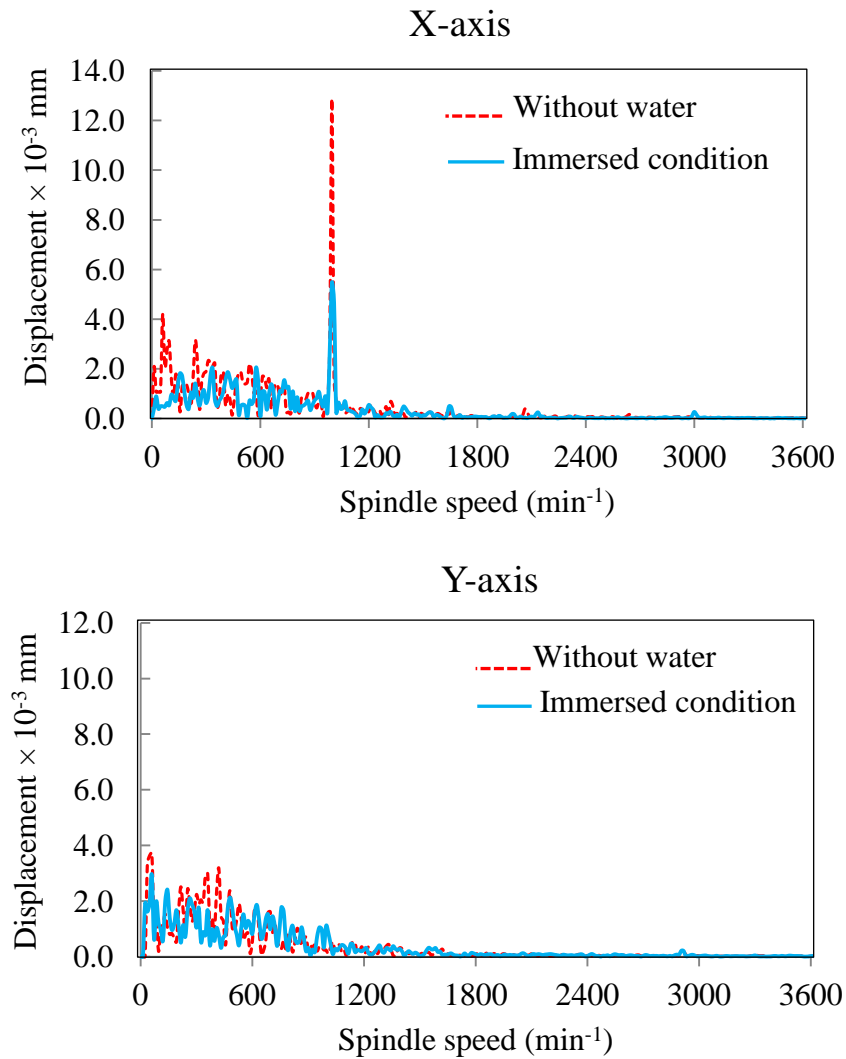


Fig.5.12 Amplitude of bench lathe operated coincides with machine resonance at 996 min^{-1}

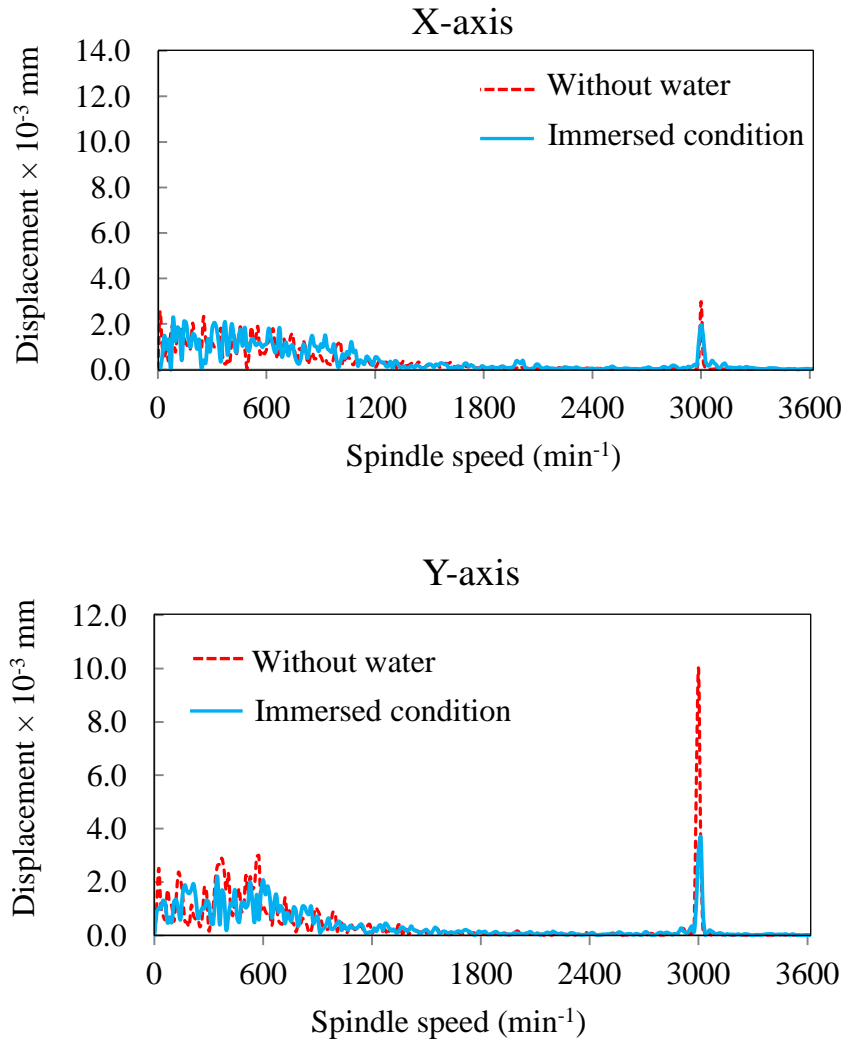


Fig.5.13 Amplitude of bench lathe operated coincides with machine resonance at 3000 min^{-1}

5.4.2 Investigation of the temperature change and thermal deformation

Thermal deformation caused by heat from the friction of bearing unit can affect the surface roughness of final cutting result. Here, the influence of immersing condition on the temperature and thermal deformation of bench lathe machine inside the strong alkaline water was measured. The specification of bench lathe shown in previous Table 5.4 was used for the experiment. The experimental setup for the investigation of the temperature change and the thermal deformation is shown in Fig. 5.14. In this experiment, the whole body of

the bench lathe except the motor was immersed in the strong alkaline water and supplied with microbubble continuously and then the characteristic of thermal deformation was investigated. For the investigation of the bench lathe temperature, the bench lathe machine was operated at the spindle speed of 960 min^{-1} , 3000 min^{-1} and 3600 min^{-1} for 2 hours. The temperature of the machine structure was measured by attaching T-type of thermocouples (shown as red circle mark ● in Fig. 5.14). Every 20 minutes, the machine was put on the idle state and the spindle was continuously rotated manually for measuring the thermal deformation of the test bar in two places (X and Y directions) using dial gauges.

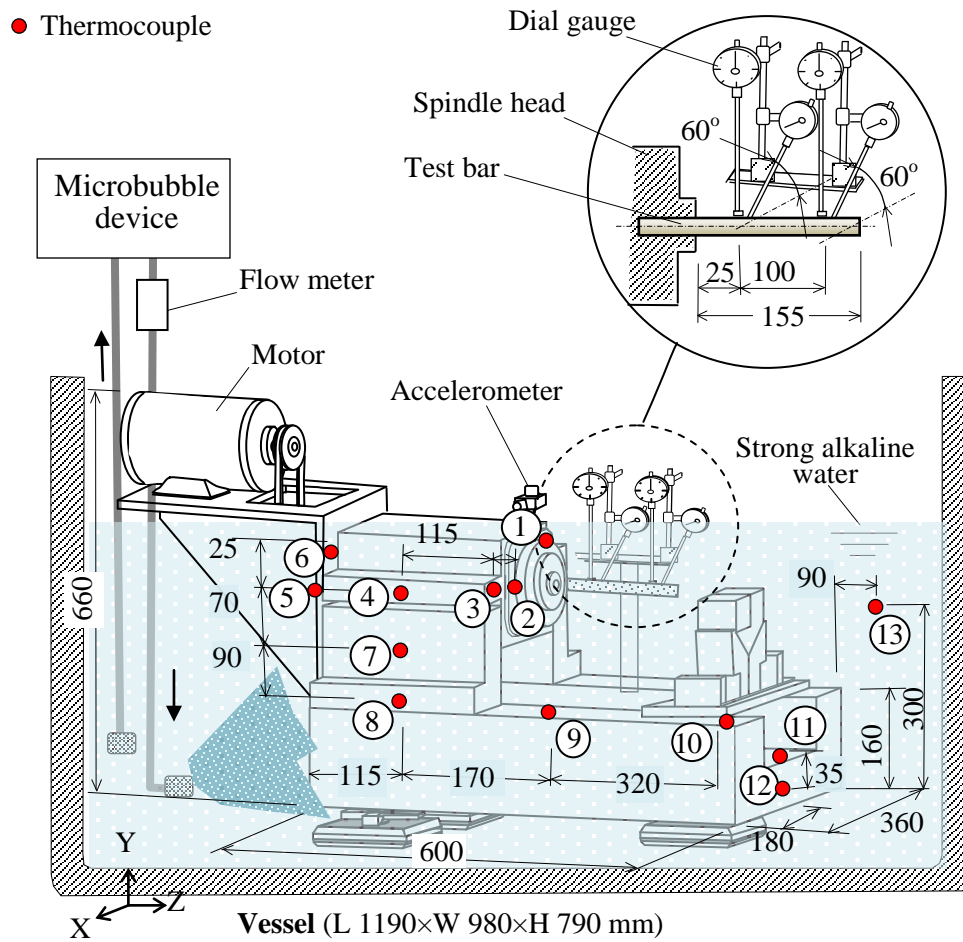
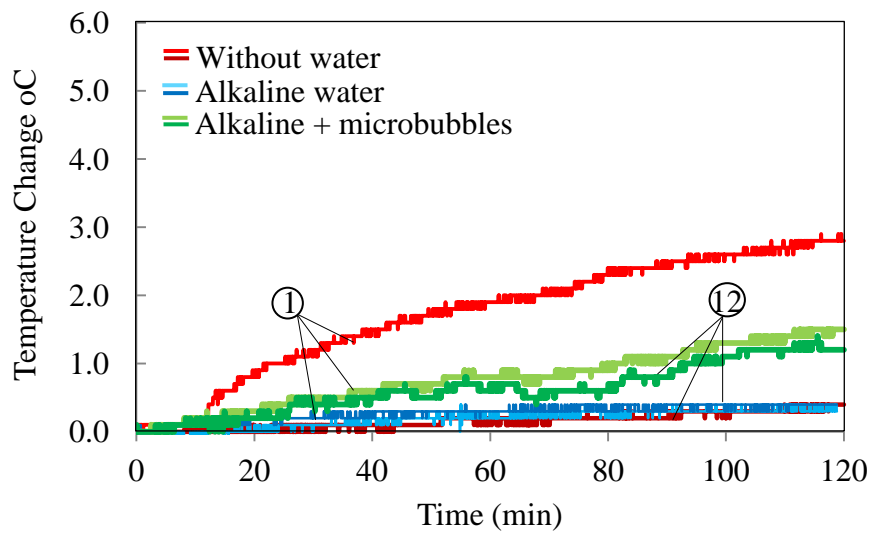
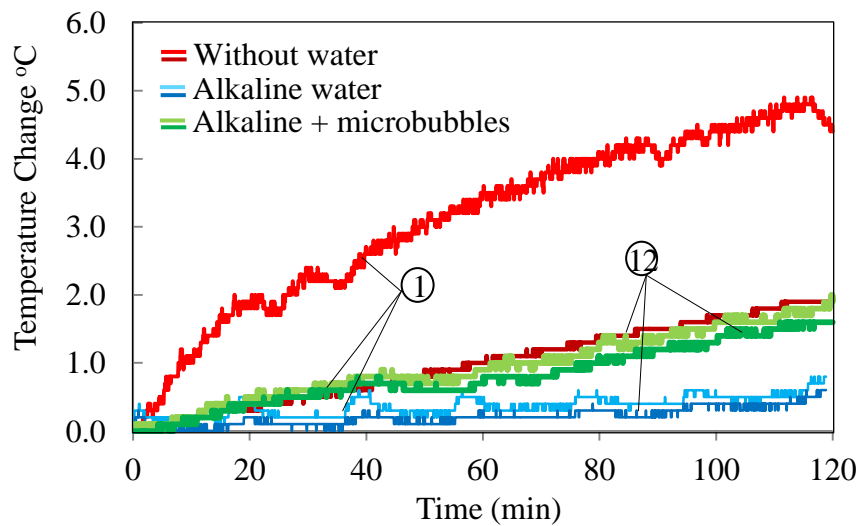


Fig.5.14 Schematic view of the experiment using the bench lathe in strong alkaline water with microbubbles

Fig.5.15 shows the experimental results of the temperature of the machine tool at spindle tip surface ① and at the end surface of machine bed ⑫. At spindle speed 996 min^{-1} , the rise in temperature (the maximum values at steady state condition) at the spindle tip surface ① which is the most influencing part of the machining accuracy were 2.9°C at dry condition, 0.4°C for strong alkaline condition, and when condition added with microbubble, the temperature was suppressed within 1.5°C . While for dry condition at spindle speed of 3000 min^{-1} ,

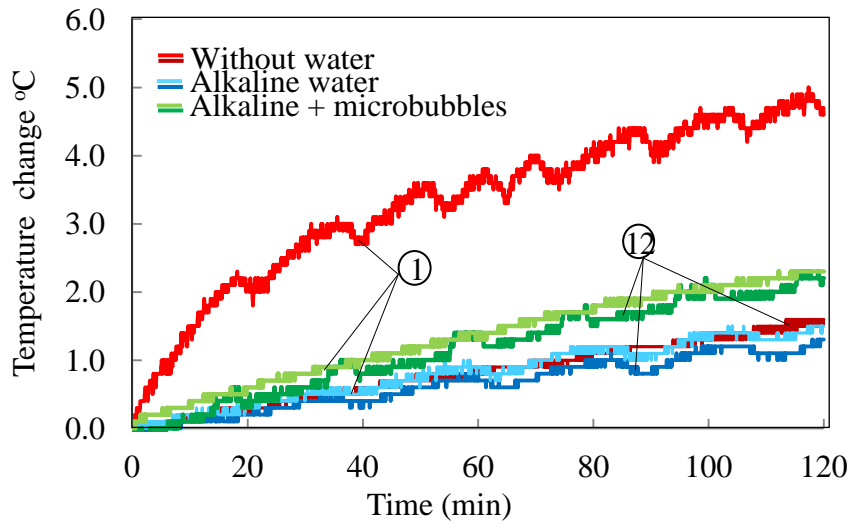


(a). Temperature change of the bench lathe operated in 996 min^{-1}



(b). Temperature change of the bench lathe operated in 3000 min^{-1}

Fig.5.15 Temperature change of the bench lathe operated in different spindle speed

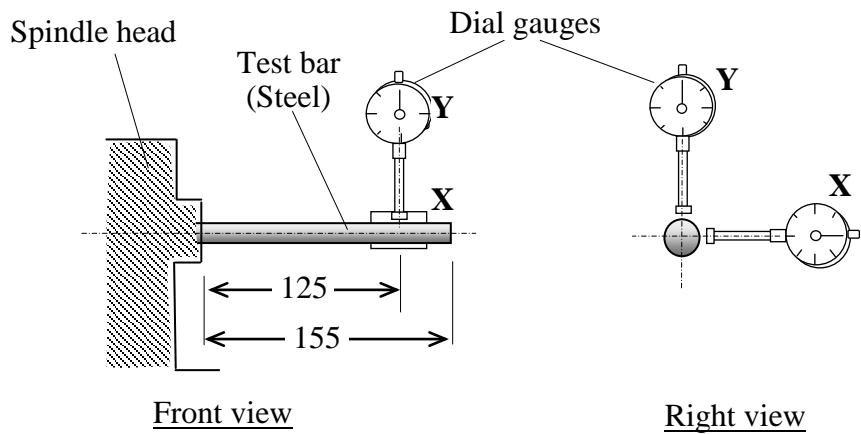


(c). Temperature change of the bench lathe operated in 3600 min^{-1}

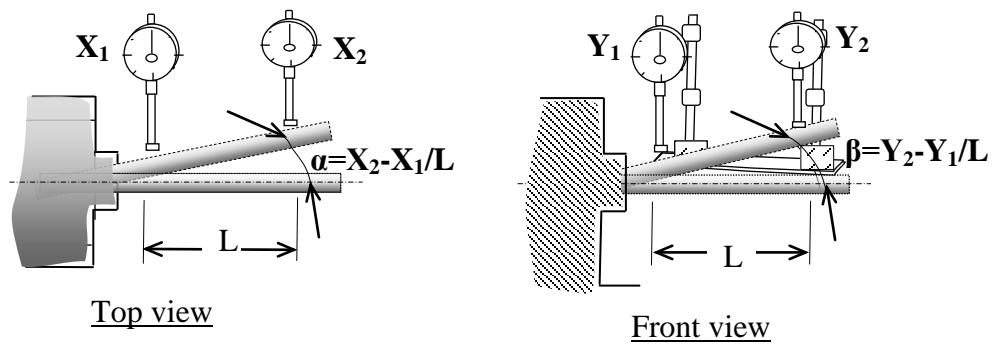
Fig.5.15. Temperature change of the bench lathe operated in different spindle speed

the temperature rise about 4.8°C , for the strong alkaline water is 0.8°C and rise to 1.8°C when alkaline water was added with microbubbles. When operated at the spindle speed of 3600 min^{-1} , for the dry condition is 5.0°C , for the strong alkaline condition is 1.4°C and for the condition added with microbubbles, the temperature was suppressed within 2.2°C . By this forced cooling effect, the thermal deformation is considered to be effectively suppressed. From these results, it was observed that when adding with microbubbles, the change in temperature is large compared to only strong alkaline water was used. This condition occurred because the heat generated by microbubble device causing the temperature of water to rise during continuous operation for a long period of time. A temperature that rise in the case of the spindle rotating were due to frictional heat of spindle bearing, while in the case of adding microbubble, as the microbubble device was operated continuously for two hours, it heated up and caused water temperature increase. Although temperature increases, in these two cases, the temperature distribution in the mechanical structure is considered very small. Thus, shorter operation time can give large cooling effect when using microbubbles.

Fig. 5.16 shows the schematic view of the dial gauges setup for measurement of thermal deformation. Here, the relative displacement and angular displacement were measured. Relative displacement was measured by placing dial gauge 25 mm from the end of test bar in horizontal and vertical direction for measuring the displacement of test bar in X and Y axis. The angular displacement was measured by calculating the difference between 2 dial gauges. The angular displacement of test bar was calculated by $\alpha = (X_2 - X_1)/L$, $\beta = (Y_2 - Y_1)/L$. Since the position of the test bar for initial setting was not concentric



(a). Setup for measurement of the relative displacement of the test bar



(b). Setup for measurement of the angular displacement of the test bar

Fig.5.16 Schematic view of dial gauges setup for thermal deformation measurement

with the machine spindle, the initial reading of the test bar deformation was done to the reference of the next reading. Fig.5.17 and Fig. 5.18 show the relative displacement and angular displacement of the tip of the test bar for the spindle speed 996 min^{-1} and 3000 min^{-1} .

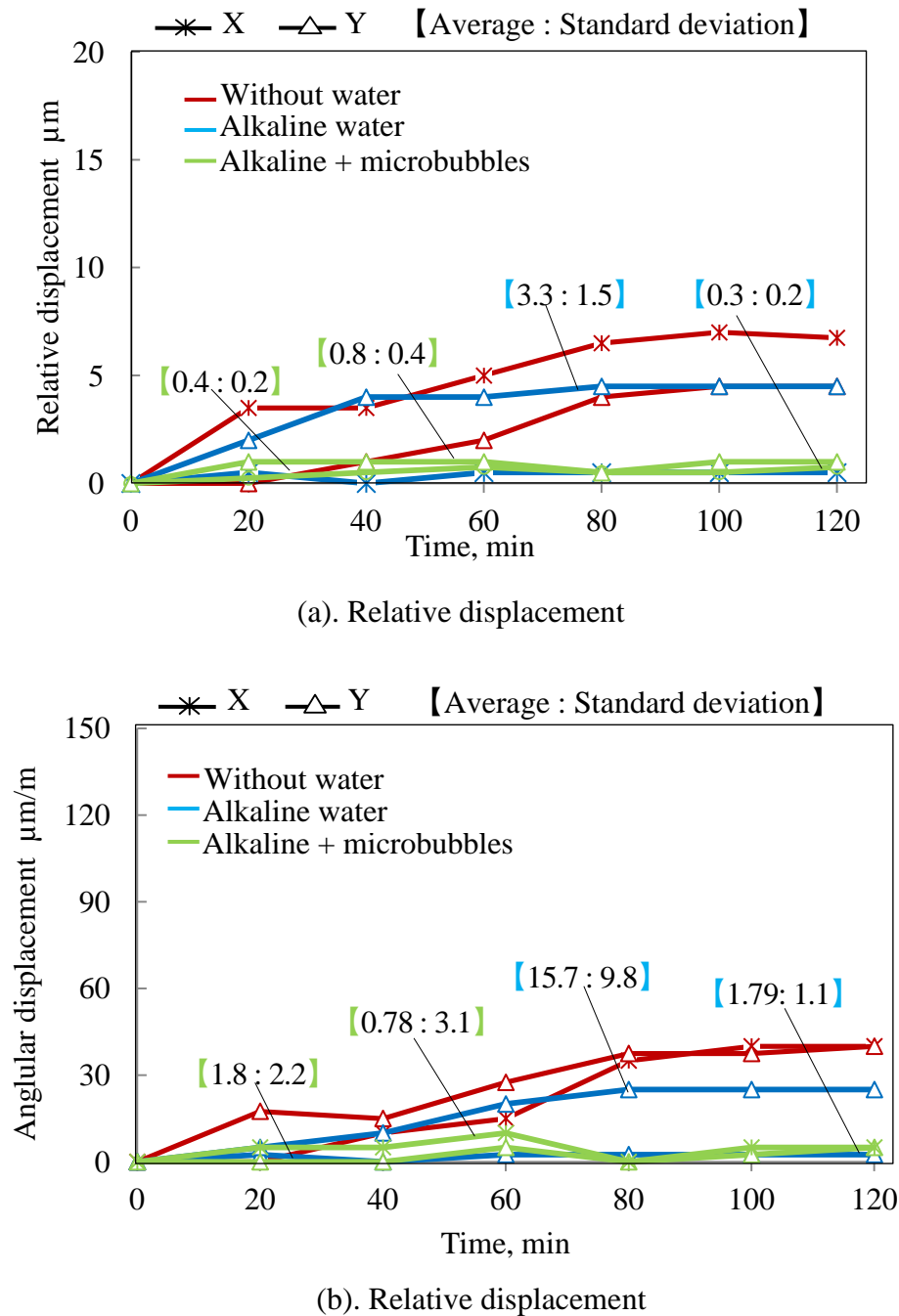
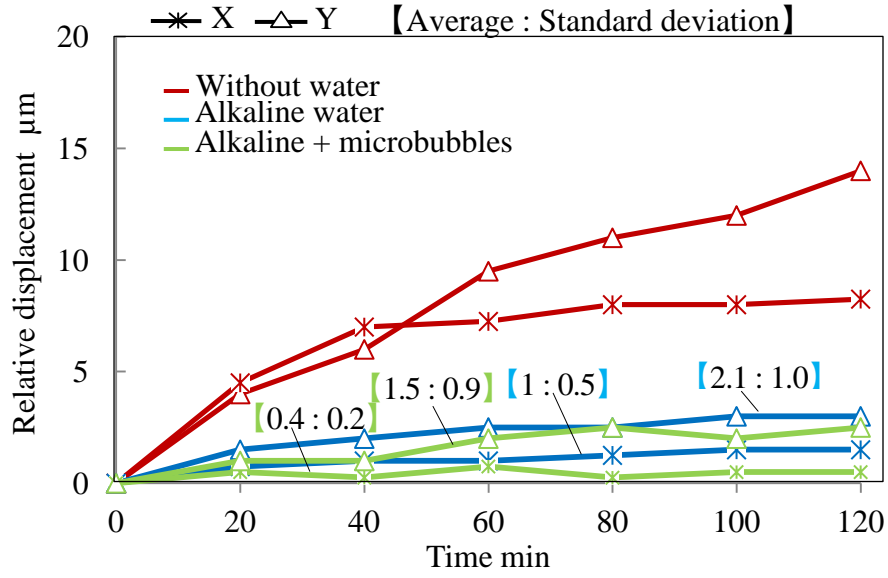
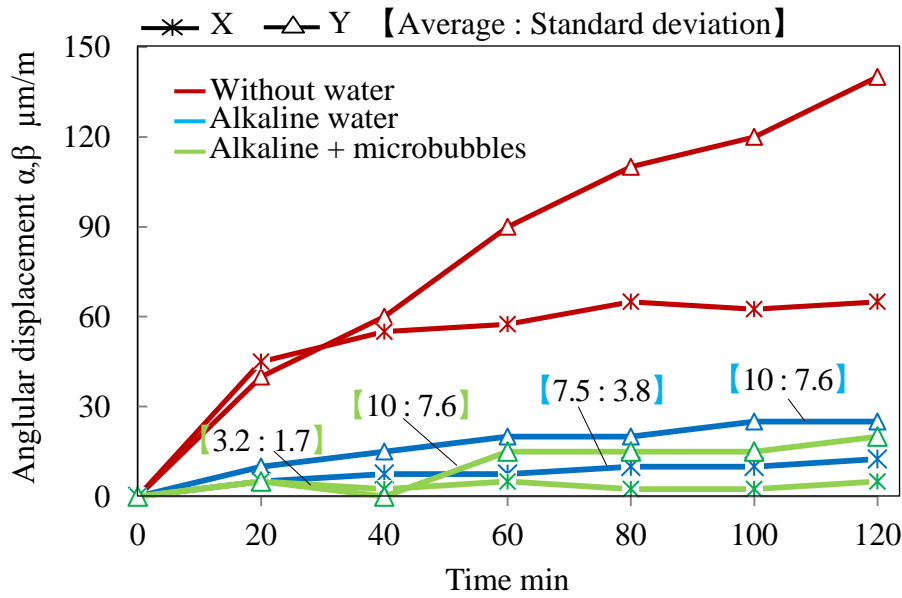


Fig.5.17 Thermal deformation of the bench lathe in strong alkaline water with microbubbles at the spindle speed 996 min^{-1}



(a). Relative displacement



(b). Relative displacement

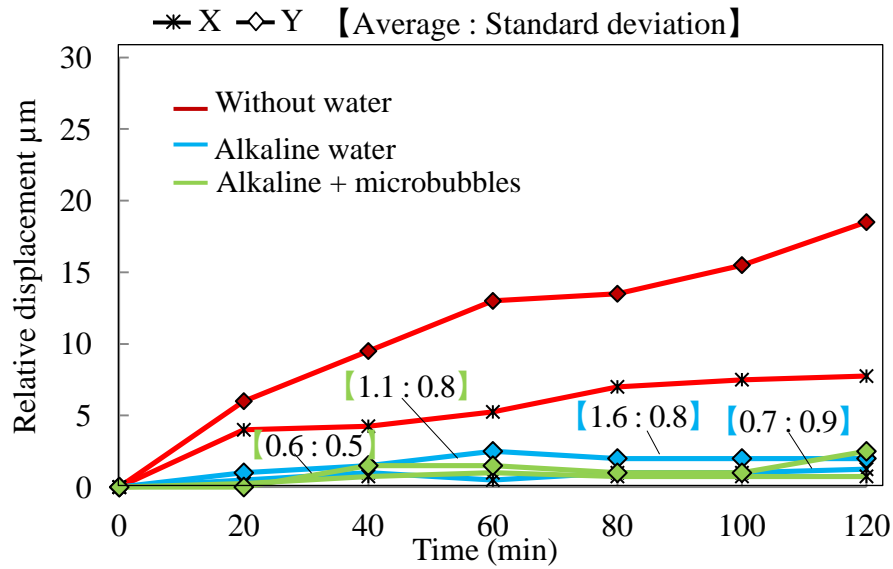
Fig.5.18 Thermal deformation of the bench lathe in strong alkaline water with microbubbles at the spindle speed 3000 min^{-1}

The data between 20~120 minutes were divided into 6 intervals, and the average values with the standard deviation of each of the six intervals are plotted. The results show that, in the dry condition, the relative displacements are large with $\Delta X=4.5\mu\text{m}$, $\Delta Y=4.8 \mu\text{m}$ and angular displacements were $\alpha=40 \mu\text{m}/\text{m}$ and $\beta=42$

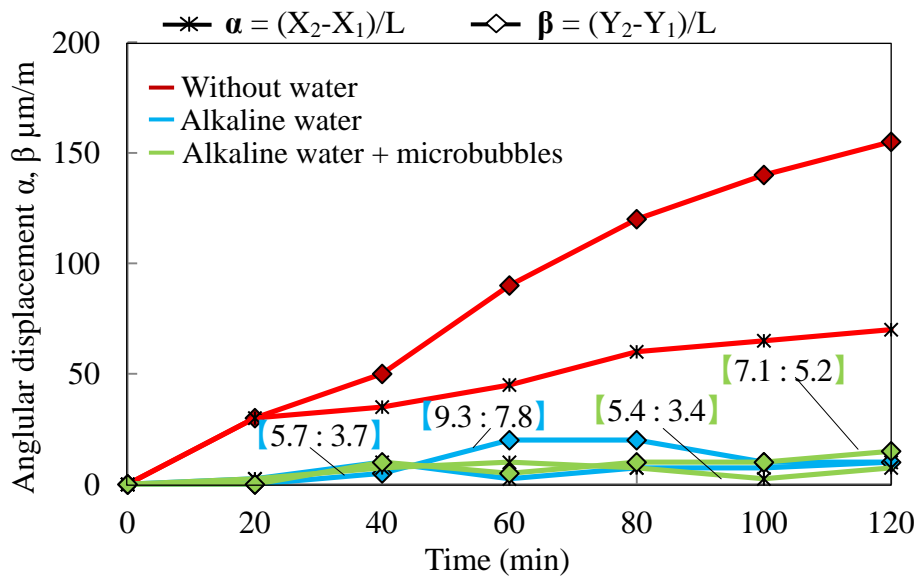
$\mu\text{m}/\text{m}$ at 996 min^{-1} . For the spindle speed of 3000 min^{-1} , the relative displacement are $\Delta X=8.3 \mu\text{m}$, $\Delta Y=14.0 \mu\text{m}$ and angular displacements are $\alpha=65 \mu\text{m}/\text{m}$ and $\beta=140 \mu\text{m}/\text{m}$. When operated inside strong alkaline water, the thermal deformations in both operation speeds reduced significantly. In addition, the thermal deformation becomes even smaller when microbubble was added. For the condition using strong alkaline water added with microbubble, the relative displacement is less than $0.5 \mu\text{m}$ in X-axis and $2.5 \mu\text{m}$ in Y-axis, while the angular displacement is less than $20 \mu\text{m}$ in X-axis and $5 \mu\text{m}$ in Y-axis for both operation speeds, respectively. Therefore, thermal deformation is suppressed remarkably. The results clearly show that the suppression in relative displacement and angular displacement from the condition without water and influence of microbubble is large. Thus, it can be said that by using an immersed bench lathe in strong alkaline water, vibration of the machine can be reduced; thermal deformation of machine structure can be effectively suppressed and resulting high processing accuracy.

For spindle speed of 3600 min^{-1} , the thermal deformation was expected to be larger than both spindle speed 996 min^{-1} and 3000 min^{-1} . This is because of the high-speed rotation that created more friction in the bearing and lead to the fast increment of heat over time. The measurement result of thermal deformation for spindle speed of 3600 min^{-1} is shown in Fig.5.19. In the dry process, relative displacements were $\Delta X=7.8 \mu\text{m}$, $\Delta Y=18.5 \mu\text{m}$, and angular displacements were $\alpha=70 \mu\text{m}/\text{m}$ and $\beta=155 \mu\text{m}/\text{m}$. For the condition using strong alkaline water added with microbubble, the relative displacement was less than $2.5 \mu\text{m}$ and the angular displacement was only $20 \mu\text{m}/\text{m}$. As a result, thermal deformation suppresses remarkably. The data between 20~120 minutes were also divided into 6 intervals, and the average values with the standard deviation of each of the six intervals are plotted. The results clearly show that the suppression in the relative and angular displacement from the condition without water and influence of microbubble are large ($\Delta X: 0.75 \mu\text{m}$

$\Rightarrow 0.61 \mu\text{m}$, $\Delta Y: 1.57\mu\text{m} \Rightarrow 1.07 \mu\text{m}$, $\alpha: 5.71 \mu\text{m/m} \Rightarrow 5.36 \mu\text{m/m}$, $\beta: 9.29 \mu\text{m/m} \Rightarrow 7.14 \mu\text{m/m}$). Thus, it can be said that by using an immersed bench lathe in strong alkaline water, the thermal deformation of machine structure can be effectively suppressed and resulting high processing accuracy with stability.



(a). Relative displacement



(b). Angular displacement

Fig.5.19 Thermal deformation of the bench lathe in strong alkaline water with microbubbles at the spindle speed 3600 min^{-1}

5.4.3 Processing quality of immersed cutting method

In the cutting experiment using the bench lathe, since the feed speed was driven manually along Z-direction, we considered that the measured results of surface roughness may contain human error. Therefore, for the investigation of our proposed control by immersing condition, instead of using the bench lathe machine, the machining center of NC milling machine shows in Fig.5.20 was used to evaluate processing accuracy for immerse cutting method. The experiment for the measurement of temperature on the tip of cutting chips, tool life and the surface roughness of the cutting were conducted for the evaluation of the effectiveness of cooling under immersing condition in the strong alkaline water.

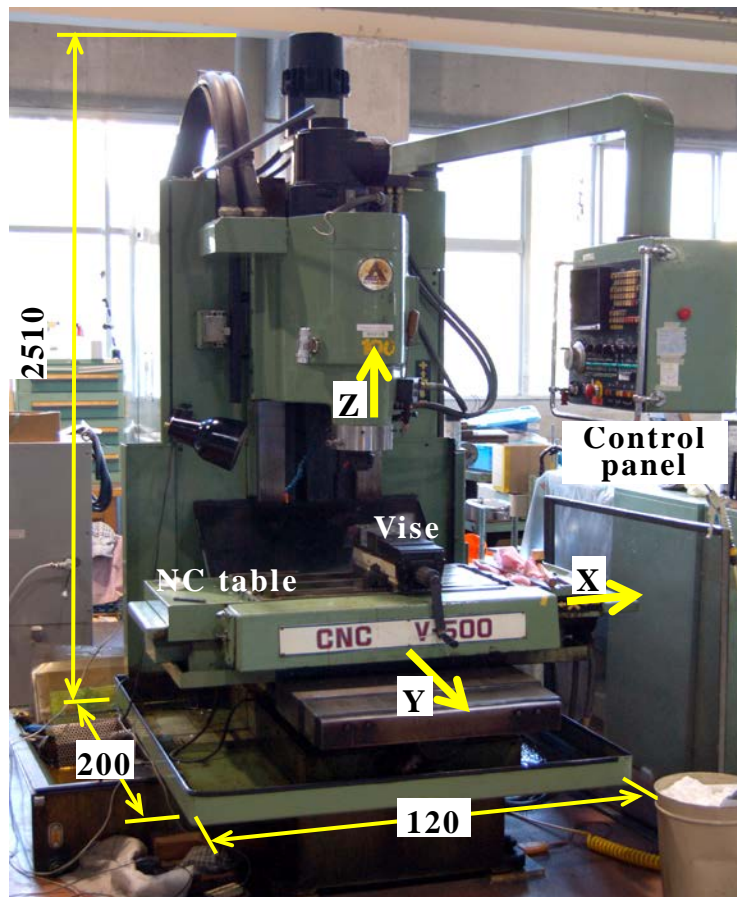


Fig.5.20 Photograph of NC milling (Unit: mm)

5.4.3.1 Evaluation of tool tip temperature

Minimize the temperature at the tool tip can extend the lifetime of tool and chips, and improve finishing surface of the workpiece. Measurement of tool tip temperature during machining is difficult because the cutter is in rotation condition, therefore the reverse setup was done by mounting a workpiece on the machine spindle while cutting tool was placed and tighten on the vise. Again, the tool tip temperature still difficult to be measured as the tool tip performing cutting during the experiment. Hence, in this condition, the measurement was done by measuring temperature at about 3 mm from the tool tip in two places, as shown in the enlarged view in Fig.5.21. The cutting condition used for this experiment is shown in Table 5.5 After the temperature data from those two points were measured and collected, the tool tip temperature was predicted and calculated using by CAE analysis. These results of the experiment were compared with the calculation result by CAE analysis to obtain the final temperature of the tool tip.

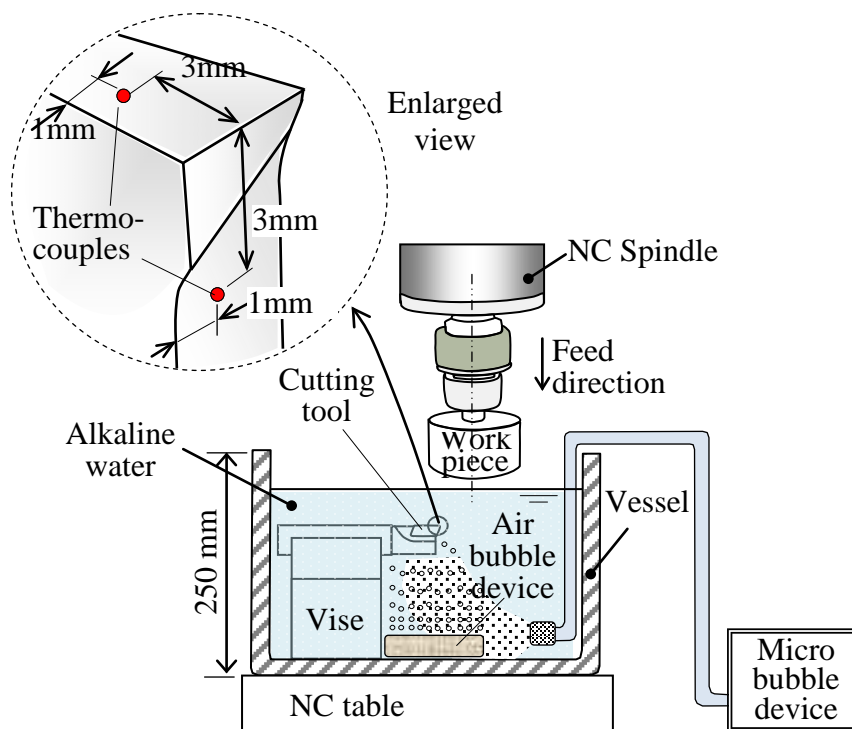


Fig.5.21 Experimental setup for measurement of tool temperature

Table 5.5 Cutting conditions for evaluation of tool tip temperature

Cutting conditions		
Cutting speed 80 m/min	Feed speed 0.25 mm/rev	Depth of cut 0.4 mm
Workpiece		
Material : Ti6Al4V	Cutting force : 3178 N/mm ²	
Tool		
Rake angle: 5°	Coated carbide	

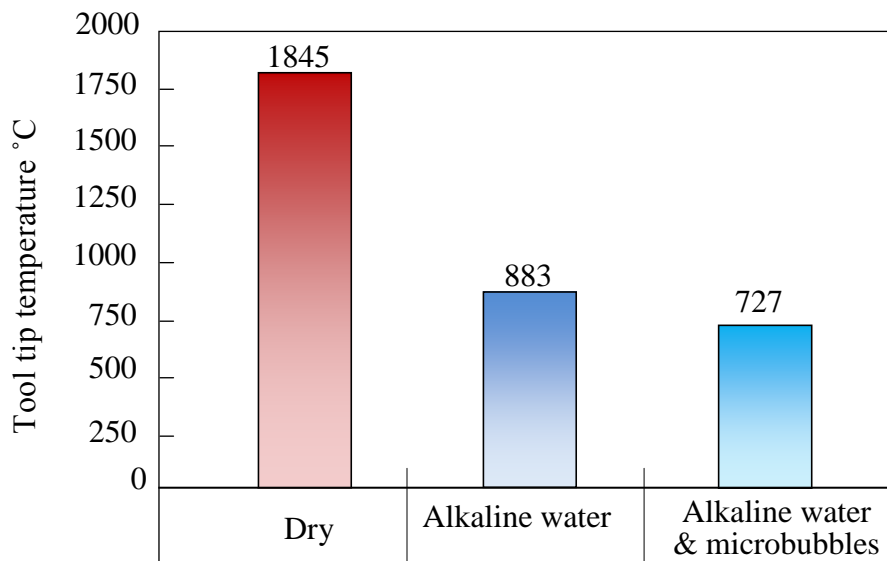


Fig.5.22 Experimental results for tool tip temperature

The calculated and comparison of the results of maximum tool tip temperature is shown in Fig.5.22. The maximum cutting tool temperature for cutting in the strong alkaline water was 48% and cutting in the strong alkaline water mixed with microbubbles was 39% compared with dry cutting. Thus, it is confirmed that the proposed cutting under strong alkaline water is extremely effective.

5.4.3.2 Evaluation of tool life

In the evaluation of tool life, cutting was performed until the cutting tool reaches its tool life. Cutting tool life is defined to be reached when the amount of flank wear reaches 0.3 mm. In this experiment, normal setup for cutting evaluation shown in Fig.5.23 with the cutting condition in Table 5.6 was used instead of the setup in previous Fig.5.21. During cutting, tool chips were frequently removed to measure their flank wear by using a microscope.

Table 5.6 Cutting conditions for evaluation of tool life

Cutting conditions	
Cutting speed	100 m/min
Feed speed	100 mm/min
Width of cut (axial)	2 mm
Depth of cut (radial)	3 mm
Workpiece	
Material	Ti6Al4V
Specific cutting force	3420 N/mm ²
Tool	
Material	Coated carbide
Rake angle	5°
Dimension	Diameter Ø25 × Length 120 mm

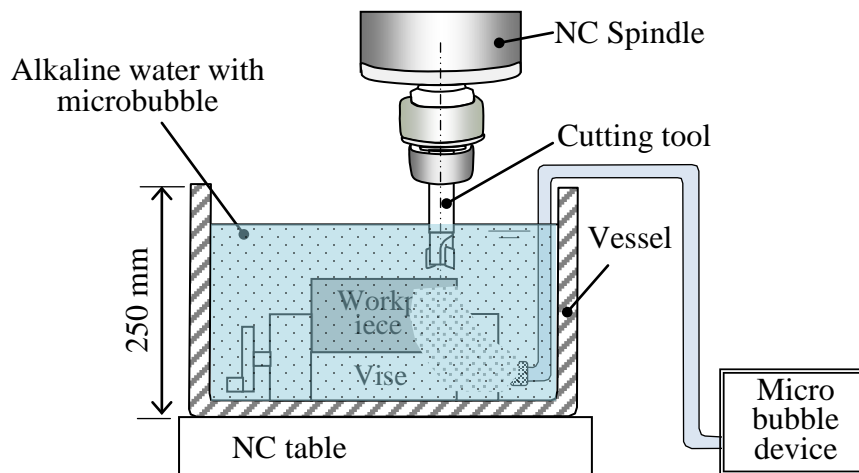


Fig.5.23 Experimental setup for evaluation of tool life

Fig.5.24 shows the results of the tool life test. The tool life for cutting in the strong alkaline water mixed with microbubble is 3 times larger compared to the dry cutting and 2 times compared to the wet cutting. Therefore, it is considered that, the proposed cutting method under strong alkaline water with microbubble is capable of removing cutting heat for cutting difficult to cut materials. Moreover, the processing condition shown in Table 5.6 is usually being used for finishing cuts of steel S45C as conventional dry cutting and wet cutting. Generally, using this cutting condition to cut Ti6Al4V material would result in more heat load on the cutting tool tip due to the unsuitable cutting condition. However, using our proposed method of cutting under strong alkaline water, the tip temperature of cutting tool was suppressed, and tool life has also become longer. Therefore, the proposed method is considered very effective for productivity and product quality.

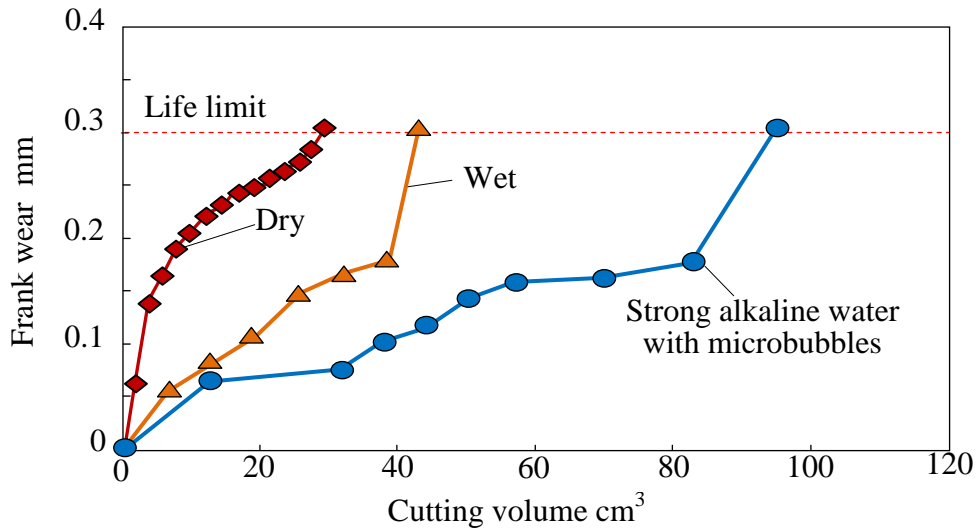


Fig.5.24 Results of the tool life

5.4.3.3 Evaluation of surface roughness

In the measurement of surface roughness, the cut surface was measured perpendicular to the cutting direction using a probe type measuring device (Mitutoyo SJ-400) shown in Fig.5.25. Both cutting surface roughness when

started cutting and at the end of tool life was measured in the experiment. Fig. 5.26 shows the measurement results of the surface roughness R_z (maximum height) for starting and ending of tool life with different cutting conditions. The result using the proposed method is 70% and 89% compared to the conventional dry and wet cutting respectively. Moreover, the variation of the surface roughness is also smaller. It can be considered that the thermal deformation of the tool was well suppressed and the cutting positioning has also become more accurate.



Fig.5.25 Photograph of the surface roughness measuring device

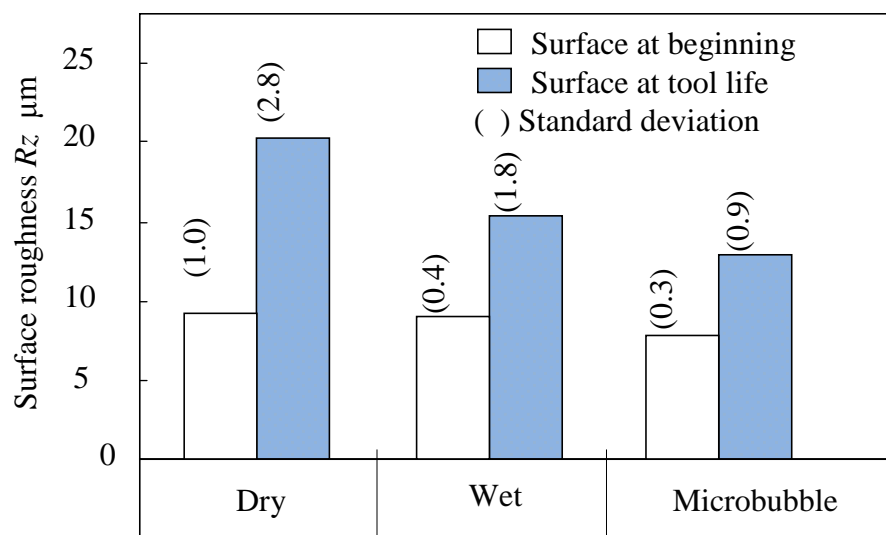


Fig.5.26 Results of the surface roughness

5.5 Summary

The results of this study are summarized as follows:

- (1) Heat transfer coefficient values for using strong alkaline water was $400 \text{ W/m}^2\text{K}$ and improved to $2350 \text{ W/m}^2\text{K}$ by applying spindle speed at 3600min^{-1} , then increased to $2550\text{W/m}^2\text{K}$ by adding microbubbles in the strong alkaline water resulting excellent cooling efficiency.
- (2) By immersing the whole machine tool in strong alkaline water, the rise in cutting tool tip temperature was suppressed about 60%, relative displacement was reduced about 89%, angular displacements were reduced about 86%, the tool life was improved 3.6 times and the surface roughness improved about 2/3 times compared with dry cutting.
- (3) Most of machine tool related materials, except aluminum, do not corrode in strong alkaline water.

Chapter (6)

ENVIRONMENTAL IMPACT OF MACHINING USING COOLING OF STRONG ALKALINE WATER

6.1. Introduction

Nowadays, environmental conservation has become an important factor in product design and manufacturing process. Eco-friendly manufacture associated with energy saving has also become a common request in production and manufacturing. ^{[6-1], [6-2]} Enhance machining performance for the improvement of product's quality, time-saving, and low-cost consumption are essential in manufacturing. ^[6-3] However, large consumption of energy, the contamination of water, and the emission during manufacturing have increased toxicity level in the environment. ^{[6-4], [6-5]} Meanwhile, as the industrialization has expanded widely in recent years, the used of less energy and lowering consumption of resources have become primary goals to be reached in order to contribute in minimizing the impact on the environment. On the other hand, the amount CO₂ emission associated with energy usage has become a major issue in inducing global warming. Hence, with the awareness of global environmental issue ^{[6-6], [6-7]}, manufacture a product should be in accordance with consideration of its impact to the environment and nature. Nowadays, many researchers have investigated and designed the machinery that are friendly and have minimal impact on the environment by reducing waste ^{[6-8], [6-9], [6-10]}. Some have studied on how to improve the quality of grease and lubrication for long time use ^[6-11], other interested in conducting investigations regarding product management in manufacturing ^[6-12]. Meanwhile, the optimization is required by assessing life

cycle products and manufacturing process in order to minimize their impact on the environmental and human health. Life Cycle Assessment (LCA) is becoming increasingly important to the product design and manufacture process. The assessment based on LCA methodology has been studied in various areas^{[6-13], [6-14], [6-15]}, while there have been very few reports on the assessment for the machining. At the same time, as manufacturing technologies have evolved with the goal of achieving high productivity, high accuracy, with low cost, the environmental consideration is required in product design and manufacture process. Therefore, in this paper, simple assessment on machining using water was performed with the consideration to the environmental aspect and its conservation. The machine tools used for the experiment in previous chapters were used for the evaluation. The emission level of each machine will be compared to the conventional cutting.

6.2. Study method for the assessment of strong alkaline water

6.2.1 Goal and scope of the study

The goal of this study is to assess the life cycle of the use of strong alkaline water as a cooling in machine tools in reducing waste environmental load. This study assesses the LCA of the researches performed in previous chapters by using water for machining such as drilling in strong alkaline water and machining with machine tool completely in submerge condition in the strong alkaline water. The amount of water used in this study was varied and depend on the need of each machine tool. For the environmental protection, the study was focused on assessing how much CO₂ is emitted to the environment for using strong alkaline water during machining compared to oil and others lubricant.

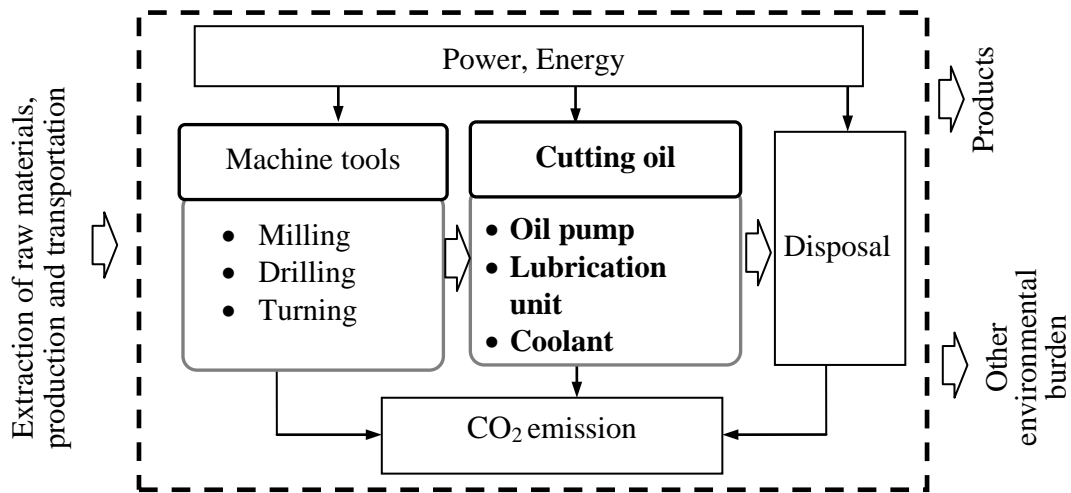
Since the study focuses on pollution caused by CO₂, the study was limited to the object and processes that emit CO₂ during machining. Hence, based on the

previous chapters, the calculation for assessment was performed to define the amount of CO₂ emission from wastes, oil, wet cutting, dry cutting, machining center, microbubble device, strong alkaline water generation equipment, pump water, and turning using lathe machine. Fig.6.1 shows simplified flowcharts of the life cycle of using conventional wet cutting and strong alkaline water. The system boundary of this LCA includes all activities involved in the production of POCA (K₂CO₃), extraction of the raw material for workpiece and cutting tool are excluded from the study, as well as the inventory analysis for raw material from crude oil. The traffic from transporting machine tool related materials and consumables for machining is also excluded. The environmental burden of CO₂ is considered to be calculated in this study. The calculation was done by calculating and comparing total electric consumption for each device during dry cutting, wet cutting, and cutting using strong alkaline water with microbubble in one year.

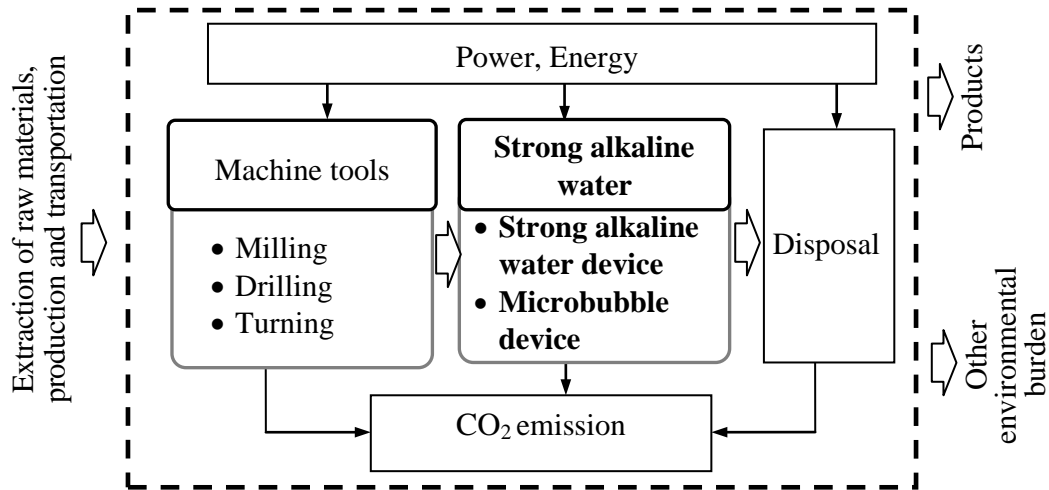
6.2.2 Study method

The method used for LCA was the unit process analysis method and input-output analysis. Here, water was used as a study object to the bench lathe machine and drill. The table of inter-industry relationship (input-output table) as well as separately determined embodied intensity of the machining was considered for the estimation of direct and indirect impacts of each element in the environment. The CO₂ emission was calculated for each of bench lathe machine and drilling machine. The total power consumption and oil disposal was calculated.

In consideration of these points, we adopted an input-output analysis method for the present study by using water during machining to improve cooling effect with the comparison to conventional wet cutting using oil based and other solvent as a cutting fluid.



(a). Flow chart of LCA using conventional wet cutting



(b). Flow chart of LCA using Cooling of strong alkaline water

Fig.6.1 Flow chart of LCA for conventional wet cutting and strong alkaline water

6.2.3 Calculation approaches

The assessment was made by calculating various gasses emitted to the environment with the potential impact of the each emission to the global warming and human health. The calculation for assessment was made for emission from the amount power consumed during machining and oil disposal. The emission from power consumption during machining was calculated using

Equation. (6.1). Where W_E is the amount of power consumed in an hour. The emission for oil usage and disposal were calculated using equation (6.2).

$$CL_{CO_2} = 0.468 \text{ (kg-CO}_2\text{/kWh)} \times W_E \text{ (kWh)}. \quad (6.1)$$

$$\begin{aligned} \text{CO}_2 \text{ emission (kg-CO}_2\text{)} = & \text{Disposed oil k}\ell \times \text{Calorific value GJ/k}\ell \\ & \times \text{EF (t-C/TJ)} \times (44 \div 12). \end{aligned} \quad (6.2)$$

In these calculations, in case of electric power consumed during machining, the emission factor was taken based on the amount of the gas emitted per kWh, while the emission factor for oil disposal was taken based on the amount of related gas emitted over energy usage during incineration of disposing oil.

6.3 Simple assessment for machining using cooling of strong alkaline water

6.3.1 Inventory for development of cutting technology under strong alkaline water with microbubbles

Titanium alloy and nickel alloy are largely used in aeronautics and astronautics machine parts. The machining technology for those materials with higher accuracy are being investigated ^{[6-16],[6-17],[6-18]}. However, both of these materials have very low thermal conductivity and consequently, most of the cutting heat generated are conducted into the cutting tool. The tool becomes extremely high in the temperature and loses its strength and hardness, which causes lower machining efficiency and poor accuracy. Since research regarding this problem has been investigated and evaluated by the machining technology using compulsory cooling under strong alkaline water with the

whole machining setup is submerged in the strong alkaline water, the impact of machining using strong alkaline water on the environment was evaluated by calculating the CO₂ emission. In this calculation, the total calculated CO₂ emission from cutting is strong alkaline water will be compared with the conventional wet cutting. The emission emitted from electricity usage during machining and from disposed oil was calculated and compared. Moreover, the amount of CO₂ emission is calculated based on the electric usage from the oil pump, the air bubble compressor, the microbubble device, the strong alkaline water device, and the water pump for eliminating chip.

Table 6.1(a) shows the amount of CO₂ emission for the conventional wet machining. Firstly, the electricity using in coolant pump on the milling machine (1.2 kW) is calculated for 250 working days (for a year) with 8 working hours a day. The total electricity for the whole year is taken (1.2 kW×8 h×250 days) and the amount of CO₂ emission, CL_{CO_2} is calculated by using equation (6.1). The emission factor for the electric usage was taken with conversion value 0.468 kg-CO₂/kWh⁽⁶⁻¹⁹⁾. Thus, the total amount of CO₂ emission is 1123.2 kg-CO₂.

Next, the amount of CO₂ emission from the oil disposal is calculated. In this calculation, the 340 ℓ of cutting oil is considered to be disposed every 6 months with is 680 ℓ /year in total. In addition, the amount of refill oil is taken to be 30 ℓ/month (30ℓ×12 month=360 ℓ/year). Hence, the total amount of the disposing oil is 1040 ℓ and the amount of CO₂ emission is calculated based on this amount using equation (6.2)⁽⁶⁻²⁰⁾. In this calculation, the calorific value of disposed oil is 40.2 GJ/kℓ and the amount of carbon emission is 19.22 t-C/TJ⁽⁶⁻²¹⁾. By using equation (6.2), the amount of CO₂ emission due to disposed oil is 2946.3 kg-CO₂. Therefore, the total amount of CO₂ emitted from both cases is 4069.5 kg-CO₂.

Table 6.1 CO₂ emission of conventional wet cutting and cutting under strong alkaline water with microbubbles

(a). CO₂ emission of conventional wet cutting

Machining center & oil pump		Waste oil disposal	
Power consumption kW	1.2	Cutting oil amount ℓ/year	680
Use condition /year	8 h ×250 days	Refill oil amount ℓ/year	360
Consumption electric quantity kWh	2400	-	-
CO ₂ emission kg-CO ₂ /year	1123.2	CO ₂ emission kg-CO ₂ /year	2946.3
Total CO ₂ emission kg-CO ₂ /year	4069.5		

(b). CO₂ emission of cutting in strong alkaline water

Calculation factors	Compressor for air bubble	Micro bubble device	Pump for removing chip	Strong alkaline water generating unit
Power consumption kW	0.95	0.56	0.0132	0.75
Amount used of strong alkaline water ℓ	-	-	-	20
Replacement cycle	-	-	-	Once a month
Production of alkaline water ℓ	-	-	-	20
Use condition /year	8 h ×250 days	8 h ×250 days	8 h ×250 days	25h
Consumption electric quantity kWh	1900	1120	26.4	75
CO ₂ emission kg-CO ₂ /year	889.2	524.2	12.4	8.8
Total CO ₂ emission kg-CO ₂ /year	1434.6			

Table 6.1(b) shows the amount of CO₂ emission in the proposed method of cutting under cooling of strong alkaline water with microbubble. The amount of CO₂ emission for using air bubble compressor is calculated by assuming that the compressor is operated 8 working hours/day and 250 working days/year, hence the amount of electric power usage in one year is 1900 kWh (0.95 kW×8 h×250 days). Using emission conversion factor based on the power consumed every hour from Tokyo electricity company which is 0.468 kg-CO₂/kWh⁽⁴⁻¹⁹⁾, The amount of CO₂ emission from operation air bubble compressor calculated using equation (6.1) is 889.2 kg-CO₂. With similarly calculation, the amount of CO₂ emission from the microbubble device and the water pump for chip removal is 524.2 kg-CO₂ and 12.4 kg-CO₂ respectively. In addition, the amount of CO₂ emission for using strong alkaline water device is also calculated. The total amount of strong alkaline water being used in the processing is about 20ℓ. The milling machine is assumed to be used for 250 days/year and changing of alkaline water is assumed to be once per month. Hence, the total amount of strong alkaline water needed in a year is 250 ℓ. The device for making alkaline water takes 2 hours for making 20 ℓ of alkaline water. Therefore, the total time required in a year is 25 hours, and the calculated electric usage is 18.8 kWh (0.75 kW×25 h). The 8.8 kg-CO₂ is obtained by using equation (6.1). Therefore, the total amount of CO₂ emission for the cutting under strong alkaline water is 1434.6 kg-CO₂.

6.3.2 Inventory of drilling technology using strong alkaline water with microbubbles

Based on the research described in chapter 4 by drilling technology using strong alkaline water with microbubble, the assessment of the environmental impact of this technique was performed by calculating CO₂

emissions. In this calculation, the amount of CO₂ emission for the conventional wet cutting and by applying the proposed method of using strong alkaline water is evaluated and compared. In the wet cutting, total amounts of CO₂ emissions were calculated from the machining center at the time of machining, the amount of the electric usage from the oil pump, and the CO₂ emissions the waste oil treatment and its disposal. On the other hand, the amount of CO₂ emissions by drilling using cooling of strong alkaline water with microbubble was calculated from the power consumption by the machining center, the microbubble generating device, the strong alkali water device, and the pump for supplying strong alkali water to the drill.

Table 6.2 shows the inventories and the calculated result of CO₂ emission for the conventional wet drilling and the drilling using strong alkaline water. The calculation result of the amount of CO₂ emission from the conventional wet drilling is shown in Table 6.2(a). Firstly, in the wet drilling, the machine center with 3.6 kW power and the oil pump with 1.2 kW power used for supplying cutting oil to the processing point was assumed to be operated 8 working hours/day and for 250 working days/year. In this case, the calculated power consumption is 9600 kW (74.8kW×8h×250 days), and when the conversion factor of CO₂ emission is set to 0.468 kg-CO₂/kWh, the amount of CO₂ emission of CL_{CO2} (kg-CO₂) can be obtained by calculated from equation (6.1). By operating the machine center and the oil pump, the amount of CO₂ emission are 4492.8 kg-CO₂/year.

In the next calculation, the amount of CO₂ emission of the waste oil disposal was calculated. This time, the oil tank with capacity 340 ℓ is assumed to be replaced two times a year, while the 30 ℓ are being added

every month which are 360ℓ (30 ℓ×12 months). Thus, the total processed oil is 1040 ℓ. The estimation of the amount of CO₂ emission can be calculated from equation (6.2). The calorific value 40.2GJ/ℓ and carbon emissions 19.22 t-C/TJ were taken. By equation (6.2), the amount of CO₂ emission of the waste oil processing and disposing is 2946.3 kg-CO₂. Hence, by wet cutting, the total amounts of CO₂ emission are 7439.1 kg-CO₂/year.

The prediction of the amount of CO₂ emission by drilling using strong alkaline water with microbubble is shown in Table 6.2b. During drilling, the machine center was used with working hours assumed to be 8 hours a day and 250 days a year. Hence, the calculated electric consumption is 7200 kWh (3.6 kW×8 h×250 days). The amount of calculated CO₂ emission by drilling using cooling of strong alkaline water is 3369.6 kg-CO₂. In addition, since the microbubble generation device and the pump to supply strong alkaline water to the drill are also used, the calculated CO₂ emission for both devices is 524.2 kg-CO₂ and 702 kg-CO₂, respectively. Furthermore, the amount of CO₂ emission of strong alkaline water generation device is also evaluated. The capacity of the container for storing strong alkali water is 16.1ℓ (350 × 230 × 200 mm), while for supplying microbubble is 3.9 ℓ, which is 20 ℓ in total of strong alkaline water needed. Assume that the machine center is run 250 days a year and the strong alkaline water is replaced once a month, nearly 250ℓ of strong alkaline water is needed in a year. Since it takes 2 hours for the strong alkaline water generating device to generate 20 ℓ of strong alkaline water which is about 25 hours a year, therefore, the expected power consumption is 18.8 kWh (0.75 kW×25 h). The amount of calculated CO₂ emission is 8.8 kg-CO₂. The total amount of CO₂ emission by drilling using cooling of strong alkaline water with microbubble is 4604.6 kg-CO₂.

Table 6.2 CO₂ emission of the conventional wet cutting and drilling using cooling of strong alkaline water with microbubbles

(a). CO₂ emission of conventional wet cutting

Machining center & Oil pump		Waste oil disposal	
Power consumption kW	4.8	Cutting oil amount ℓ/year	680
Use condition /year	8 h ×250 days	Refill oil amount ℓ/year	360
Consumption electric quantity kWh	9600	-	-
CO ₂ emission kg-CO ₂ /year	4492.8	CO ₂ emission kg-CO ₂ /year	2946.3
Total CO ₂ emission kg-CO ₂ /year	7439.1		

(b). CO₂ emission of drilling using cooling of strong alkaline water

Calculation factors	Machining center	Micro bubble device	Water supply pump	Strong alkaline water generating unit
Power consumption kW	3.6	0.56	0.75	0.75
Amount used of strong alkaline water ℓ	-	-	-	20
Replacement cycle	-	-	-	Once a month
Production of alkaline water ℓ	-	-	-	20
Use condition /year	8 h ×250 days	8 h ×250 days	8 h ×250 days	25h
Consumption electric quantity kWh	7200	1120	1500	18.8
CO ₂ emission kg-CO ₂ /year	3369.6	524.2	702	8.8
Total CO ₂ emission kg- CO ₂ /year	4604.6			

6.3.3 Inventory for immersing machine tool and machining in the alkaline water for CO₂ reduction

The assessment of environmental impact by immersing machine tool and performs cutting under strong alkaline water is done similarly to the two previous machining. The simple evaluation of the impact of strong alkaline water to the environment was performed by examining and calculating the CO₂ emission. In this calculation, the CO₂ gas emitted by machining using conventional wet cutting and using strong alkaline water during submersion of the bench lathe was compared. When using conventional cooling, total CO₂ emission emitted from operating the machine tool, the oil pump, the cooling refrigerator, and the waste oil disposal were calculated. On the other hand, in the case of the cooling by submerging bench lathe machine, the amount of CO₂ emission was calculated from the amount of electric power consumed by using the microbubble generator device, the strong alkaline water generator, and the chips removal pump. Table 6.3 shows the inventories and the calculated result of CO₂ emission for conventional wet cutting and cutting by submersion of bench lathe machine completely in strong alkaline water. The calculation result of the amount of CO₂ emission of the conventional wet cutting using bench lathe machine is shown in Table 6.3a. In a conventional cutting, the total power consumption for the machine center (3.6 kW), oil pump (1.2 kW) and refrigerating device (2.2 kW) for 8 hours per day with the assumption to run for 250 days a year are 7.0 kW. By this assumption, the total calculated power consumption is 14000 kW (7.0 kW×8 h×250 days). Since the conversion factor of the CO₂ emission for power consumption is set to 0.468 kg-CO₂/kWh, the total amount of CO₂ emission of CL_{CO2} (kg-CO₂) can be obtained by calculating using equation (6.1). Hence, by operating the machine center, oil pump and cooling refrigerator, the annual amount of CO₂ emission are 6552 kg-CO₂.

The amount of CO₂ emits from waste oil disposal is also calculated. Here, the oil tank with capacity 340 ℓ are assumed to be replaced two times a year, whilst the 30 ℓ will be used for refilling every month which is 360ℓ (30 ℓ × 12 months), and therefore the total usage of oil is 1040 ℓ/year. Based on this assumption, the amount of CO₂ emission can be calculated. In this calculation, the calorific value 40.2GJ/ℓ and carbon emissions 19.22 t-C/TJ were chosen from property of lubrication oil. Thus, the calculated CO₂ emission for waste oil processing and disposing in one year is 2946.3 kg-CO₂. The total CO₂ emission by conventional wet cutting from power consumption and oil processing is 9498.3 kg-CO₂/year.

Table 6.3b shows the inventory and calculated result of CO₂ emission during immersing bench lathe machine and machining inside strong alkaline water. During performing this experiment, because it was difficult to perform cutting using the prototype bench lathe machine, the machine center was chosen to be used for cutting evaluation during the experiment. Since the machine center was used for cutting evaluation instead of bench lathe machine, the assessment will be done only for machine center. In this calculation, the machine center with main power 3.6 kW is assumed to be operating 8 hours a day and 250 days a year. Hence, the total power consumed in a year is 7200 kWh (3.6 kW × 8 h × 250 days). By taking the conversion factor of CO₂ emission from the electric usage 0.468 kg-CO₂/kWh, the amount of CO₂ emission calculated using equation (6.1) is 3370 kg-CO₂. Using the similar calculation, the calculated amount of CO₂ emission emitted from power consumption using the microbubble generation device and the pump for chip removal are 524 kg-CO₂, 12 kg-CO₂ respectively. Furthermore, the amount of CO₂ emission of the strong alkaline water generation device is also evaluated. The 26094 ℓ of strong alkaline water is assumed to be used during machining for one year. This amount of strong alkaline water was estimated by subtracting the volume of strong alkaline water filled into container (used for machine center

Table 6.3 CO₂ emission of conventional wet cutting and cutting by submersion machine tool in strong alkaline water

(a). CO₂ emission of conventional wet cutting (without submersion)

Machining center & Oil pump			Waste oil disposal	
Power consumption	kW	7.0	Cutting oil amount ℓ/year	680
Use condition	/year	8 h ×250 days	Refill oil amount ℓ/ear	360
Consumption electric quantity	kWh	14000	-	-
CO ₂ emission	kg-CO ₂ /year	6552	CO ₂ emission kg-CO ₂ /year	2946
Total CO ₂ emission	kg-CO ₂ /year	9498		

(b). CO₂ emission of cutting by submersion of machine tool in strong alkaline water

Calculation factors	Machinin g center	Micro bubble device	Water supply pump	Strong alkaline water generating unit
Power consumption kW	3.6	0.56	0.0132	0.75
Electric quantity for strong alkaline water 1 ℓ kWh/ ℓ				0.075
Replacement cycle	-	-	-	Once a month
Amount of strong alkaline water ℓ	-	-	-	26094
Use condition /year	8 h ×250 days	8 h ×250 days	8 h ×250 days	24h×365 days
Consumption electric quantity kWh	7200	1120	26.4	1957
CO ₂ emission kg-CO ₂ /year	3370	524	12	916
Total CO ₂ emission kg- CO ₂ /year	4822			

submersion) with the volume of the NC milling machine center itself, and added with some amounts for the refilling every month. The volume of the container, which should be cover the size of machine center, is 27000 ℓ (=W3000 mm × D3000 mm × H3000 mm×10⁻⁶). The volume of all machine parts is 1026 ℓ (=The total mass of machinery 8000 kg ÷ Density of steel 7800 kg/m³ × 10³). Hence, the remaining 25974 ℓ was assumed as the approximation of the amount of strong alkaline water used for submersion of the machining center. For refilling, 10 ℓ of strong alkaline water was assumed to be added every month to maintain the water level, thus 120 ℓ (=10 ℓ/month×12 month) is required as a supplement for one year. Since the alkaline water generator device is used to generate strong alkaline water, its electric consumption is also required to be assessed. The strong alkaline water generator operates using 0.75 kW power. Because it is possible to generate 10 ℓ of strong alkaline water with pH 12.5 in an hour, the amount electricity of used for generating 1ℓ of strong alkali water is 0.075 kW/ℓ (0.75 kW × 1 h ÷ 10 ℓ), and about 1957 kW/year. The amount of CO₂ emitted from this consumption is 916 kg-CO₂. Thus, the overall amount of electricity required to be used for machining under immersed condition using machine center for 1 year is 4822 kg-CO₂.

6.4 Impact analysis for machining using strong alkaline water

6.4.1 Impact to the environment

In this section, the impact of machining using strong alkaline water on the environment is discussed. The comparison by strong alkaline water cutting and conventional wet cutting will also be made to define which best for environment conservation, especially less contribution to global warming.

The comparison of CO₂ emission for three machining explained in section 6.3 is shown in Fig.6.2, Fig.6.3, and Fig.6.4 for cutting technology inside strong

alkaline water and microbubble, drilling using strong alkaline water and microbubble, and cutting by immersion of the machine tool, respectively. The comparison between the conventional wet cutting by cutting inside strong alkaline water and microbubble is shown in Fig 6.2. The amount of CO₂ emission can be reduced 2634.9 kg-CO₂, (64.7 % reduced) in a year. This is due to the oil free usage in cutting using strong alkaline compared to the conventional wet cutting. Thus, it can be considered that, this cooling technique is very effective and capable of reducing CO₂ emission.

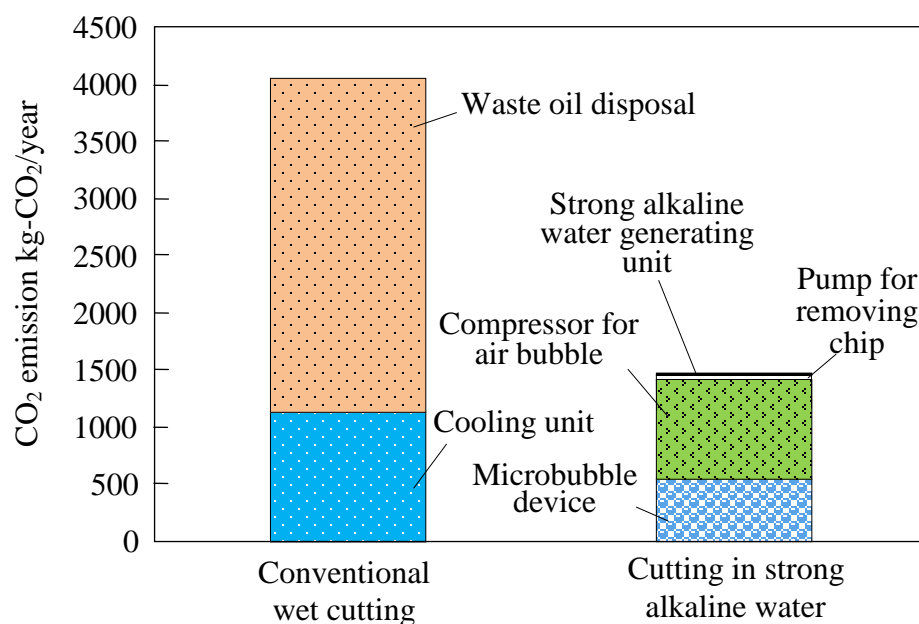


Fig.6. 2 Comparison of CO₂ emission for cutting inside strong alkaline water and microbubbles

The comparison of CO₂ emissions for drilling using strong alkaline water with microbubble is shown in Fig. 6.3. The amount of CO₂ emission can be reduced about 2834.5kg-CO₂ in a year when drilling using cooling of strong

alkaline water compared to the conventional wet drilling, which is about 38.1 % reduction. Same as stated earlier, this reduction is because cooling using strong alkaline water does not require cutting oil hence reduce carbon emission significantly.

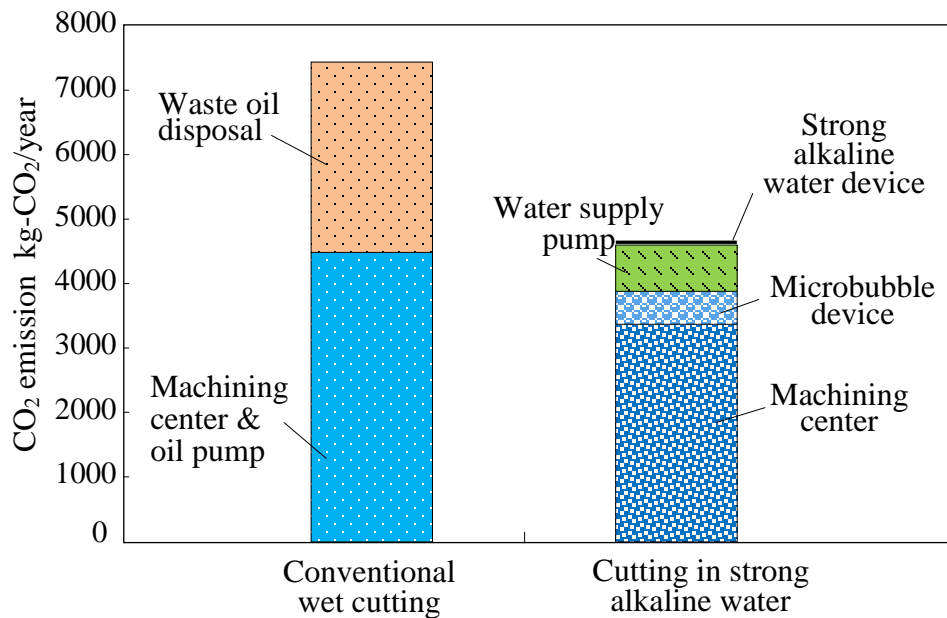


Fig.6.3 Comparison of CO₂ emission for drilling using strong alkaline water with microbubbles

Fig.6.4 shows the comparison of the amount of CO₂ emission for cutting under immersion on the machine tool. CO₂ emission reduces 4678 kg-CO₂ (49.2% reduction) for operating under immersed condition in strong alkaline water for one year. Since few devices like cooling unit and oil pump used in wet cutting, the power consumption in conventional wet cutting increase, hence higher CO₂ emission. In addition, since cutting under immersed condition does not use lubrication oil during machining, CO₂ emissions become lower. Thus, by

cooling using strong alkaline water, large emission from oil processing can be reduced, cleaning after processing is not required, which can reduce the environmental impact, and also it is considered to be extremely effective for manufacturing and industrial application.

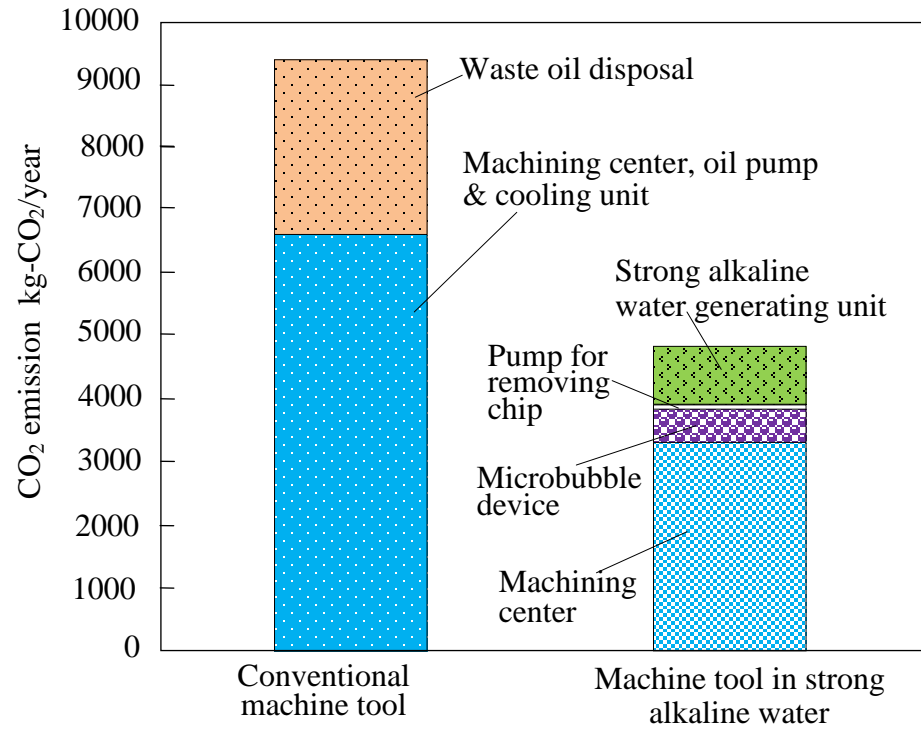


Fig.6. 4 Comparison of CO₂ emission for machining under immersion of machine tool

When three machine tools are operated at the same time, the potential impact of the emission to the global warming is calculated. Fig. 6.5 shows the comparison of overall emission from three machine tools to the global warming. The result shows that by machining using conventional wet cutting it contributes 21006 kg-CO₂-eq/year to the potential of the global warming occurrence. On the other hand, by machining using cooling of strong alkaline

water, it only contributes about 10861 kg-CO₂-eq/year, which is about 48% reduction from the conventional wet cutting. Since CO₂ emission reduces significantly, other gases emission such as CH₄ and N₂O that are not discussed in this study may also reduce as well, hence reduces other potential impact to the environment such as acidification, ozone depletion, smog formation and eutrophication as well.

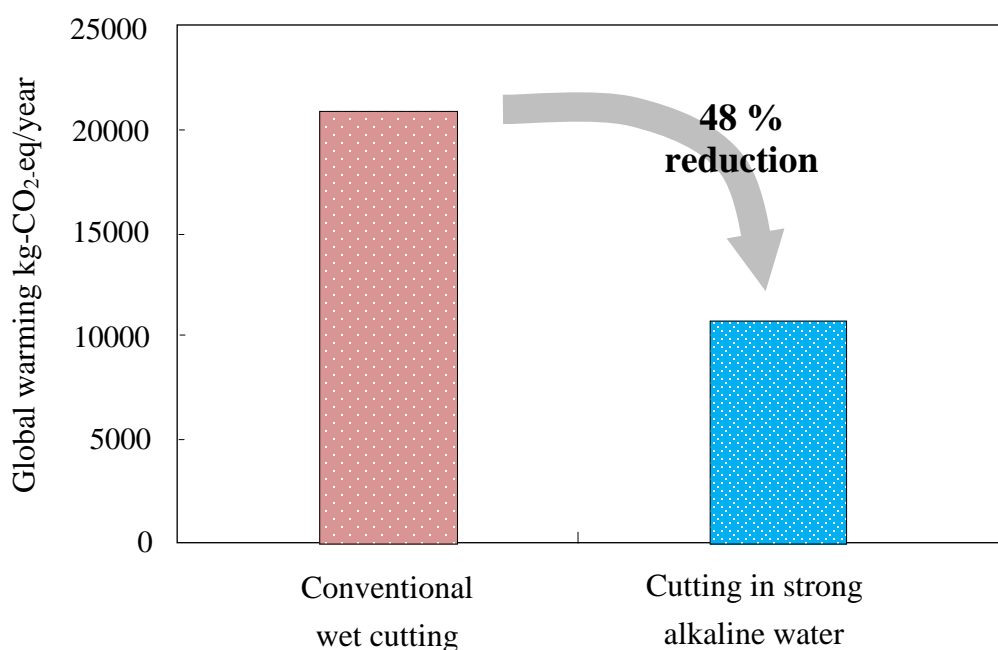


Fig.6.5 Comparison of the potential impact to the global warming

6.4.2 Impact to the human health

Besides the importance in conserving the environment, human health is the top priority that required great care. Thus the effect of strong alkaline water to the human health was assessed. As shown in Table 6.4, the soluble compound used to produce strong alkaline water is 2.18 g/liter of potassium carbonate

(K₂CO₃) which at only 0.1% in strong alkaline water. Hence, strong alkaline water is 99.9% is water. Table 6.5 shows the effect of strong alkaline water to the human health. Since 99.9% of strong alkaline water is water, inhaling and skin contact during encounters with strong alkaline water is considered safe. However, since the irritation to the skin may occur in some people, precaution such as wearing masks and washing hands and face after using strong alkaline water is highly recommended. In addition, drinking strong alkaline water is unsafe and should be avoided. Hence, further investigation in the future is required to assess the impact of the strong alkaline water to the human health specifically.

Table 6.4 Properties of strong alkaline water

Properties of strong alkaline water	
Assistant compound	Potassium carbonate (K ₂ CO ₃)
Concentration	99.9% water, 0.1% K ₂ CO ₃
pH	12.5
Dynamic viscosity	1.002 x10 ⁻³ kg/m.s
Specific heat	4.184 J/g°C
Color	Colorless
Oiliness aspect	None

Table 6.5 Effect of strong alkaline water to human health

Activity	Effect to the health
Smell	○ None
Touch (Skin contact)	○ Hand and face
Inhale	○ From atmosphere
Drink	△ and ×

○ : No problem △ : Avoid × : Prohibit

6.5 Summary

The use of cutting oil during machining causes a significant waste and emission for which the environmental implications are often discussed and debated. While, the growing uses of strong alkaline water as cooling started to be considered for the environmental prospective. The results indicate that the choice of a comparative assessment is an effective solution to show that cooling by strong alkaline water is environmentally preferable than cooling by cutting oil. The result from study shows that the use of strong alkaline water as cooling contributes less in jeopardizing the environment and human health. Although it is considered safe for skin contact, some precautions as explained earlier are required. In addition, further investigation is required to assess the impact of the strong alkaline water specifically. Comparing to the conventional wet cutting, strong alkaline water usage help in reduce about 48% of its impact to the global warming. Hence, reduce its impact on the environment. Therefore, it can be said that beside inhibit corrosion, prolong tool life and improve surface roughness of final cutting, strong alkaline water is also environmentally friendly.

Chapter (7)

CONCLUSIONS

In this research, the technology using strong alkaline water in machining is studied and evaluated. Control machine tool resonance using water mix PEO polymer, drilling using cooling of strong alkaline water and machining by immersion of machine tool in strong alkaline water is developed and evaluated. The evaluated results and conclusions of each chapter are explained as follows:

Chapter (3): The control technique regarding resonant frequency is developed for the establishment of optimum cutting conditions. The control factors such as control for machine density, stiffness and support position were considered and evaluated. Since there are multiple countermeasures which can be used from these control factors, the analysis based CAE was firstly done to obtain the best countermeasure for each control factor. The result from CAE analysis was used for experimental evaluation to obtain the optimum combination control from three control countermeasures. The optimum combination control was evaluated and proposed. By using the proposed control technique based on the each operation speed of machine tool, the resonant frequency of machine tool can be shifted and avoided. Since this study was done by applying the proposed method to the bench lathe machine, it can be also easily applied to the other machine tools when the deformation of the machine tools is known. From the experimental results of this study, it can be said that,

- (1) The method for controlling the resonant frequency of the machine tool was developed by changing density of machine structure, stiffness and support positions.

- (2) By filling water mixed with 6wt% polymer to the machine structure can reduce the resonant frequency and achieved higher damping ratio simultaneously.
- (3) The real cutting by applying this method was evaluated, and the resonance was successfully avoided and surface roughness of the final cut was also improved.

Chapter (4): In this chapter, for reducing thermal load on the cutting tool tip, technology by cooling using strong alkaline water is developed. Since water corrodes most metal material, the corrosion resistance of the some common materials used for workpieces and cutting tools water was evaluated by submerged in strong alkaline for 2 months. In addition, since strong alkaline water can lose its alkalinity becomes normal water when leaves in open air for a long period of time, the changes in the pH were tested by placing strong alkaline water in the environment with different temperature. It is revealed from the test that the pH of strong alkaline water only reduces 0.1, 0.3 and 0.5 in an environment with temperature $12^{\circ}\text{C}\pm 1$, $20^{\circ}\text{C}\pm 1$, and $40^{\circ}\text{C}\pm 1$ respectively. For improving cooling efficiency, the method by supplying strong alkaline water with microbubbles was developed. By adding microbubbles, heat generated during cutting can be reduced because of the improvement in the evaporative cooling. The evaluation for this method was performed by drilling test using trough-hole drill. At final, the proposed cooling method was evaluated by drilling experiments. The cutting tool life and cutting surface roughness is investigated and evaluated by experiments. From this study, it can be concluded that,

- (1) By adding microbubbles to the strong alkaline water, it produces extremely large forced cooling effect with high heat transfer coefficient value about $2500\text{W}/\text{m}^2\text{K}$.

- (2) By using the proposed method, supplying strong alkaline water added with microbubble to the drill with through holes, the temperature rise at tool tip could reduced about 70%, the work surface roughness improved about 30% and the tool life also improved 6.5 times, compared with dry cutting.
- (3) Strong alkaline water does inhibit corrosion in most of the workpieces and the cutting tool except aluminium hence it is applicable for machining.

Chapter (5): In this chapter, the whole machine structure, the cutting system, the cutting tool, the workpiece and the setting equipments, except the motors are made to be submerged in the strong alkaline water and the water evaporated forced cooling is created to the whole cutting parts. Moreover, air bubbles and microbubbles are added in the strong alkaline water for improving the cooling effect with extremely high heat transfer rate to reduce the heat on the cutting tool effectively. Since in chapter (4) only some materials were tested for corrosion behavior in strong alkaline water, in this chapter, various machine tools related materials are tested. For the effectiveness of the immersing machine tool, the thermal deformation and vibration of machine tool are investigated. In addition, cutting tool life and cutting surface roughness are investigated and evaluated by experiments. This study was performed by immersing bench lathe machine in strong alkaline water; however, other machine tools can also be immersed as long as some of the machine parts such as bearings and linear guides need to be coated with CBN or DLC to act as solid lubricant for self lubricating and friction reduction. In addition, considering to the potential of electric shock and fire hazard that may occur, precaution is required to be taken in case of wiring during installation of the machine. From this research, it can be concluded as follows;

- (1) Heat transfer coefficient values for using strong alkaline water was 400 W/m²K and improved to 2350 W/m²K by applying spindle speed at

3600min⁻¹, then increased to 2550W/m²K by adding microbubbles in the strong alkaline water resulting excellent cooling efficiency.

(2) By immersing the whole machine tool in strong alkaline water, the rise in cutting tool tip temperature was suppressed about 60%, relative displacement was reduced about 89%, angular displacements were reduced about 86%, the tool life was improved 3.6 times and the surface roughness improved about 2/3 times compared with dry cutting.

(3) Most of machine tool related materials, except aluminum, do not corrode in strong alkaline water.

Chapter (6): In this chapter, the impact of using strong alkaline water to the environment and human health was discussed. Three machining processes such as milling, drilling and turning are used for the assessment. The CO₂ emission was calculated based on the electric power consumption during machining and oil disposal. In addition, to show the effectiveness of machining using cooling of strong alkaline water, the potential impact on the global warming from the usage of conventional wet cutting and cutting using strong alkaline water was presented and compared. Moreover, the impact on the human health was also discussed. It is concluded from the study that the use of strong alkaline water as cooling contributes less in jeopardizing the environment and human health. Although it is considered safe for skin contact, some precautions as explained earlier are required. In addition, further investigation is required to assess the impact of the strong alkaline water specifically. Comparing to the conventional wet cutting, strong alkaline water usage help in reduce about 48% of its impact to the global warming. Hence, reduce its impact on the environment. Therefore, it can be said that strong alkaline water is also environmentally friendly.

Since the utilization of water during machining is still restricted, a study on high-accuracy and effective machining utilizing water for environmental conservation is performed. Some of the countermeasures to use water in machining are discussed and developed in this research. Firstly, in the chapter (3), the control technique to control the machine tool's resonance is developed with consideration for maintaining optimum cutting condition. In this research, water is proposed to be used as a countermeasure to modify the resonance frequency of machine tool because of its availability and easy for processing. However, since the small amount of water will not change resonant frequency much, unless, in large amount, the mixture with the polymer PEO is proposed to improve the damping characteristic to effectively suppress vibration. Therefore, the combination control between water and the others control techniques such as reinforcing structure and changing number and the position of the support was evaluated and proposed. Since it is difficult to avoid machine tool resonance without changing the cutting condition, using the proposed control can avoid machine tool resonance without modifying cutting condition; hence improves accuracy and cutting quality. In addition, by maintaining the cutting condition in its optimal condition, better surface roughness like by grinding can be achieved, which as a result, machining processing time and machining cost can be reduced. In the chapter (4), the new cooling method by cooling using strong alkaline water was proposed. Since normal water is restricted during the machining process, the new cooling by strong alkaline water with microbubbles was proposed. Water was restricted during the machining process because of its characteristic to induce corrosion in metal. Oppositely, strong alkaline water does not corrode any machine tool related materials except aluminums, hence considered applicable in machining. The mixture of strong alkaline water with microbubbles of air improves cooling effect even greater. The applicability of the proposed method is

evaluated by experiments. From this cooling method, it is possible to reduce temperature on the tooltip which can longer tool's life, improves processing accuracy and achieves better surface roughness of the final cutting result. In the chapter (5), the machine tool, the whole cutting system, the cutting tool, the workpiece, and the setting equipments are made to be submerged in the strong alkaline water. The water evaporated forced cooling is supplied for reducing the heat on the cutting tool effectively. In addition, the thermal deformation and vibration behavior are also investigated. The practical applicability of this method is investigated and evaluated by the experiments. By this research, the compulsory cooling method for cutting low thermal conductivity materials with high-efficiency, which still does not exist in the conventional cutting methods, is revealed and established. The thermal deformation of the machine tool can be suppressed. As a result, the tool life and the surface roughness improved significantly. Finally, in the chapter (6), the impact of utilizing strong alkaline water during machining to the environment and the human health was assessed. The amount of CO₂ emits during machining and oil disposing process was calculated. In addition, the annual potential impact to the global warming was calculated and compared between the conventional wet cutting by oil and the cutting by using strong alkaline water. The calculated result shows that using strong alkaline water during machining is more friendly to the environment compared to the conventional wet cooling by oil. And also, since strong alkaline water consists of 99% water, it has less effect to the human health. However, the precautions as discussed earlier are required in order to prevent further problems.

From the above studies, this research, 'A study on high-accuracy and efficient machining utilizing water with compound for environmental conservation' can be considered applicable in the industries effectively.

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Appendices

(1) Dissertation in Japanese version (論文日本語訳)

(2) Dissertation in Tetum version (Tradução iha
versaun Tetum)

Appendix I

(論文日本語訳)

環境保全のために水を使用した高精度・高効率 な加工に関する研究

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目次

1 章 緒論	付 1-4
1.1 環境保全の重要性	付 1-4
1.2 ものづくりににおける水利用	付 1-5
1.3 切削加工のための水の効果.....	付 1-6
1.4 加工における従来の水の取扱い	付 1-7
1.5 研究目的と 論文の構成	付 1-9
2 章 水の特 性	付 1-14
3 章 工作機械の共振周波数を管理する技術の開発	付 1-15
4 章 マイクロバブルを混入した強アルカリ水を用いたドリル加工 技術	付 1-26
5 章 CO ₂ 削減のために強アルカリ水中に工作機械を浸漬する技術 の開発	付 1-37
6 章 強アルカリ水を使用した加工の環境インパクト	付 1-47
7 章 結 論	付 1-48

1 章 緒 論

1.1 環境保全の重要性

最近，製造や生産の領域で環境に配慮したものづくり技術が要求されている．また，現状の技術革新は 10 年前よりも多彩で効果的な対策を供与できるようになってきているので，環境保全の配慮は製品設計や製造工程で行われつつある．さらに，安全作業と環境対策の実行について，ここ数十年で需要度が増しつつある．また，さまざまなエネルギーが開発され^{[1-1], [1-2]}，高精度の工作機械も製造され^{[1-3], [1-4]}，顧客を十分に満足させる高品質な製品が生産される状況になってきている．しかし，研究者は製造，装置・加工方法・工具・生産方法の開発の間に環境問題を解決することにこれからも熟慮しなければならない．そこで，これらの研究開発による改善が，環境を阻害しないように遂行されなければならない．しかるに，技術科学の進歩にともなって，汚染もひどい状況になっており，生物学的な環境が日々退化させられている．そのため，このひどい汚染状況から環境を保全するために，環境問題に配慮したものづくりが考えられた．さらに，近年，地球温暖化が大きな問題となっており，環境保全を考慮することが，ものづくりにかかわる技術者や研究者の必須課題となっている．

この環境保全の領域では，多くの対策が施されている^{[1-5], [1-6]}．製造，生産の現場では，環境保全の具体例として，クリーンなものづくり，ごみ処理，汚染管理^{[1-7], [1-8]}などのさまざまな対策が施されている．このクリーンなものづくりは，有害物質，産業ごみ，汚染，産業廃棄物，生産時の廃棄物などを低減，回避，除去するアプローチである．実際にはこの汚染管理や環境保護は，産業ごみ，汚染，産業廃棄物，生産時の廃棄物が発生してしまった後に，はじめて行われている．私たちには，この地球上で見出される最も容易な物質として水が考えられ，クリーンなも

のづくり，汚染管理，環境保護は，高品質なものづくりと環境保全の両立を前提として，この水を使用して成し遂げることができると考えられる．

1.2 ものづくりにおける水利用

水は人類において地球上で最も重要な物質の 1 つである．日々の生活で使用され，また多方面においての利用が見いだされている．産業界，製造業界において，水はものづくり領域で最も重要な資源の 1 つである．金属，紙，化学製品，燃料，石油，その他の工業製品などの産業生産物において，その製造プロセスで水は必要不可欠である．また，産業は言うに及ばず，農業や日常生活も水に依存している．その産業生産物の良し悪しは水に影響される．水は，洗浄，溶剤，クーラント，輸送，エネルギー源として利用できる．この産業水の使用の大半は，工業用水である．多くの製造プロセスが大量の摩擦発熱や化学反応熱を発生するので，水は機械や装置の冷却に使用される．水は潤滑や洗浄にも使用される．ときには，食べ物や飲料として商品そのものに含有されることもある．このように，産業用水の多くの適用が行われており，実質的にはすべての工業製品において水が要求されていると言っても過言ではない状況である．先端科学技術分野の会社や研究者は，水を産業領域における重要資源の 1 つと位置づけ始めている．そこで産業用水の有効利用が進められつつある．しかしながら，金属加工のようなものづくりの領域では，水利用に関してまだ多くの制約がある．加工の際に水を使用すると工作物や機械が水によって腐食してしまうのである^{[1-9],[1-10]}．しかしながら，大量の水が，入手が容易で輸送も容易，環境保全にもなることから，最近の研究でも加工のための水利用の新アプローチが行われている．実際に，切削油剤として水をベースにしたクーラントによる冷却方法や冷却対策が行われている^{[1-11], [1-12], [1-13]}．それらのクーラントは防錆対策が施され，

冷却効率も改善されている。しかし、水に添加物された物質は、環境と人間の健康には好ましくないものであり、そのため、本研究では強アルカリ水のみを使用することを提案している。この強アルカリ水の利用によって、工具と工作物を効率よく冷却するために利用が可能である。この強アルカリ水の特性、相互作用に関しては 2 章でその詳細を記述する。強アルカリ水を使用することで、冷却効率は改善し、加工コストは低減し、同時に加工精度が改善し、工具寿命が延びている。また、環境保全が可能で、作業者の健康に問題がないことも特長である。

1・3 切削加工のための水の効果

先に述べたように、水は重要であり、あらゆる産業分野で使用されているが、加工で直接使用することは敬遠されている。このように、ものづくりへの水利用はまだまだ進展していない。水によって金属が腐食することが、加工領域で水が敬遠される理由である。実際に腐食は、自然に発生し、水がある環境下であたりまえに発生する。まさに、水の流れが高い所から低い所に流れるように、すべての自然現象が最も低いエネルギー状態へと移行するのである。実際に鉄鋼材料は、きわめて自然に化学結合を起こしながら、最も低いエネルギー状態へと移行する。その化学結合は、最も自然界でポピュラな酸素と水の結合形態で、鉄酸化物が水和して錆びる現象である。それは、錆びるだけでなく、発熱、鉱物溶解、硬化、アルカリ化の現象を伴う。また、鉱物の腐食挙動は、それが従属している環境に依存しており、錆びる状況は金属が置かれている環境に依存する。

ものづくりにおける腐食は、多くの負のインパクトがある。加工の際に金属が水で腐食するとき、製品の精度と品質が低下する。工作物が不良品となり、価値がなくなる。また、腐食は工作機械やその他の機器にも発生し、価値の低下、不良動作、ブレイクダウン、寿命の短命などの

大きな問題を起こしている．そこで，現在でも多くの環境対策が施されている．装置の腐食や工業製品の腐食対策は，作業者の健康と水の浄化システムに影響する．機械や装置の突発的な事故は、環境悪化の原因となる機械のブレークダウン，火災，爆発，有害物資の排出を引き起こす．さらに，腐食は一般消費者の経済活動にも影響を与える．

一方，この腐食被害から脱して，この腐食現象が抑制されたとき，水は多くの利得をもたらしてくれる．これらの利得は以下のとおりである；

- 高効率な冷却
- 有効で入手容易
- 洗淨
- 安価
- 輸送
- 環境保全

これらの利点に着目して，多くの研究者達が水によって発生する腐食対策の研究をスタートさせている．

1・4 加工における従来の水の取扱い

現在に至るまでに，加工における水利用はとても少なかった．しかし，徐々に利用されつつある状況である．加工の際に水利用した従来の方法は，冷却と環境保全のための例がある．そのいくつかは，以下のとおりである．

[1] 冷却

[2] 潤滑

[3] 洗淨

しかしながら、これらの適用例はまだ不動の地位を得ているわけではない。

上記の[1]に関しては、加工の間に使用される水溶性切削油剤として多くの生産現場で使用されているが、界面活性剤や防腐剤が混入されており、環境負荷や作業者への影響が指摘される。実際に、これらの添加剤によって、環境負荷や作業者への被害報告が一時間問題となっていた^{[1-14], [1-15]}。また、これらの購入、輸送、廃棄にも多くのコスト、労力、エネルギーを必要とする。さらに、クーラントと溶剤は下水として自然界に破棄することができず、高価な破棄コストが必要になる。環境保全のためにクーラントや切削油剤の改良の要求が、近年ますます増えている。このように、水溶性切削油剤はまだ完全ではなく、研究開発の余地がある。

上記の[2]に関しては、潤滑のための水利用は産業界、加工業界ではまだほとんど行われていない。一部で、きわめて小さい水の粒子をオイルでコーティングして潤滑に使用した例はある。水が蒸発した際の気化熱冷却効果をねらったものであるが、金属部品の錆や損傷の可能性があり、工作機械の寿命を短くする可能性もある。しかしながら、環境への懸念と有効性に関して、腐食現象さえ回避できれば、水は最も有効な資源である。現時点では、何人かの研究者は、水を含む流体を潤滑に使用する研究を行っている^{[1-16], [1-17]}。これらの研究は決して完成したものではなく、潤滑と耐食の点で改良の余地がある。

上記の[3]に関しては、洗浄水は産業界や加工業界では幅広く利用されている。金属以外で作られている工業製品では、洗浄のために水を使うことが容易に行える。金属製品に対しては、洗浄水として使用する前に、防錆剤や他の溶剤を混ぜる必要がある^{[1-18], [1-19]}。水溶性洗浄剤としては、pH8.5 以上のアルカリ水や油脂が含まれている。製造業以外の産業界、加工業界を問わず、水は幅広く洗浄剤として使用されている。

このように、冷却媒体としての水は、環境保全に配慮しながら、高精度な機械加工をするためになくてはならないものである。加工分野ではあまり水が適用されていない現状を把握しつつ、本研究では環境保全への配慮と高精度な機械加工を両立するために、加工分野に水を適用することにした。

1.5 研究目的と論文の構成

本研究目的は、環境保全に配慮しながら、高精度な機械加工を行うために、水の新しい利用方法を開発することである。加工過程で冷却のために水を使用することによって、冷却効果が改善され、加工の間の熱影響が最小化され、加工の際に発生する廃棄物も低減できる。冷却効果の改善は、工具発熱を強制冷却でき、最終的に高精度な工作物を製作できる。同時に、加工廃棄物処理が低価格で可能となり、環境や作業者に害をあたえる排気ガスの最小化も可能となる。さらに、利便性、有用性、流動性から、水はどこへでも輸送でき、管理できる。それゆえに、本研究では加工業界や産業界において水を有効利用する手法を開発することにした。本研究のフローを図 1.1 に示す。

1 章では、緒言として、本論文の背景、目的、現在までのものづくりにおける水利用の状況説明を解説している。

2 章では、水の特性について述べ、金属ごとの耐食性について述べている。さらに、金属の腐食対策として強アルカリ水の使用を提案し、この強アルカリ水に対する素材の耐食性を明らかにしている。

3 章では、水の新しい利用例として、水を使用して工作機械の共振周波数を制御することによって、共振現象を制御して最適加工条件のよって高精度、高生産性なものづくり手法を提案する。共振周波数のコントロ

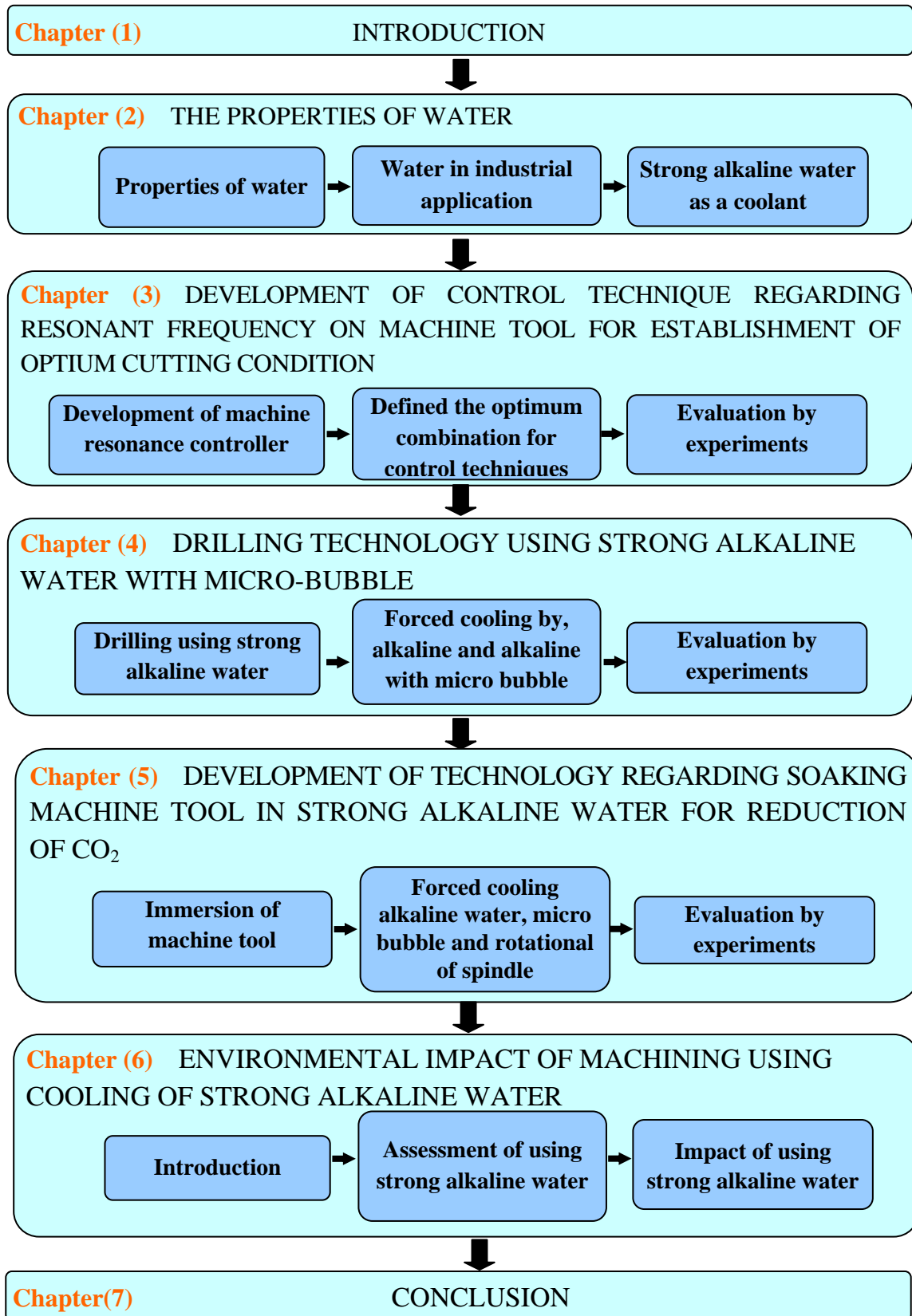


Fig.1.1 Flow chart of this research on manufacturing with high quality and high efficiency using water

ール方法としては、3つのコントロール技術を最適に組合せるもので、本章で最適制御技術として提案、評価している。

4章では、強アルカリ水とマイクロバブルを使用したドリル加工を提案している。これは、冷却効果を改善する手法をドリル加工に対して行ったものである。マイクロバブルを混入した強アルカリ水の冷却効果が明らかにし、マイクロバブルを混入した強アルカリ水の熱伝達率とドリルの工具寿命を実験で明らかにしている。

5章では、強アルカリ水中での工作機械を完全浸漬させ、加工を行った場合の効果を明らかにした。卓上旋盤を改造し、強アルカリ水中に完全浸漬させた。その状態で、機械の熱変形特性と加工精度が実験で明らかにした。さらに、この卓上旋盤を使用して、強アルカリ水ミストの気化熱冷却特性の影響も明らかにしている。

6章では、加工領域において水利用した場合の簡単な LCA について論じている。本研究における新しい提案が、環境と作業者にどのようなインパクト与えているかを調査し、評価して明らかにしている。

7章では、本研究を総括し、まとめている。

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2 章 水の特性

本章では，高精度なものづくりと環境保全を両立するために使用する水の特性を明らかにしている．

内容は，一般的な水の特性，工業界で使用する水の特性（洗浄，比熱，気化熱冷却，密度，腐蝕），クーラント用アルカリ水，アルカリ水製作過程について述べている．

英論文中の本文では，この「水の特性」に関して 2 章で記述しているが，本論で使用する強アルカリ水に関しては，3 章 工作機械の共振周波数を変更する技術の開発，4 章 マイクロバブルを混入した強アルカリ水を用いたドリル加工技術，5 章 CO₂ 削減のために強アルカリ水中に工作機械を浸漬する技術の開発の 3 つの章の前半に記述しているので，この章では省略する．

工作機械の共振周波数を変更する技術の開発*

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Development on Technique Regarding Change of Resonance Frequency on a Machine Tool

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In the 21st century, various kinds of materials are being used for high quality, and high confidence in various purposes. The establishments of optimum cutting condition for those materials are also being demanded for high productivity. On the other side, there exist many resonance frequencies for a machine tool. When a compulsory vibration of a machine tool congregates to the resonance frequency, extremely high vibration occurs on the machine tool structure and the geometrical accuracy of the work-piece also becomes lowered. For this condition, other cutting condition must be selected outside the range of the resonance frequency. Therefore, the technique for controlling resonance frequency on a machine tool was developed for establishment of optimum cutting condition. Resonance frequency can be controlled by changing stiffness and appearance density of a machine tool. In particularly, resonance frequency under 100Hz has very large influence on the vibration of the machine and thus for the accuracy of the product. Therefore, simple and rational reinforced structure for high stiffness, and lightweight structure for low density were considered for controlling of resonance frequencies less than 100Hz. Injection of water was used for creating high density in a machine tool structure. Moreover, the positions of supports under the machine tool were also changed for controlling vibration. The experiments were done using the techniques mentioned above. From the results, it is concluded that, (1) The technique for controlling resonance frequency on a machine tool was effective for cutting with optimum machining condition, (2) Reinforced structure, lightweight structure, injection of water and changing position of supports were very effective for controlling resonance frequency.

Key Words : Control, Resonance Frequency, High Stiffness, Low Density, Reinforce, Cutting Condition

1. 結 言

工作機械構造は、その形状、大きさ、材質（ヤング率と密度）、支持方法を決定した段階で、その共振周波数が決まる。一方、加工する部品の図面と工作物材質が設定され、それを加工する工具の種類とその材質が決定された段階で最適加工条件の設定が可能になる。その加工条件を実現化するために工作機械を稼働した段階で、稼働部の強制振動の周波数と使用する機械の共振周波数がたまたま一致してしまい、健全な加工ができないことがよくある。このとき、今までは工作物の寸法精度、形状精度、表面粗さ、工具寿命を最適にするための加工条件をあきらめざるを得ない現状であった。これは、大量生産を行う場合にはきわめて大きな問題であった^{(1), (2), (3), (4)}。

そこで、本報では工作機械構造を簡易的に組み替えることにより、工作機械構造の共振周波数を変更する技術を開発する。具体的には、(1)工作機械重量の軽量化と重量化による機械構造の重量の変更、(2)工作機械構造へのリブ補強と簡易穴あけによる機械構造の剛性の変更、(3)支持点の組合せを変更してモード形状の変更に伴う共振周波数の変更の3つを組み合わせることによって、工作機械構造の共振周波数を変更する技術を開発し、卓上旋盤を使用した実験によってその手法の有効性を評価する。なお、実験に使用した卓上旋盤は下方から上方（Y方向）に向かってバイトで切込みを行う機構である。

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2. 共振周波数の変更方法の提案

共振周波数を変更するために、その容易さと迅速性の観点から、(1)機械構造の重量の変更、(2)全体の剛性の変更、(3)支持点の変更によるモード形状の変更の3つを採用することにした。(1)の機械構造の重量を変更するためには、①構造材の板厚変更、②密度の異なる材料の使用、③構造部材の一部を除去・構造部材の追加、④ベッド等の空間部への水注入や錘の付加などの4つの方法が考えられる。この中で①、②、③は重量だけを変更するだけではなく、全体の剛性（後述）にも影響を与えてしまうので注意が必要である。また、①と②は工作機械の大きな改造が必要であり、簡便な変更には不向きであるため、本報では③と④による機械構造の重量の変更を行うことにする。(2)の全体の剛性を変更するためには、⑤構造材の板厚変更、⑥ヤング率の異なる材料の使用、⑦構造部材の一部を除去・構造部材追加の3つの方法が考えられる。重量を変更するときと同様に、⑤と⑥は工作機械の大きな改造が必要であり、簡便な変更には不向きであるため本報では採用せず、⑦による全体の剛性の変更を行うことにする。また、(3)の支持点の変更によるモード形状の変更のために、工作機械の支持点（ボルトポケットの位置）の位置を変えることで共振周波数とそのモード形状を変えることにした。

具体的に共振周波数を変更するためのパラメータ設定の説明を図1に示す。本報の評価実験で使用する卓上旋盤を例として説明する。まず、共振周波数を下げるために機械構造に水を注入して重量化（高密度化）する方法を制御パラメータⅠとした。この方法によって、共振周波数の下方への回避が期待される。また、その水注入の効果を確実にするために水にポリマの混入も行った（後述）。これは、水注入による共振周波数の下方への変更に、減衰比の向上の効果を重量しようと考えたものである。つぎに、事前解析（FEMによる固有振動解析）の結果をもとにして、1次モードと2次モード（図1参照）の変形がモータ付近で大きいのでそれを補強し、共振周波数を上げるために軽量化したフレームで補強することを制御パラメータⅡとした。最後に、工作機械の支持点の数と場所を変えて共振周波数とそのモード形状を変える方法を制御パラメータⅢとした。この方法は容易に変更可能であり、実用性が高いと考えられる。なお、本報ではこれらの変更は、加工精度に大きく影響を与える100 Hz⁽¹⁾以下を対象周波数領域とした。

制御パラメータⅠで水を使用する際に、粘性を増加させ減衰比を上げる方法を試行する。ここでは、水にポリマPEO(=Polyethylene oxide)を混合し、その減衰比の向上の程度を実験によって調べた。図2に示す長さ $l=300$ mm、厚さ $t=2$ mmの鋼製パイプ内に水もしくはポリマPEOを混入した水を充填して両端面から $l/3$ の2箇所をワイヤでつり、中央部をインパクトハンマで加振し、その裏面につけた加速度ピックアップで振動測定をし、測定した対数減衰率から減衰比を求めた。測定結果には鋼製ボックスの減衰特性の影響も含まれているので、FEM解析を用いて先の測定結果とカーブフィットするためのポリマPEOを混合した水単体の減衰比を逆解法で求めた。図3にポリマ密度と減衰比の実験結果を示す。ポリマを混入した水は、減衰比を向上させる効果が大きかった。ポリマ含有量を大きくするとその効果は大きくなるが、ポリマ濃度を6 wt%以上にすると粘性が上がり、注

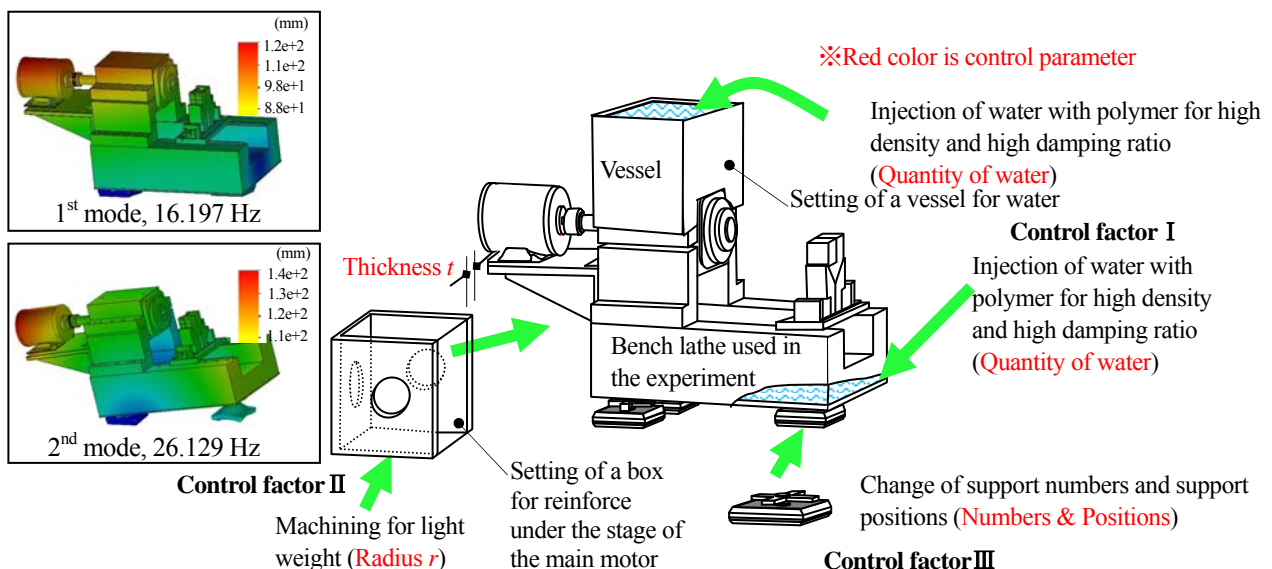


Fig. 1 Explanation of several parameters and countermeasure for control of the resonance frequency in a machine tool

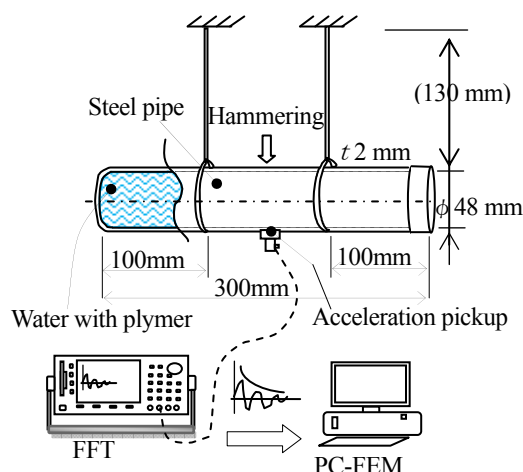


Fig. 2 Experimental setup for measuring damping ratio

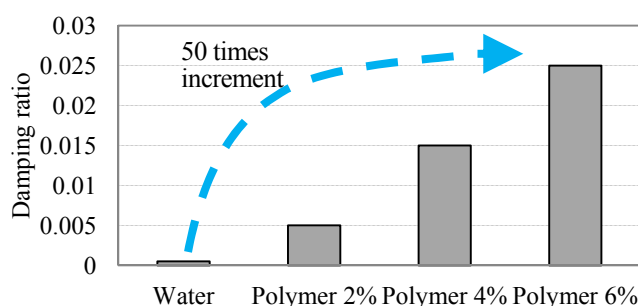


Fig. 3 The relationship between damping ratio and the density of polymer (Experimental result)

入・抽出が困難になったため、使用限界としてポリマ濃度を 6 wt% した。これにより、水注入により共振周波数を下方に回避させると同時に、振動振幅も低減できると考える。また、この減衰比の向上は図 2 のような単純なパイプ構造の 1 次モードの振動に対する実験結果であり、次章より CAE や実機実験によって、その定性的かつ定量的な有効性の評価を行う。

3. CAE シミュレーションによる制御因子（密度・剛性・支持）の検討

図 4 に検討のための有限要素法モデルを示す。(1)共振周波数を下げるために機械構造に水を注入して重量化（高密度化）、(2)共振周波数を上げるために軽量化（低密度化）と補強構造（高剛性化）、(3) 機械の支持点を代えて

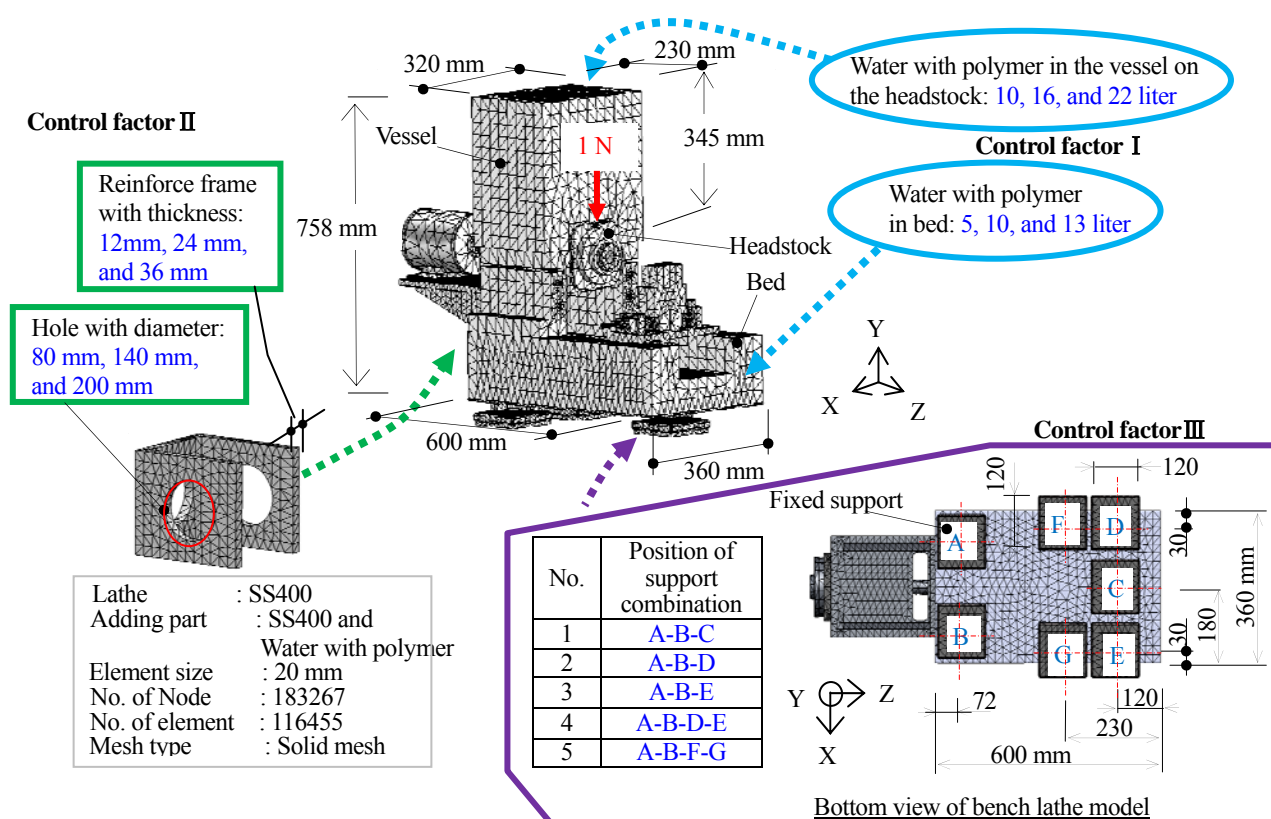


Fig. 4 FEM model for investigation of influence regarding density, stiffness and support

共振周波数とそのモード形状の変更をそれぞれ検討するためのモデルである。

(1)共振周波数を下げるために機械構造に水を注入して重量化（高密度化）：水を注入する箇所はベッドと主軸台上に設けた容器の2つである。水のモデルはヤング率が 1×10^{-6} GPaとさきわめて小さい固体要素とした。解

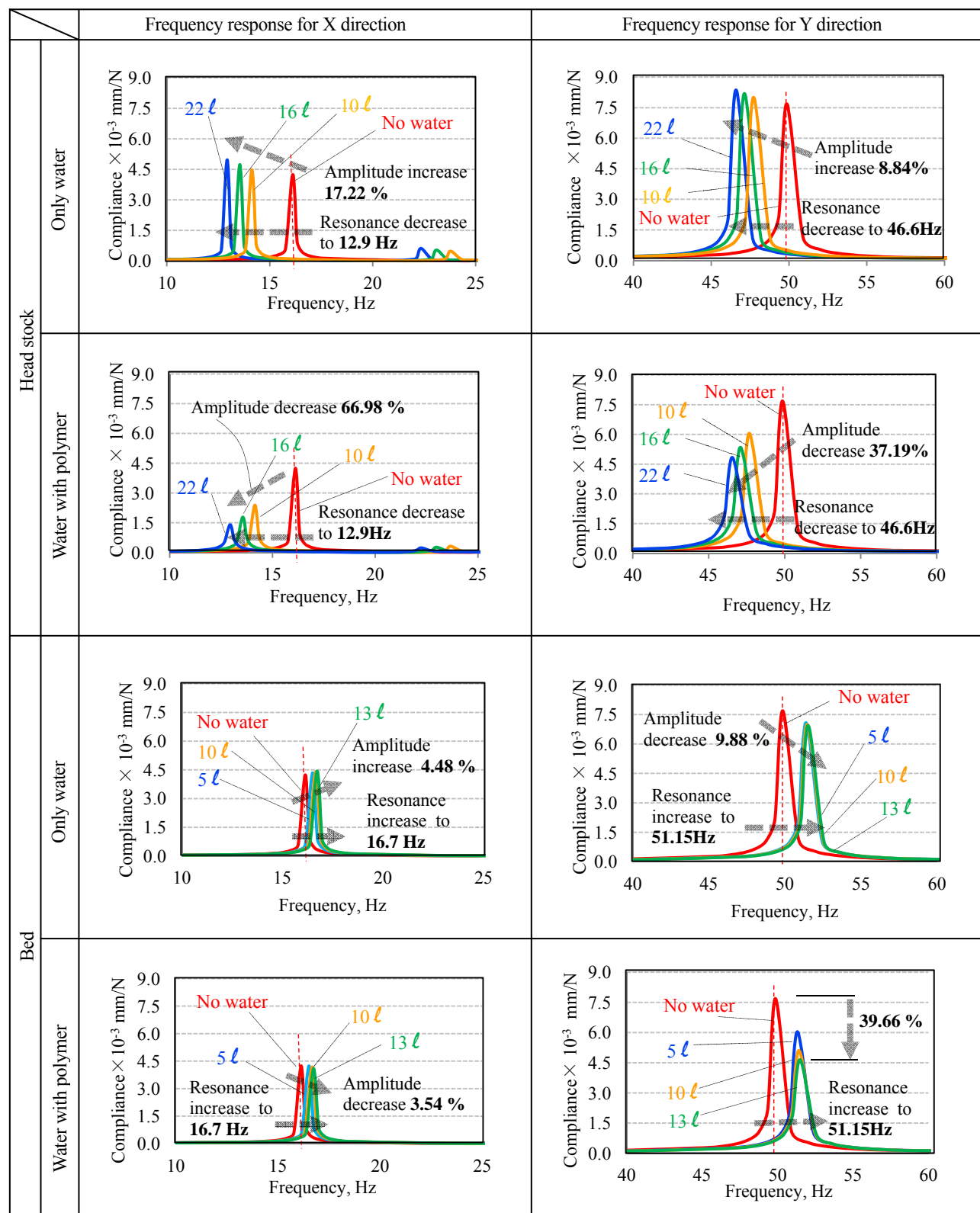


Fig. 5 Frequency response of the bench lathe with different densities (Calculation using FEM)

析で使用した減衰比は予備実験（図 3）の結果から得たものである。水にポリマ PEO を混入することでゼリー状にして減衰比を向上させた場合の検討も行った。解析は、図 4 に示す支持点（A-B-C）での自由振動解析を行った後、主軸台端面上部の Y 軸方向に加振力 1N を加えた場合の強制振動解析を行った。

図 5 に周波数応答の解析結果を示す。縦軸がコンプライアンスであるため、そのまま工作物の表面粗さに影響する振動振幅に大きく関係する。主軸台への水注入によって 10 Hz 程度共振周波数を低減できる可能性があることを示唆している。また、ポリマを混入してゼリー状にした水の場合はその減衰特性の向上が顕著であり、本報では以後このポリマ混入を常時使用することにした。逆にベッドへの水注入によって、2~3Hz 共振周波数が増加している。これは構造下方の重量のみが増加したことにより、共振周波数のみならず、モード形状が変化したことによるものである。また、この水注入による共振周波数の変更は、タンクとポンプの設備使用で済み、短時間・容易な作業であるにもかかわらず、きわめて大きな効果が期待できる。

(2)共振周波数を上げるために軽量化（低密度化）と補強構造（高剛性化）： 補強箇所は、自由振動解析の低

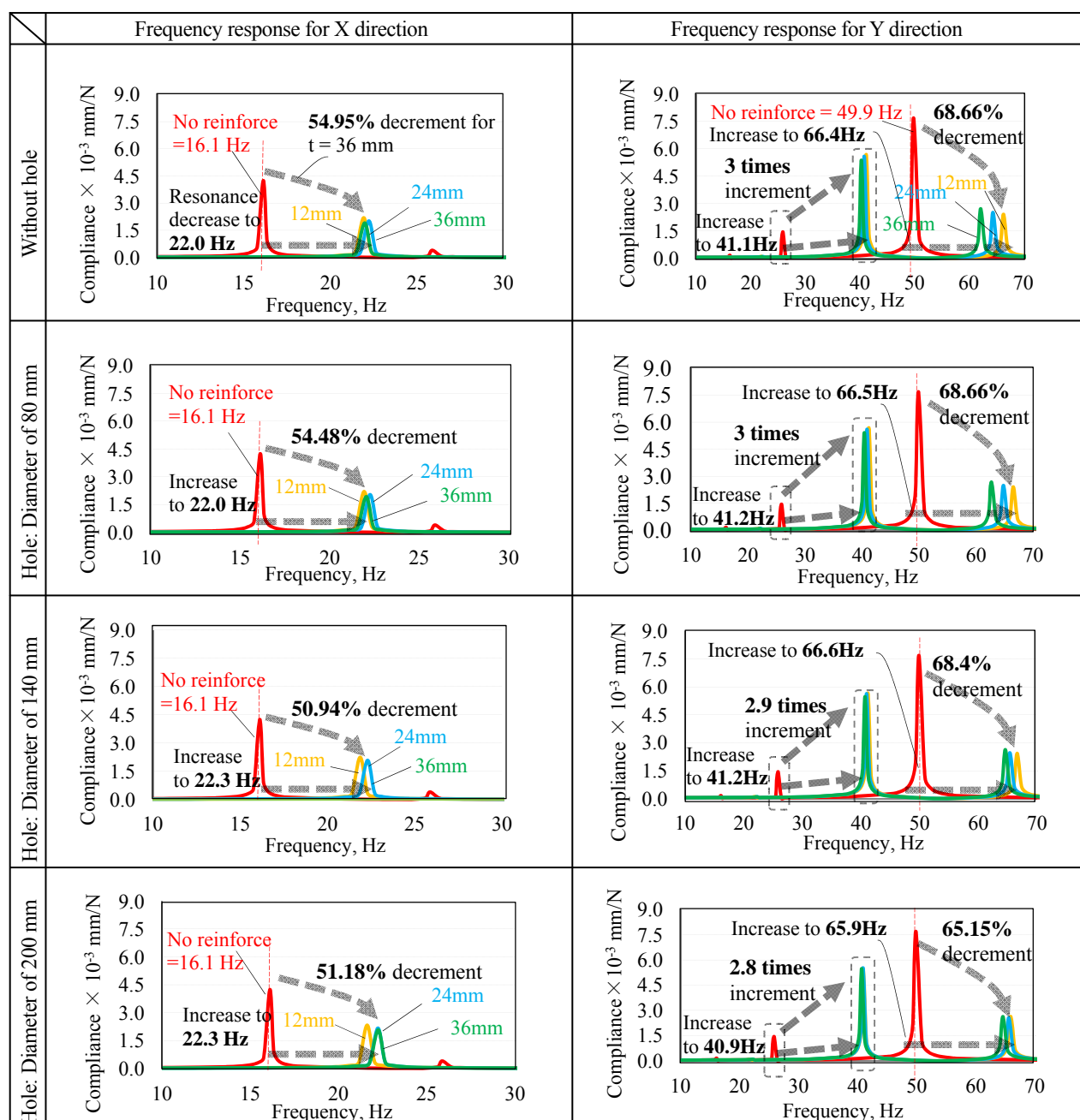


Fig. 6 Frequency response of the bench lathe with different stiffness (Calculation using FEM)

次のモードがモータ台付近に集中していたことを受け、モータ台の補強による高剛性化を行った。補強材板厚が 12 mm, 24 mm, 36 mm の 3 種類、その補強板中央部(3 か所)を直径 80 mm, 140 mm, 200 mm の円形に穴をあけ軽量化(低密度化)をした場合についてそれぞれ解析を行った。ここでも、解析は、図 4 に示す支持点(A-B-C)での自由振動解析を行った後、主軸台端面上部の Y 軸方向に加振力 1N を加えた場合の強制振動解析を行った。

図 6 に周波数応答の解析結果を示す。縦軸がコンプライアンスである。補強によって 10 Hz から 15 Hz 程度共振周波数を増加させることができる可能性があることを示唆している。1 次モードでは共振周波数が上方に移動したにも関わらず、むしろコンプライアンスが大きくなった。これは、50Hz 付近に大きな振動現象を起こす共振周波数があり、1 次モードがそれに近付いたために起こった現象と考える。また、2 次モードでは補強による高剛性化でコンプライアンス値も低下している。このように、共振周波数を上方へ変更するための制御因子としてきわめて有効であるが、複数の共振周波数が同時に上方へ移動するため、問題視していたモードの共振周波数を回避しても、その隣のモードが問題になる場合もあるので注意が必要である。今回は 12mm の板厚で充分に効果があると考えられる。また、補強板中央部を円形にくり抜いて軽量化した場合にはその効果はさほど大きくはなかった。このモータ台補強構造設置による共振周波数の変更は、鋼構造物のみの使用で済み、短時間・容易な設置作業であるにもかかわらず、きわめて大きな効果が期待できる。

(3) 機械の支持点を代えて共振周波数とそのモード形状を変更：これは先の(1)と(2)の制御因子を施さないモデルについて、図 4 に示すように 5 種類の組合せの支持点で支持した場合の解析を行った。ここでも、解析は、図中に示す支持点での自由振動解析を行った後、主軸台端面上部の Y 軸方向に加振力 1N を加えた場合の強制振動解析を行った。図 7 に周波数応答の解析結果を示す。縦軸がコンプライアンスである。支持点の組合せの違いによって 10 Hz から 20 Hz 程度共振周波数を変化させることができる可能性があることを示唆している。支持の仕方によって振動のモードが多少変わるため、コンプライアンス値も多少変化している。この支持点の組合せを変えることによる共振周波数の変更は、あらかじめ機械構造内に複数のボルトポケットを装備しておき、必要に応じてボルトで調整するだけなので、短時間・容易な作業であるにもかかわらず、きわめて大きな効果が期待できる。

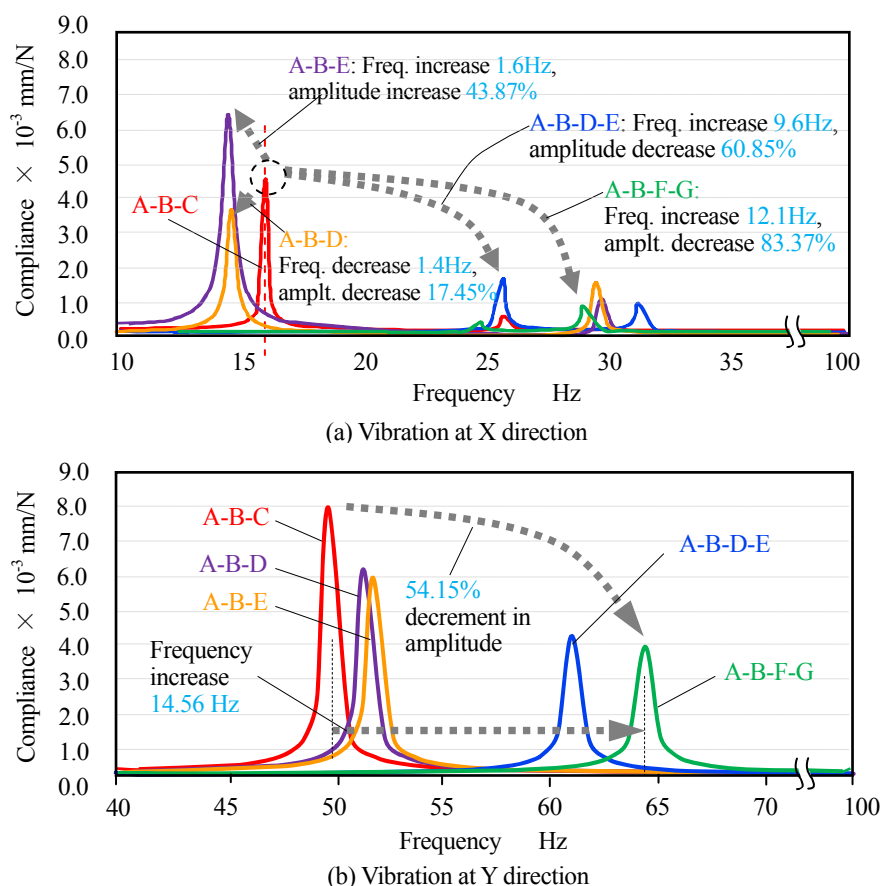


Fig. 7 Frequency response of the bench lathe from X-axis (top) and Y-axis (bottom) with different supports

4. 卓上旋盤へ本手法の適用

図 8, 表 1 に示す卓上旋盤へ本手法を適用し, その有効性を評価する. 図 8 に実験のセットアップも示す. インバータによる主軸回転数の変化に対して, 主軸台端面の X 方向と Y 方向に貼った加速度ピックアップの出力を FFT に取り込み, 振動振幅を測定する. 表 2 に制御因子 I, II, III の共振周波数を変更するパラメータを示す. 制御因子 I の共振周波数を下げるために機械構造に水を注入して重量化 (高密度化) する対策では, 前章の FEM 解析結果に従って容器を製作し, ボルト締結で主軸台上に設置した. その容器に水 (ポリマ PEO を 6 wt% 混入) を注入し, その注入量をパラメータとして, 主軸回転数と主軸台先端の振動振幅の関係を測定する. このとき, 補強フレームなしで, 支持は A-B-C とする. 制御因子 II の共振周波数を上げるために軽量化 (低密度化) と補強構造 (高剛性化) では, 前章の FEM 解析結果に従って, 板厚 12 と 36 mm のモータ台の補強フレームを 2 つ製作し, それぞれのフレームをモータ台にボルト固定したときの主軸回転数と主軸台先端の振動振幅の関係を測定し

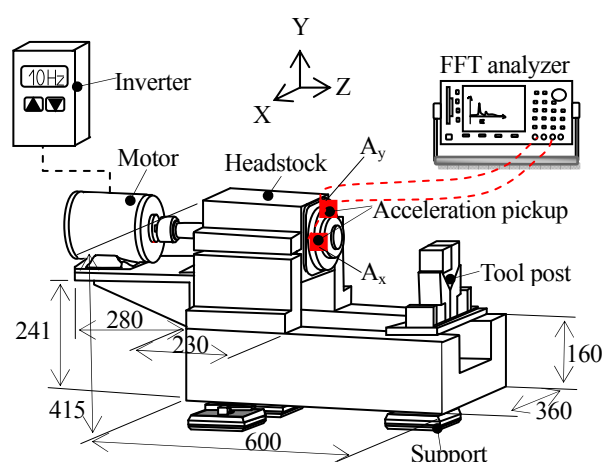


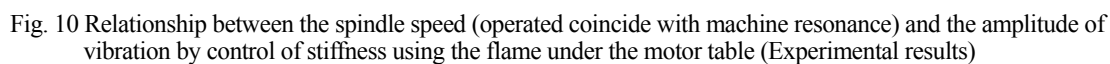
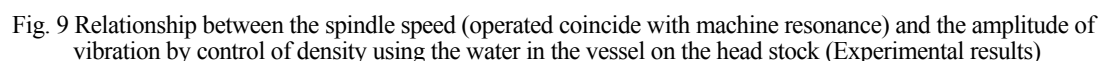
Fig. 8 Experimental set up and the bench lathe for experiment

Table 1 Specification of the bench lathe for experiment

Head stock	Height of center from bed	177 mm
	Height of center from floor	337 mm
	Spindle speed	Max.3600 min ⁻¹
	Front bearing	50BNC10TYDBB
	Rear bearing	45BN10TYDB
Bed	Size	600×360×160 mm
Tool post	Stroke of Y axis	30 mm
Table	Stroke of Z axis	200 mm
Motor	Power	0.75 kW
	Speed	Inverter control
Weight		200 kg

Table2 Experimental parameters for the control factor I, II and III

Control factor I 	Injection of water in the vessel on the head stock	0, 10, 16, and 22 liter (Water with polymer 6 wt%)	
Control factor II 	Reinforce Support point	Thickness	12, 36 mm (Without hole)
Control factor III 	Support combination No. 1	A-B-C	
	Support combination No. 2	A-B-D	
	Support combination No. 3	A-B-E	
	Support combination No. 4	A-B-D-E	
	Support combination No. 5	A-B-F-G	



した。このとき、注水なしで、支持は A-B-C とした。最後に、制御因子Ⅲの支持点変更による共振周波数とそのモード形状の変更では、前章の FEM 解析結果に従って、5 種類の支持点の組合せで支持した場合をパラメータとして、主軸回転数と主軸台先端の振動振幅の関係を測定した。このとき、注水と補強フレームはなしとした。また、先の 3 章の CAE の解析結果から、以下の図 9 から図 11 で共振周波数の変更が起こっていると考えた。

図 9 にポリマを混入した水の注入による共振周波数の変更の実験結果を示す。何も対策を施さない卓上旋盤の振動測定結果から共振状態が主軸回転数 996 min^{-1} と 2784 min^{-1} 付近にあると考えられるが、主軸台上部の容器にポリマを混入した水の注入による共振周波数の変更によってその共振周波数が下側に変更され、しかも減衰比が大きいため、主軸回転数 996 min^{-1} と 2784 min^{-1} 付近振動振幅がきわめて小さく抑制されているものとする。

図 10 に構造補強による共振周波数の変更の評価結果を示す。ここでも何も対策を施さない卓上旋盤の振動測定結果から共振状態が主軸回転数 996 min^{-1} と 2784 min^{-1} 付近にあることを基準にして、構造補強を施したことによって共振周波数が上側に変更され、しかも高剛性化によって振幅も小さくなっているため、主軸回転数 996 min^{-1} と 2784 min^{-1} 付近振動振幅がきわめて小さく抑制されているものとする。また、全域においても振動振幅は小さく、きわめて効果的な手法として評価できる。なお、補強フレームの板厚を 12 mm から 36 mm としても結果はほとんど変わらなかった。

図 11 に支持点変更による共振周波数の変更の評価結果を示す。ここでも、A-B-C の支持点組合せで卓上旋盤の振動測定結果から共振状態が主軸回転数 996 min^{-1} と 2784 min^{-1} 付近にあると考えられるが、支持点変更による共振周波数の変更によってその共振周波数がさまざまに変化しており、支持点の組合せで共振周波数が変更できることがわかる。また、支持点は機械の水平状態を維持するためだけでなく、加工精度にきわめて大きな影響があると考えられる。

以上の実験結果から、ポリマを混入した水の注入による共振周波数の変更、構造補強によって共振周波数の変更、支持点変更による共振周波数の変更の最適な組合せは表 3 のとおりとなる。この組合せに従って、主軸回転数と主軸台先端の振動振幅の関係を測定・比較した結果が図 12 である。対策がない場合に比べて、振動振幅が 1/10 以下に抑制されており、3 種類の共振周波数の変更を組合せることによって、きわめて効果的な振動対策が可能となった。

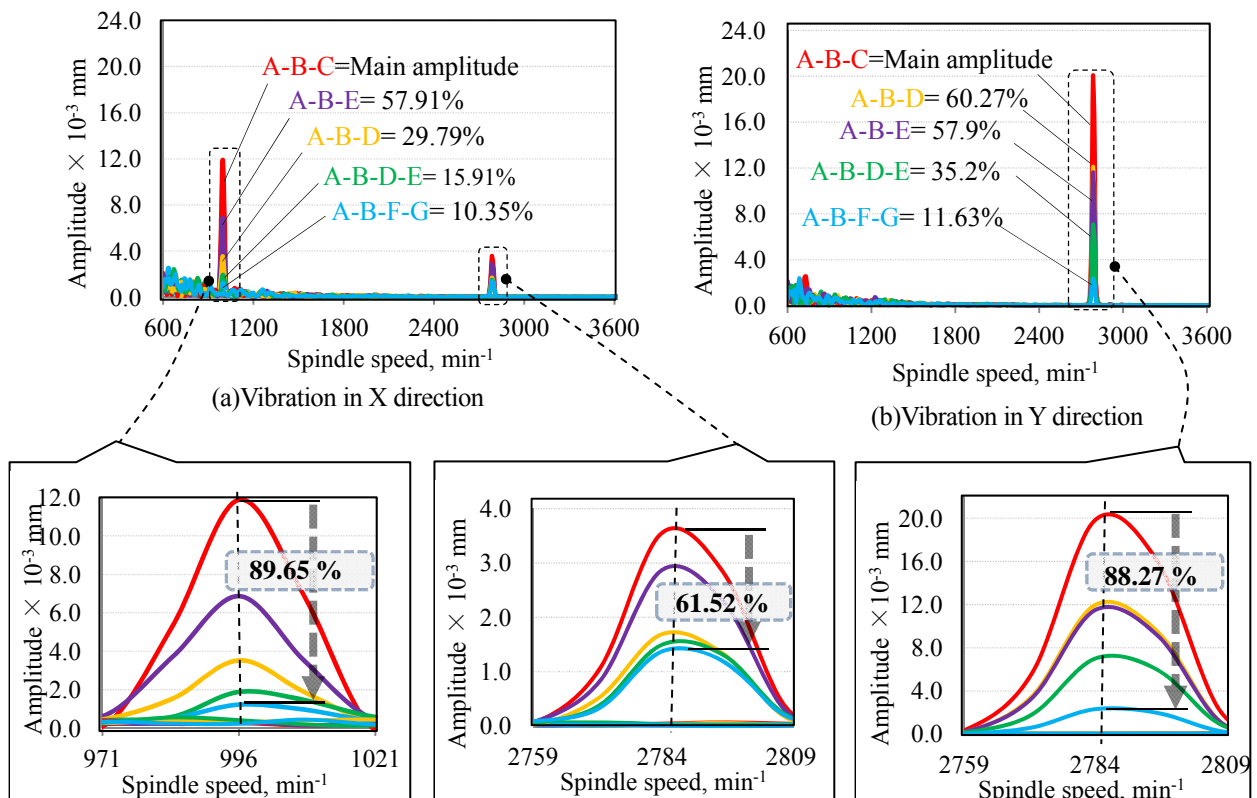


Fig. 11 Relationship between the spindle speed (operated coincide with machine resonance) and the amplitude of vibration by control of support (Experimental results)

Table 3 Optimum combination for three countermeasures

Spindle speed min^{-1}	Control factor I (Density)	Control factor II (Stiffness)	Control factor III (Support)
600	-	-	A-B-C
800	-	12 mm	A-B-F-G
996	22 liter	-	A-B-C
1200	10 liter	-	A-B-D
1500	-	12 mm	A-B-E
2000	10 liter	-	A-B-E
2500	22 liter	-	A-B-F-G
2784	16 liter	-	A-B-F-G
3000	-	12 mm	A-B-D-E
3600	10 liter	-	A-B-C

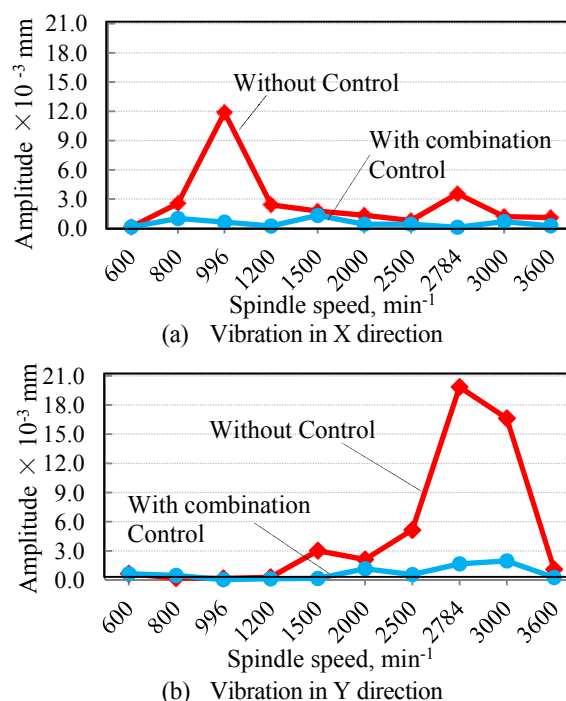


Fig. 12 Amplitude of vibration at optimum density, stiffness and support (Experimental results)

5. 実切削による評価

最後に、卓上旋盤を用いて実切削を行い、本手法の有効性を評価する。

表 4 に示す加工条件を使用した。共振周波数の変更では前節の結果を踏まえて、主軸台上部の容器にポリマを混入した水の注入による共振周波数の変更と支持点変更による共振周波数の変更の最適な組合せで加工を行う。なお、比較のために対策のない従来の支持をした場合のセットアップでも同様の実験を行った。

図 13 に実切削前に無負荷状態での卓上旋盤の周波数応答（主軸端面の Y 方向：図 8 参照）の測定結果を示す。共振周波数の変更によって機械の共振周波数と機械の稼働による強制振動の周波数が一致することが回避されていると同時に、振動振幅も小さくなっており、振動に対して機械構造の動剛性が向上していた。

図 14 に Y 方向（工具切込方向）の切削時の振動波形を示す。共振周波数の変更の有無によって振動振幅差が

Table 4 Cutting condition for evaluation of this method

Cutting speed		158 m/min
Feed speed		0.1 mm/rev
Spindle speed		2784 min^{-1}
Cutting depth		0.2 mm
Tool	Material	Carbide, T725X
	Type	Round
	Nose radius	6 mm
Work piece		Brass, $\phi 18 \text{ mm} \times 40 \text{ mm}$
Control of resonance frequency	Density	16 liter
	Stiffness	-
	Support	A-B-F-G

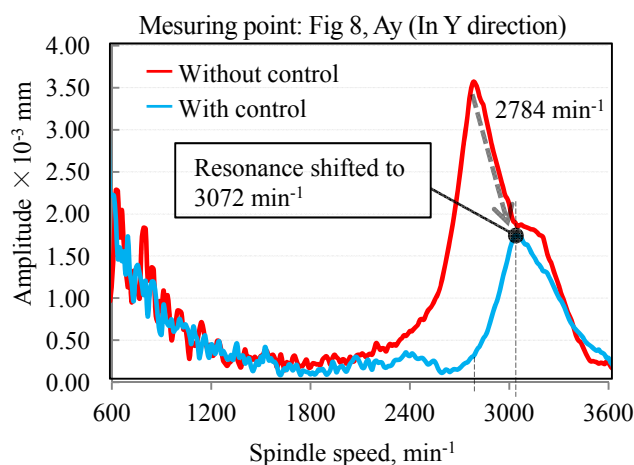


Fig. 13 Frequency response of the bench lathe with control of resonance frequency (Experimental results)

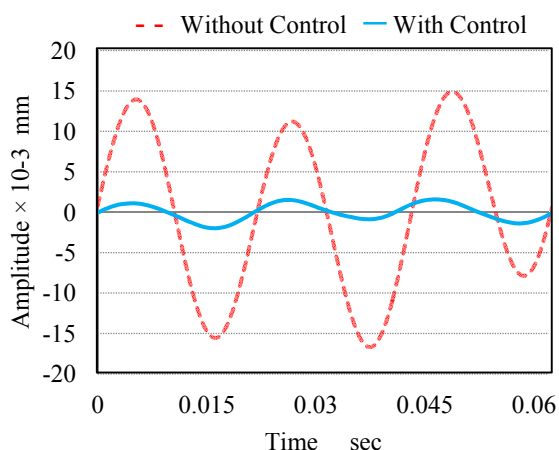


Fig. 14 Result of vibration regarding the lathe during cutting at Y direction (Experimental results)

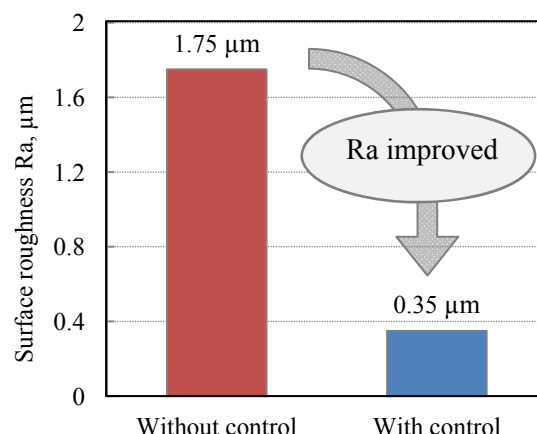


Fig. 15 Surface roughness of the work piece using control resonance frequency (Experimental results)

極めて大きくなっていった。とくに、この加工条件では、従来の卓上旋盤では共振周波数に相当する主軸回転数で加工せざるを得ない条件であったが、共振周波数の変更によって共振現象を回避できたので、このように振動振幅が小さくなったものとする。

図 15 に加工後の工作物の表面粗さを示す。従来の卓上旋盤で加工した場合にその表面粗さが Ra 1.75 であったのに対して、共振周波数の変更の場合の表面粗さが Ra 0.35 であり、切削加工であるにもかかわらず研削加工面のような表面粗さの小さい加工が可能であった。このことは、先の図 14 の結果と良く対応している。

以上のように、共振周波数を変更する手法は、最適な加工条件を容易に設定することができ、高品位な加工が容易に可能となった。なお、本報で使用した卓上旋盤は外寸法 $600 \times 360 \times 160$ mm、重量 200kg であり、①の重量変更で使用したポリマを混入した水量 220l は、機械重量の 11.7 wt% ($= 22\text{kg} \times 1.06 \div 200\text{kg} \times 100$) であり、②の剛性変更では、板厚 12mm の鋼板 16.5kg (機械重量の 8.3 wt%) を使用し、③の支持点変更では 7 箇所の支持点をそれぞれ使用した。これらを汎用工作機械や大型工作機械に適用する場合には、①から③の各変更に必要な重量や数量を確保するためには限界があり、CAE 等でそれらの限界を推定し、サイズや形状の設計変更が必要になると考える。

6. 結 言

本研究の結果をまとめると以下のとおりである。

- (1) 機械構造の密度、剛性、支持を変更して工作機械の共振周波数の変更を行う手法を確立した。
- (2) とくに、ポリマを混入した水を機械構造部に注入することにより、共振周波数低減と減衰比増大を同時に達成することができた。
- (3) 卓上旋盤に本手法を組み込み実切削で評価したところ、共振点を避け、表面粗さの改善を可能にすることができた。

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マイクロバブルを混入した強アルカリ水を用いたドリル加工技術*

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Drilling Technology Using Strong Alkali Water with Micro-Bubble

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In the 21st century, as it is important to produce products with care for protecting the earth, a producer must be careful to conserve energy, save resources and reduce waste which pollutes environment. On the other hand, in case of a drilling, much cutting oil was also used for lubrication and cooling. This is large problem for protecting the earth. Therefore drilling technology using strong alkali water with micro-bubble was developed. A drill with through hole was used for this technology. Cooling effect of strong alkali water with micro-bubble was firstly investigated on the experiment. Then heat transfer coefficient of the drill with through hole was evaluated for cooling capacity. Tool life of the drill using strong alkali water with micro-bubble was also evaluated in the experiment of drilling using Ti6Al4V which has small thermal conductivity and is a material with difficult machining. It is concluded from the results that; (1) Cooling of strong alkali water with micro-bubble was very effective, (2) Heat transfer coefficient of the drill using strong alkali water with micro-bubble was 3.5 times of that of dry drilling, (3) Tool life of the drill using strong alkali water with micro-bubble was 6.5 times of that of dry drilling and 2 times of that of ordinary wet drilling respectively, (4) The drilling using strong alkali water with micro-bubble was economical and eco-friendly.

Key Words : Drilling, Cooling, Drill with Through Hole, Drill, Tool, Heat Transfer Coefficient

1. 緒 言

穴あけ加工は、加工点が工作物中にあり、工具は熱的にきわめて過酷な状況にさらされている。そのため、従来の高速度鋼や超硬製のドリルのほかに、多少の靱性を犠牲にして耐熱性を強化したサーメット製⁽¹⁾のドリルも使用され始めている。スルーホール付きドリルに高圧切削油剤を供給する手法⁽²⁾も行われているが、その冷却効果が不十分であり、しかも環境保全の観点からも好ましいものではない。また、工具表面の摩擦係数を低減し、切削発熱を小さくするために DLC⁽³⁾や TiAlN⁽⁴⁾の固体潤滑剤の表面塗布もよく行われているが、これらの固体潤滑剤は、強度と寿命の点からまだ十分とは言えない。

そこで本研究では、スルーホール付きのドリルに水を供給し、その水の気化熱現象⁽⁵⁾を利用して強制冷却する加工技術を開発した。具体的には、水では工作機械や工作物を腐食してしまうので、鋼に対して防食性のある pH12.5 の強アルカリ水を使用し、さらに、気化熱冷却効果を促進するためにマイクロバブルを添加したものである。まず、この強アルカリ水の最適仕様を実験によって明らかにした。つぎに、ドリルの熱負担を軽減するために、マイクロバブルを添加した強アルカリ水をスルーホール付きのドリルに供給し、ドリル先端の切削発熱を水の気化熱冷却現象で強制冷却する方法の効果を実験で評価した。また、ドリルの寿命試験によって本手法の工業

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的な有効性を評価した。最後に、本手法の環境保全特性とコストの簡単な評価も行った。

2. マイクロバブルを添加した強アルカリ水の最適仕様

2・1 加工に関連する金属の強アルカリ水に対する耐食性

切削時の水の気化熱による冷却効果は、切削油剤のそれに比べてきわめて大きい⁽⁶⁾にも関わらず、現状において工場内の工作機械で使用されている例は少ない。それは、水が工作機械、工作物、その周辺の機械要素などの鋼製部品を腐食するためである。しかし、pH12.5を超える強アルカリ水は、前記の鋼製部品を腐食することはない。さらに、界面浸透性、剥離分解能力、乳化・分離能力がそれぞれ大きいため、その洗浄力が極めて大きく、しかも除菌・腐敗防止作用もあるため、広域におよぶ洗浄剤として最近よく使用されつつある。また、強アルカリ水を大気中に放置しつづけると、pHは7.0に漸近しアルカリ性を失いたただの水になるため、環境保全を促進できる洗浄剤として注目されている^{(6),(7)}。

ここでは、加工関連材料の耐強アルカリ特性を実験で明らかにする。表1に実験で使用する強アルカリ水を生成する装置の仕様を示す。仕様に示されるように、小型の生成装置で、極めて容易にpH 12.5の強アルカリ水を生成することができる。腐食工学において平衡状態で金属イオン濃度 (mol/l) の対数値が-6以下のときにその金属は腐食されないとみなされている。そこで、強アルカリ水の腐食特性⁽⁷⁾に関しては、鋼の場合、pH 10以上のアルカリ水中では腐食が起こらないことになる。同様に、ニッケル基合金のベースとなるニッケルの場合は、pH 8.5～pH 13.0の領域が化学的不動態領域である。また、チタン合金のベースとなるチタンの場合は、pH 13.0以下領域で化学的不動態領域である。これらから、チタン合金やニッケル基合金などの工作物を強アルカリ水中に完全に浸漬した状態にして、水の気化熱によって強制冷却しながら、工具への熱影響の軽減を行う場合、その強アルカリ水のpH値は、pH 10.0～pH 13.0が適切と考えられる。そこで、これらの材料のアルカリ水中における腐食特性を実験で確認する。表2に示すように、温度 $20 \pm 1^\circ\text{C}$ 、湿度 60%一定の恒温室に2カ月間放置した。アルカリ水は1週間に1度入れ替えをしてpH値を維持した。





Table 1 Specification of the system for making strong alkaline water

Method of generation	Closed generation type
Value of pH	pH 12.5
Quantity of generation	10 l/h
Voltage & Power	100 V & 300W
Size	495W×430D×1100H

Table 2 Condition of corrosion test

Medium in the vessel	Strong alkaline water (pH 12.5) ⁽⁸⁾
Ambient conditions	Room temp.: $20 \pm 1^\circ\text{C}$, Humidity: 60%
Period	Two months

Table 3 The results of the materials tested in strong alkaline water with pH12.5 (for two month)

Work piece materials	Condition in strong alkaline water			Tool materials	Condition in strong alkaline water
Ti (pure)	○			High speed tool	○
				Carbide (S30T, T725X)	○
Ti6Al4V	○			Cermet (NS530)	○
				Ceramics (LX11)	○
Inconel 718	○			CBN (KBN525)	○
				Diamond (DA2200)	○
Steel (S45C)	○			Coating materials of tool	Condition in strong alkaline water
Aluminum	×			TiN	○
Copper		Changed to dark brown		TiC	○
				DLC	○
Brass		Changed to dark green		TiAlN	×
				TiAlCr	×

Symbol: ○ = No change, × = Corroded

耐強アルカリ特性の実験結果を表 3 に示す。工作物としては、純チタン、チタン合金、ニッケル基合金のほか、工業製品としてよく使用されている鋼 (S45C)、アルミニウム、黄銅、銅を、工具材種としては、高速度工具鋼、超硬、サーメット、セラミックス (アルミナ)、CBN、ダイヤモンドを、また、工具のコーティング材料としては、TiN、TiC、DLC、TiAlN、TiAlCr をそれぞれ試料として使用した。これらの材料を pH 12.5 の強アルカリ水の入った試験管に入れ、表 2 の条件で実験を行った結果である。アルミニウム、アルミニウム合金以外の金属は、強アルカリ水中および強アルカリ水面付近に 2 カ月間放置しても、目視観察では腐食は観察されなかった。そのため、鋼、チタン合金、ニッケル合金を強アルカリ水中に完全に浸漬した状態にして、切削加工を行うことが可能であると考えられる。しかし、アルミニウムを使用する場合には、強アルカリの影響で腐食が促進されるので、注意が必要である。また、銅、黄銅は表面が変色することに注意が必要である。

2・2 マイクロバブルの最適仕様

本研究では、ドリルのスルーホールを通して加工点にきわめて冷却効率の高いマイクロバブルを添加した強アルカリ水を供給したいと考えている。

そこで、まず、マイクロバブルの基本特性として、水中に放出したマイクロバブルの水中における寿命を測定した。強アルカリ水が 30 ℓ入った水槽に 8 ℓ/min のマイクロバブル (PMS 社の液中パーティクルカウンターE2 使用、測定範囲は 2 μm から 125 μm 、粒径は直径値の粒径分布⁽⁹⁾を図 1 に示す) を 10 分間供給し、白濁した強アルカリ水 (pH12.5) が透明になるまでの時間を測定した。その際、強アルカリ水に 32 ℓ/min の気泡 (1~2 mm と 3~5 mm) を供給した場合についても測定を行った。その結果、図 2 に示すとおり、マイクロバブルは強アルカリ水中で 5 分間程度保持されており、容器内の強アルカリ水にマイクロバブルを供給した後、各種工作機械に配管を通して搬送し、加工時の強制冷却に利用することが可能である。しかし、1~2 mm もしくは 3~5 mm 程度のサイズの気泡になると強アルカリ水中で数秒しか保持されず、1 台の工作機械において加工点まで数 mm の気泡が混ざった強アルカリ水を供給することが困難であると考えられる。そのため、本報では以後の実験においてマイクロバブルを供給した強アルカリ水のみについて検討することにした。

マイクロバブルを供給した強アルカリ水の強制冷却能力を把握するために、見かけ上の熱伝達率を測定した。それに先だってマイクロバブル発生装置によって、どの程度強アルカリ水中に空気が含まれるかを確認する。図 3 に示すように実験装置は、マイクロバブル装置で容器から強アルカリ水を吸い上げ、そこにマイクロバブルを含有させ、流量計 A を通した後に最終的にメスシリンダに補給する構造である。まず、マイクロバブルを含有した強アルカリ水をメスシリンダに一定量供給し、その水量を測定する。10 分後 (白濁が透明になる時間の 2 倍) に再度強アルカリ水量を測定し、その差から強アルカリ水に含有されていたマイクロバブルの空気の量を求め、これを強アルカリ水 10 当たり含有していたマイクロバブルの空気の量とした。

図 4 に示すように、実験結果としてマイクロバブル装置によって発生するマイクロバブルの量は流量が 8 ℓ/min のときに多く含まれていることがわかった。この流量は、マイクロバブル装置に供給する空気圧によって調整す

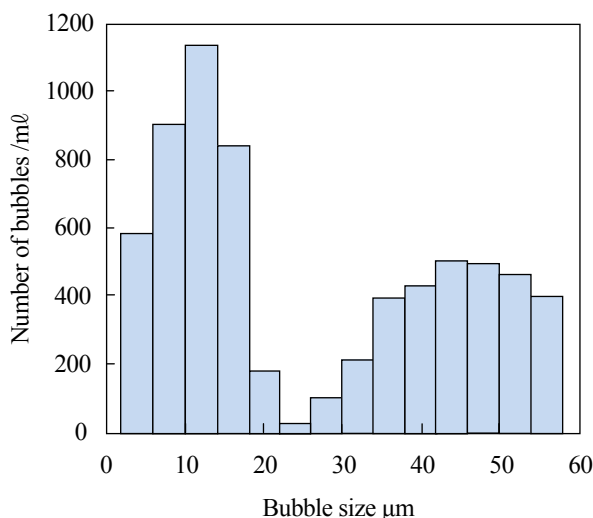


Fig. 1 Bubble size distribution of micro bubble ⁽⁹⁾

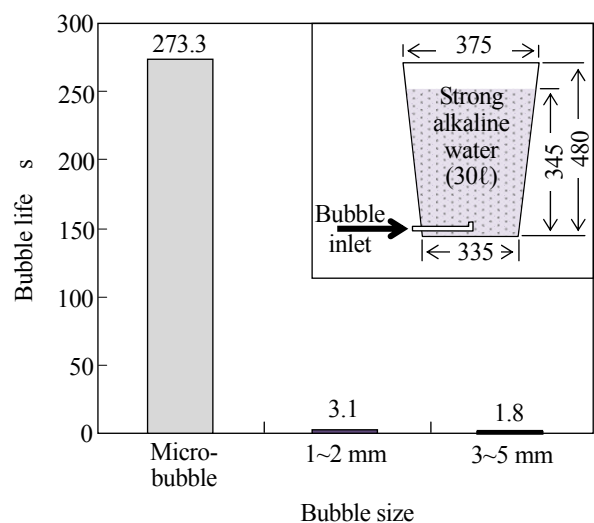


Fig. 2 Relation between bubble size and its life in strong alkaline water

ることが可能であり、本実験では 0.4 Pa の空気圧を供給したときに最高量のマイクロバブルが発生するように設計された装置を使用することになる。それ以上に圧力を上げたときは、マイクロバブルの量が減少していくことも確認した。使用している流量計 A のほうが圧力計より精度が高いので、以後、強アルカリ水中に含有するマイクロバブル量を管理するためには、流量計 A の値を使用することにした。

マイクロバブルを含有した強アルカリ水の強制冷却能力を把握するために、見かけ上の熱伝達率を測定した。図 5 に示すように、ラバーヒータ ($100 \times 100 \times 2 \text{ mm}$) を 2 枚の鋼 (SPCC, $100 \times 100 \times 1 \text{ mm}$) で両側から挟み、それを強アルカリ水の入っているメイン容器の中央に宙吊り状態で配置した。ラバーヒータに電源を入れ (50 W)、鋼表面に貼った 10 点の熱電対 (片面 5 点 $\times 2$) の温度が定常状態になった段階で、鋼表面平均温度と水槽の平均水温 (鋼板に貼った熱電対の垂直 75 mm の位置に合計 10 本の熱電対を設置) から見かけ上の熱伝達率を測定した。スルーホール付きのドリルに冷却油剤を供給することを想定して、最大吐出圧力 2.1 MPa 、最大吐出流量 10 l/min のポンプによって、メイン容器にマイクロバブルを含有した強アルカリ水を供給し、その対流による熱伝達率の違いを測定したので、本実験は相対的な評価のみに用いるための見かけ上の熱伝達率測定である。このとき、流量計 B の循環している強アルカリ水量と見かけ上の熱伝達率の関係を測定した。また、補助に、マイクロバブル装置を設置し、マイクロバブルを含有した強アルカリ水を上記のポンプに供給できるようにした。この際、アルカリ水中に供給するマイクロバブル量を変化させ、実験のパラメータとした。これらにより、メイン容器を

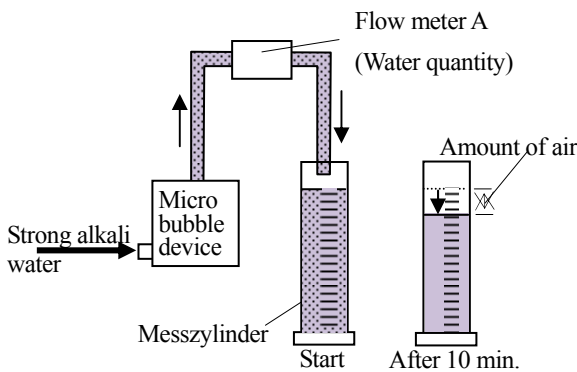


Fig. 3 Experimental set-up for measuring amount of micro bubble in alkaline water

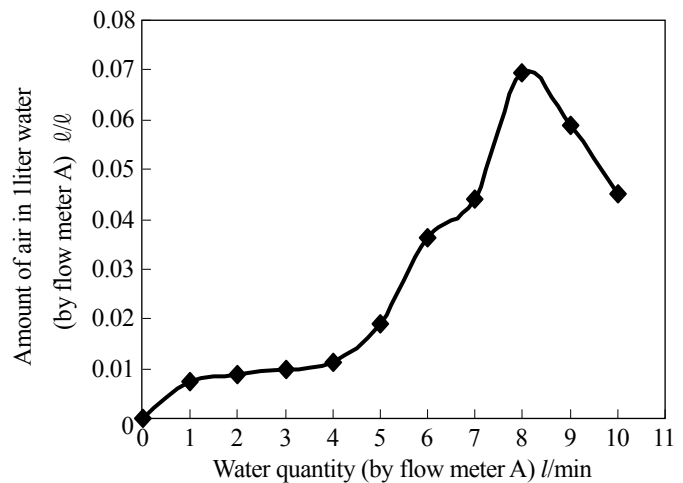


Fig. 4 Experimental results for amount of air in alkaline water (Water quantity is used for control factor of micro bubble)

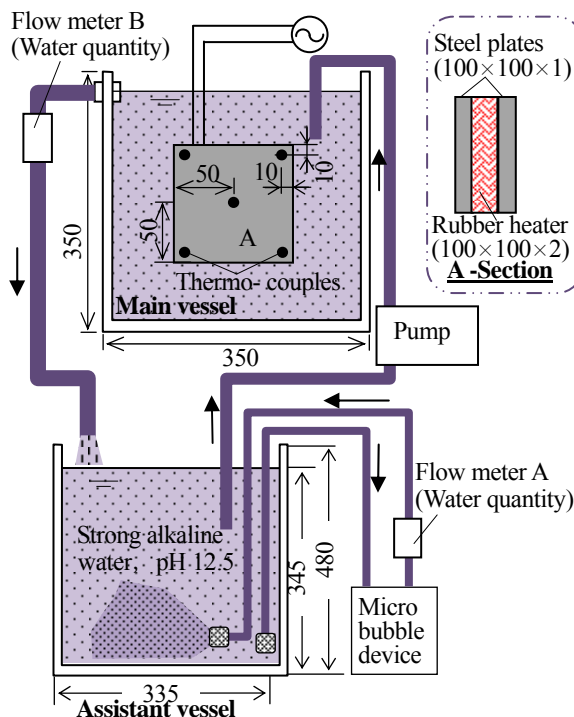


Fig. 5 Experimental set-up for measuring heat transfer coefficient of alkaline water with bubbles

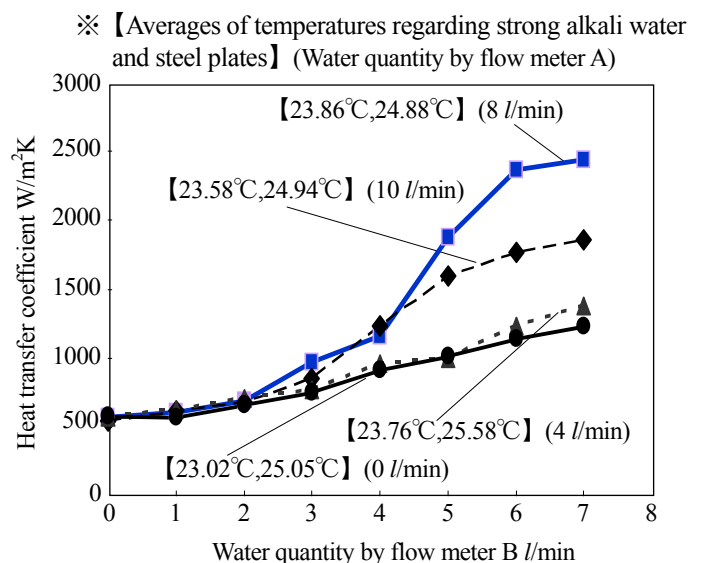


Fig. 6 Relationship between the water quantity and the heat transfer coefficient

スルーホール付きドリルと見立てて、それにマイクロバブルを含有した強アルカリ水を供給したときの強制冷却能力を相対評価した。図5の強アルカリ水の水温が定常状態に達してから熱伝達率の測定を開始した。

図 6 に見かけ上の熱伝達率の測定結果を示す。ポンプによる強アルカリ水の供給を行わない場合（強アルカリ水の自然対流状態）に $500 \text{ W/m}^2\text{K}$ 程度であった見かけ上の熱伝達が、強アルカリ水のみを 7 l/min 対流させた場合に $1200 \text{ W/m}^2\text{K}$ ，さらに、マイクロバブルを含有（ 8 l/min ）した強アルカリ水のみを 7 l/min 対流させた場合に $2500 \text{ W/m}^2\text{K}$ （ \equiv ラバーヒータ電力 $50 \text{ W} \div$ 鋼板面積（ $0.1 \text{ m} \times 0.1 \text{ m} \times 2$ 面） \div （鋼板平均温度 24.88°C - 平均水温 23.86°C ））と冷却能力が向上していた。ここで、見かけ上の熱伝達率はラバーヒータに入力された電気エネルギーが 100% 水温上昇に使われたとして計算した値であり、実験装置から周囲空間や床面への熱放射や熱伝導、対流冷却での熱損失が加味されていないため、真値と比較して高い値となっている。強アルカリ水に含有させるマイクロバブル量が多くなるに従って見かけ上の熱伝達率も向上しており、含有された空気によって冷却の効率が向上したことが伺える。この結果より、マイクロバブルを含有する強アルカリ水を対流させることで大きな冷却効果があり、その有効性が確認できた。

3. スルーホール付きのドリルにマイクロバブルを添加した強アルカリ水を供給した穴あけ加工

3·1 工具温度

マイクロバブルを添加した強アルカリ水をスルーホール付きのドリルに供給した場合のドリル先端温度を実験で調べた。ここでは、工具温度に大きな影響がある工具先端の凝着性や切りくずの排出性に関する考察はできず、強アルカリ水の工具先端温度の参考値を得ることになる。図 7 にドリル温度を測定する実験装置を示す。実験は実切削ではなく、2 枚のセラミックスヒータをドリル（φ 15mm，スルーホール付き）の 2 枚の切れ刃先端部にシリコンボンドで接着し、T 型熱電対をドリル切れ刃付近と溝（切れ刃から 3 mm の位置）の各 2 箇所シリコンボンドで貼った。あらかじめ工作物（S45C、Ti6Al4V）に空けておいた穴とドリル先端が密着するように、穴の底部に厚さ 2 mm のシリコンボンドを塗布・固化させておき、実験時にはドリルのスラスト方向に 20 N の荷重をかけた。実験では、T 型熱電対の測定限界とセラミックスヒータおよびシリコンボンドの使用限界を考慮して、Max 300℃の実験を行うことにした。そのため、乾式状態でドリル切れ刃の定常状態の温度が 300℃になる電圧 29.8 V、電力 0.12 kW（セラミックスヒータ 1 個当たり）を固定条件として使用した。工作物は S45C と Ti6Al4V の 2 種類で、側面を 5mm 厚の発泡スチロール（熱伝導率 0.04 W/mK）で断熱して、側面からの冷却の影響をできる限り抑制した。実験は、乾式状態の場合、強アルカリ水のみをスルーホールに供給（7 l/min）した場合、20 l の強アルカリ水の入っている水槽に 8 l/min のマイクロバブルを含有してスルーホールに供給（7 l/min）した場合の 3 種類について行った。

図 8 に工作物が S45C と Ti6Al4V の場合のドリル先端温度測定結果を示す。S45C の結果は、乾式よりも強アルカリ水の強制冷却効果が 3.5 倍程度大きかった。マイクロバブルを含有した強アルカリ水の冷却効果も乾式の 3.5 倍程度であった。こちらのほうが、強アルカリ水のみよりも強制冷却効果がわずかに良いことがわかるが、あまり大きな効果が見られない。これは、T 型熱電対の測定限界とセラミックスヒータおよびシリコンボンドの使用

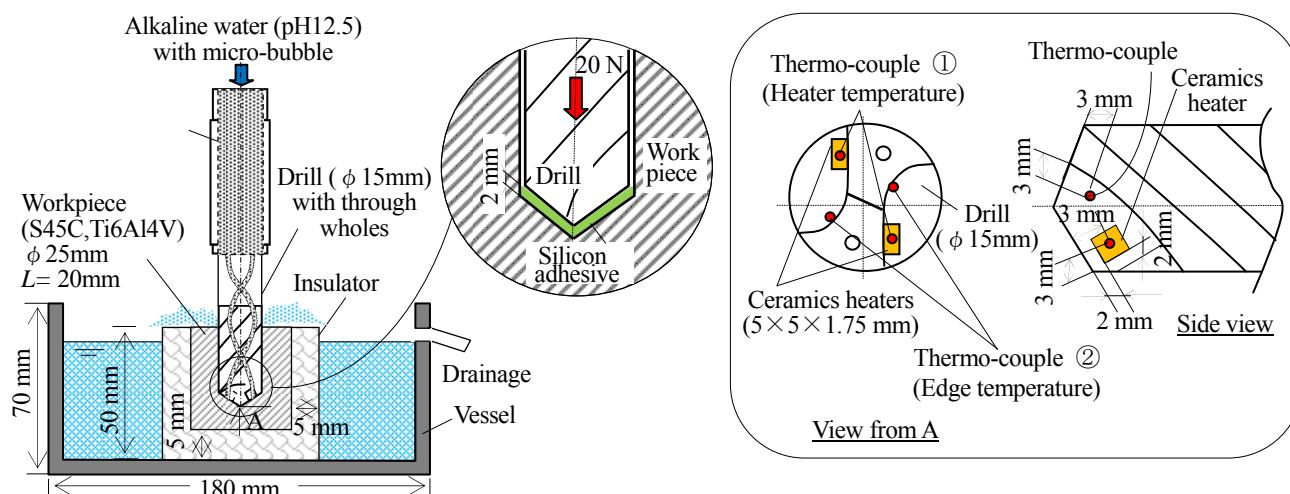


Fig. 7 Experimental set-up and position of thermo-couples for measuring temperature on the edge of the drill

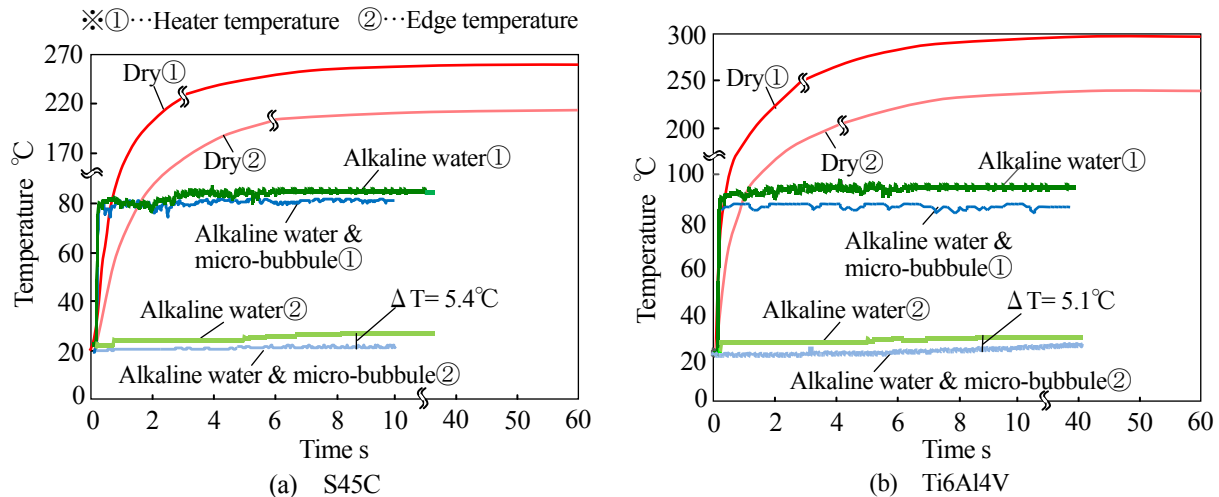


Fig. 8 Temperatures on the edge of the drill for different cooling conditions

限界を考慮して温度をこれ以上高温にすることができなかったために、気化熱による強制冷却効果が顕著に現れなかったことが原因であると考えられる。しかし、強アルカリ水による冷却効果は十分であり、これは、ドリルの強度や硬度を維持するために有効に利用できると思われる。とくに、工作物が Ti6Al4V のような低熱伝導材料で工具に対する熱負荷が大きくなる場合や、効率の良い冷却が求められる深穴加工では有効であると考えられる。また、実切削では、強アルカリ水による冷却効果のみでなく、潤滑効果も含まれることになる。

3・2 表面粗さ

ここでは実切削を行い、加工面の表面粗さを測定して、マイクロバブルを添加した強アルカリ水の強制冷却効果を評価する。表 4 に評価のために使用した穴あけ加工条件を示す。φ15 mm のドリルで S45C を穴あけするときに良く使用される条件である。そのため、工作物が Ti6Al4V の場合にはドリルに大きな熱負荷のかかる条件である。表面粗さを測定する工作物は、加工開始時のものと寿命判定される寸前のものを使用した。表面粗さ測定は、穴深さ 5 mm, 15 mm, 25 mm の位置の各 3 か所、合計 9 箇所を測定し、その平均値をとった。ただし、25 mm まで到達せずに寿命を迎えるものに関しては、ドリルの肩部が侵入し始めた箇所と寿命寸前の箇所を測定し、その平均値をとった。ここで実験は、乾式切削の場合、従来の湿式切削（エマルジョンの切削油剤を、予備実験で最も冷却効果の大きかったかけ方で、30 l/min 供給）の場合、強アルカリ水のみスルーホールに供給（7 l/min）した場合、40 l の強アルカリ水の入っている水槽に 8 l/min のマイクロバブルを添加してスルーホールに供給（7 l/min）した場合の 4 種類について行った。スルーホールは小径でしかも切りくずが抵抗となるため、その流量を確保するために吐出圧力は 2.1 MPa と比較的高圧のポンプを使用している。

図 9 に表面粗さの測定結果（算術平均粗さ Ra）を示す。加工開始時に、マイクロバブルを添加した強アルカリ水の強制冷却を使用したときの表面粗さは、乾式切削のそれに比べて 30% 程度、切削油剤のそれに比べて 17% 程度改善されていた。これはマイクロバブルを含有した強アルカリ水による大きな強制冷却効果によってドリルが効果的に冷却されたために、ドリルの熱変形抑制によるドリル径の変動が小さかったこと（工作物穴径が乾式

Table 4 Drilling condition for evaluation of the forced cooling of alkali water with micro bubble

Specification of drill		Drilling condition	
Diameter	φ 15 mm	Spindle speed	500 min ⁻¹
Length	125 mm	Cutting speed	24 m/min
Material	Carbide with TiN	Feed speed	40 mm/min
Through hole	φ 2mm × 2 holes	Depth of drilling	From 0 to 25 mm
Specification of cooling medium		Work piece	S45C and Ti6Al4V
Medium	Strong alkali water (pH12.5)		
Micro bubble	8 l/min in 40 l alkali water		

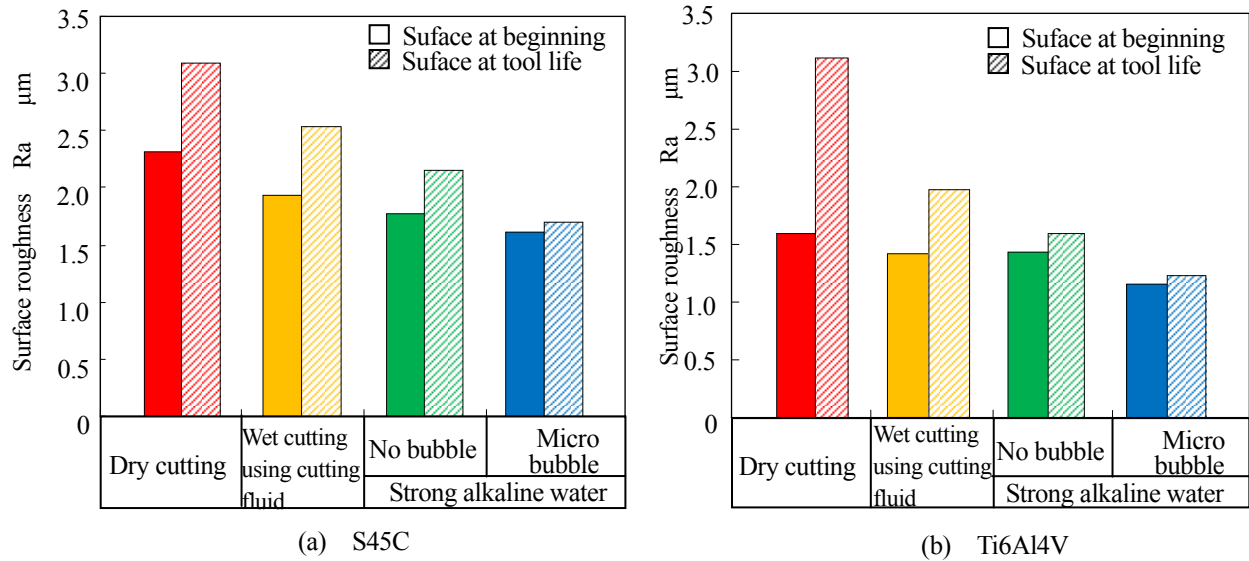


Fig. 9 Surface roughness on the hole of the drilling using the forced cooling of alkali water with micro bubble

切削でφ15.23mmのところ、マイクロバブルを添加した強アルカリ水の場合はφ15.16mm)、ドリルの硬度・強度の低下が抑制されドリルの切れ味の低下が少なかったこと、ドリルの剛性低下が低いことがそれぞれ影響したものと考えられる。なお、これらの結果には、強アルカリ水による冷却効果のみでなく、潤滑効果も含まれている。

3・3 工具寿命

スルーホール付きのドリルにマイクロバブルを添加した強アルカリ水を供給した場合の工具寿命を測定、評価した。先の表4の穴あけ加工条件を使用して加工を行った。ここでも実験は、乾式切削の場合、従来の湿式切削（エマルジョンの切削油剤を、予備実験で最も冷却効果の大きかったかけ方で、30 l/min 供給）の場合、強アルカリ水のみをスルーホールに供給（7 l/min）した場合、40 lの強アルカリ水の入っている水槽に8 l/minのマイクロバブルを添加してスルーホールに供給（7 l/min）した場合の4種類について行った。工具寿命の判定は、図10に示すようにドリルのエッジ部の摩耗量が0.15mmに達した時点で工具寿命と判定した。

図11に示すように、金属材料は常温では熱軟化係数は1.0であり公称の硬度であるが、融点では熱軟化係数は0.0であり硬度が0となる。また、その間で熱軟化係数はほぼ線形となる⁽¹⁰⁾。例えば、H_{RC}92、融点2500℃の超硬を例にとると、常温での硬度はH_{RC}92、800℃ではH_{RC}62.5（=92×（1.0-800÷2500））、1250℃ではH_{RC}46（=92×（1.0-1250÷2500））と軟化する。800℃での硬度H_{RC}62.5は工具として使用可能であるが、1250℃での硬度H_{RC}46では、鉄鋼材料を切削する工具としての使用が困難である。このように、工具の温度はその硬度に大きく

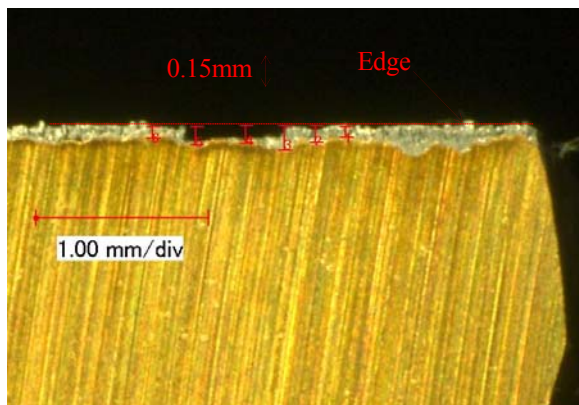


Fig. 10 Photograph of edge of the drill for judgement of tool life

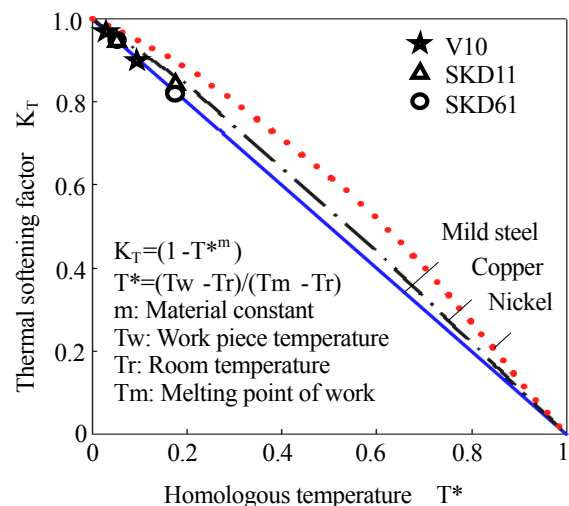


Fig. 11 Relationship between the softening factor and the temperature

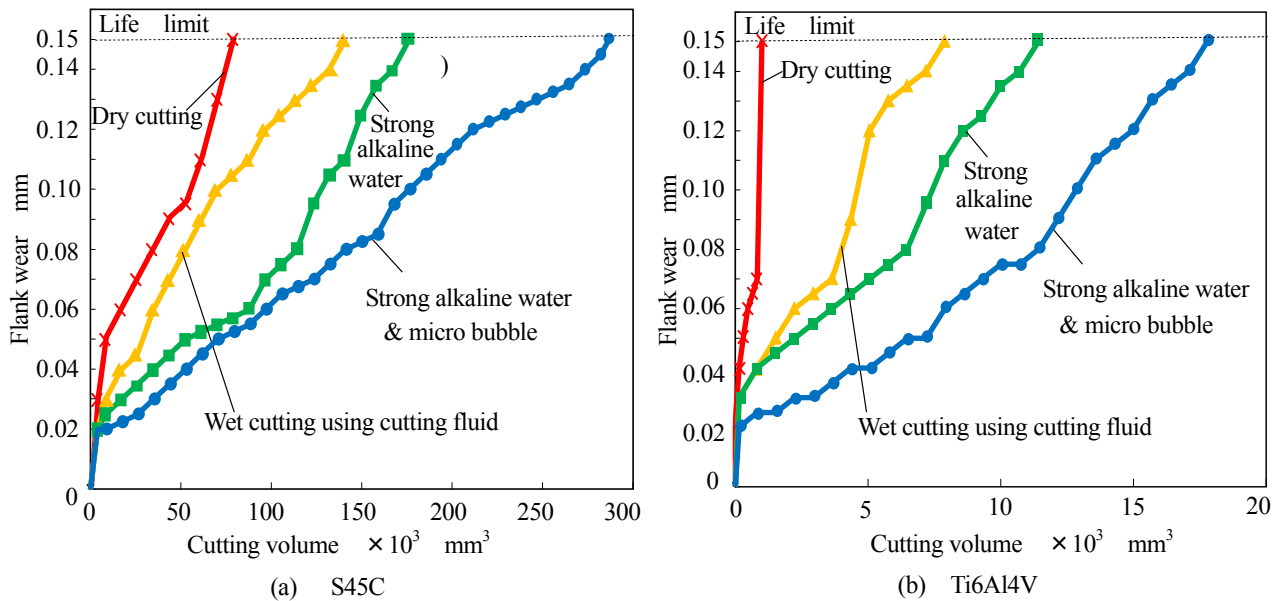


Fig. 12 Results of tool life regarding the drill using the forced cooling of alkali water with micro bubble

影響し、軟化した工具による加工を余儀なくされており、それが工具寿命にも大きく影響する。そのため、ドリル先端部を効率よく強制冷却できれば、ドリルの軟化を抑制でき、硬いまのドリルで切削が可能であり、工具寿命は伸びると考えられる。しかし、同時に工作物も冷却され、比切削抵抗が大きくなり、逆に工具寿命が短くなる可能性があることに注意が必要である。

図 12 に工具寿命の測定結果を示す。(a)の S45C が工作物の場合、マイクロバブルを添加した強アルカリ水の強制冷却を使用したときの工具寿命は、乾式切削のそれに比べて 6.5 倍に、切削油剤のそれに比べて 2 倍に、強アルカリ水だけのそれに比べて 1.6 倍程度それぞれ改善されていた。これはマイクロバブルを添加した強アルカリ水の大きな強制冷却効果によってドリルが効果的に冷却され、ドリルの硬度低下が少なかったためと考えられる。(b)の Ti6Al4V (低熱伝導材料) が工作物の場合、マイクロバブルを添加した強アルカリ水の強制冷却の効果がさらに顕著であった。乾式切削や切削油剤を用いた湿式切削では正常な穴あけ加工が困難であった。これは、工作物と切りくずの熱伝導率が低いことから切削発熱が集中的にドリルに伝導して、ドリルの温度上昇、硬度軟化が積極的に起きたためと考えられる。これらの結果は、マイクロバブルを添加した強アルカリ水の強制冷却を使用すれば、従来は困難であった低熱伝導材料の穴あけ加工が可能になることも示している。なお、これらの結果にも、強アルカリ水による冷却効果のみでなく、潤滑効果も含まれている。

4. 環境保全特性と加工コストの簡単な考察

最後に、CO₂排出量を検討することによって本手法の環境負荷に対する簡単な評価を行った。ここでは、従来の湿式切削と本手法適用の場合の CO₂ 排出量を比較する。湿式切削では稼働時のマシニングセンタとオイルポンプの消費電力量と、廃油処理時の CO₂ 排出量から合計の CO₂ 排出量を算出した。また、本手法の場合はマシニングセンタ、マイクロバブル発生装置、強アルカリ水生成装置、ドリルに強アルカリ水を供給するポンプの消費電力量をもとに CO₂ 排出量を算出した。

表 5 に従来の湿式切削の CO₂ 排出量の計算結果を示す。まず、湿式切削では主電力 3.6 kW のマシニングセンタと切削油剤を加工点に供給するオイルポンプ 1.2 kW を 1 日 8 時間、1 年のうち 250 日稼働させた場合を想定した。この場合算出される消費電力量は 9600kWh (4.8kW×8 h×250 days) であり、CO₂ 排出量への換算係数を 0.468 kg-CO₂/kWh とすると、推定される CO₂ 排出量 CL_{CO_2} は式(1)から求めることができる⁽¹¹⁾。

$$CL_{CO_2} = 0.468 \times W_E \quad (1)$$

ここで、 W_E は消費電力量 (kWh) であり、各装置で発生する消費電力量とする。これよりマシニングセンタおよびオイルポンプの稼働による CO_2 排出量は 4492.8 kg-CO_2 である。

次に、廃油処理時の CO_2 排出量を計算した。ここではオイルタンク容量 340 l を 1 年間で 2 回交換するとし、また 1 カ月に 1 回 30 l を追加するとして $360 \text{ l} (30 \text{ l} \times 12 \text{ month})$ 、合計 1040 l の廃油を処理する場合を想定した。推定される CO_2 排出量は式(2)から求めることができる^{(12),(13)}。

$$\text{CO}_2 \text{ 排出量 } \text{kg-CO}_2 = \text{廃油量 } \text{k l} \times \text{発熱量 } \text{GJ/k l} \times \text{炭素排出係数 } \text{t-C/TJ} \times (44 \div 12) \quad (2)$$

ここで発熱量は 40.2 GJ/k l 、炭素排出係数は 19.22 t-C/TJ である⁽¹⁴⁾。式(2)を用いて廃油処理時の CO_2 排出量を求めると 2946.3 kg-CO_2 となる。以上より湿式切削による CO_2 排出量は合計 7439.1 kg-CO_2 となる。

本手法を用いた際に予想される CO_2 排出量を表 6 に示す。従来の湿式切削時に使用したマシニングセンタを本手法においても用いるとし、1 日 8 時間、1 年のうち 250 日稼働させた場合を想定した。この場合算出される消費電力量は $7200 \text{ kWh} (3.6 \text{ kW} \times 8 \text{ h} \times 250 \text{ days})$ であり、本手法における CO_2 排出量は式(1)を用いて 3369.6 kg-CO_2 と算出される。また、マイクロバブル発生装置、ドリルに強アルカリ水を供給するポンプの CO_2 排出量を求めるとそれぞれ 524.2 kg-CO_2 、 702 kg-CO_2 となる。さらに、強アルカリ水生成装置による CO_2 排出量を検討する。強アルカリ水を貯蔵する容器の容量は $16.1 \text{ l} (350 \times 230 \times 200 \text{ mm})$ であり、これにマイクロバブルの管路口への使用に伴った追加分として 3.9 l を足し合計 20 l とする。1 年のうち 250 日マシニングセンタを稼働させ、1 か月に 1 回強アルカリ水を交換することを想定すると、強アルカリ水はほぼ 250 l 必要となる。装置は 1 回の稼働で 2 時間要し、 20 l の強アルカリ水を生成することができるため、1 年間に 25 時間稼働することが考えられ、想定される消費電力量は $18.8 \text{ kWh} (0.75 \text{ kW} \times 25 \text{ h})$ である。 CO_2 排出量は、式(1)を用いて 8.8 kg-CO_2 と算出される。そのため本手法適用後の CO_2 排出量は合計 4604.6 kg-CO_2 である。

図 13 に CO_2 排出量の比較を示す。 CO_2 排出量は今回の条件において 1 年間稼働した場合、 2834.5 kg-CO_2 の削減効果 (38.1 %削減) が得られることがわかる。これは、加工中に切削油剤を使用しないことによって、廃油処理

Table 5 CO_2 emission of conventional wet cutting

Machining center & Oil pump			Waste oil disposal		
Power consumption	kW	4.8	Cutting oil amount	ℓ/year	680
Use condition	/year	8 h ×250 days	Refill oil amount	ℓ/year	360
Consumption electric quantity	kWh	9600			
CO ₂ emission	kg-CO ₂ /year	4492.8	CO ₂ emission	kg-CO ₂ /year	2946.3
Total CO ₂ emission	kg-CO ₂ /year	7439.1			

Table 6 CO_2 emission of cutting in strong alkaline water

Calculation factors	Machining center	Micro bubble device	Water supply pump	Strong alkaline water generating unit
Power consumption kW	3.6	0.56	0.75	0.75
Amount used of strong alkaline water ℓ	-	-	-	20
Replacement cycle	-	-	-	Once a month
Production of alkaline water ℓ	-	-	-	20
Use condition /year	8 h ×250 days	8 h ×250 days	8 h ×250 days	25h
Consumption electric quantity kWh	7200	1120	1500	18.8
CO ₂ emission kg-CO ₂ /year	3369.6	524.2	702	8.8
Total CO ₂ emission kg-CO ₂ /year	4604.6			

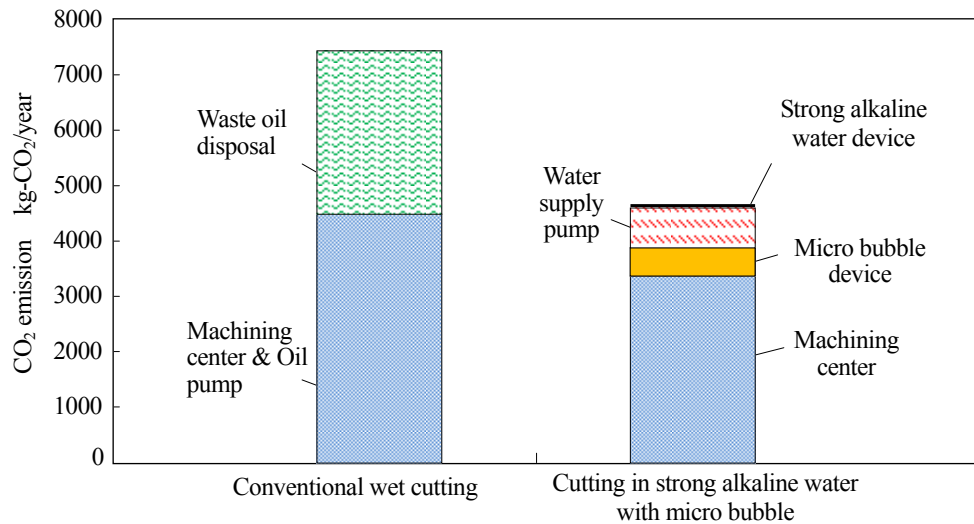
Fig. 13 Comparison of CO₂ emission

Table 7 Running condition and cost table (Using one machining center, For 1 year, Work piece: S45C)

Cost table	Wet drilling		Drilling using strong alkali water with micro bubble	
	Detailed data	Cost	Detailed data	Cost
Working energy of the machine tools or the equipments 1 kWh=16 Yen	(Machining center 3.6 kW+Oil pump 1.2kW) × 8 h×250 days = 9600kWh	153,600 Yen	(Machining center 3.6 kW+ Micro bubble device 0.56 kW + Pump 0.75kW +) × 8 h×250 days+ Strong alkaline water 0.75 kW×25h = 9838.75 kWh	157,420 Yen
Price of drill φ 15 mm with through hole ※ 1 piece=27,300 Yen ⁽¹⁵⁾	120 holes/h×8 h×250 days÷2500 holes/piece=96 pieces ※ 2500 holes/piece ⁽¹⁶⁾	2,620,800 Yen	120 holes/h×8 h×250 days÷5000 holes/piece=48 pieces ※ 5000holes/piece(Reference(16) & Fig.12)	1,310,400 Yen
Cutting oil : Purchase price 700 Yen/ℓ Disposal cost 33Yen/ ℓ	Cutting oil 680 ℓ/year+ Refill oil 360 ℓ/year =1040 ℓ/year	762,320 Yen	—	—
	Total	3,536,720 Yen	Total	1,467,820 Yen

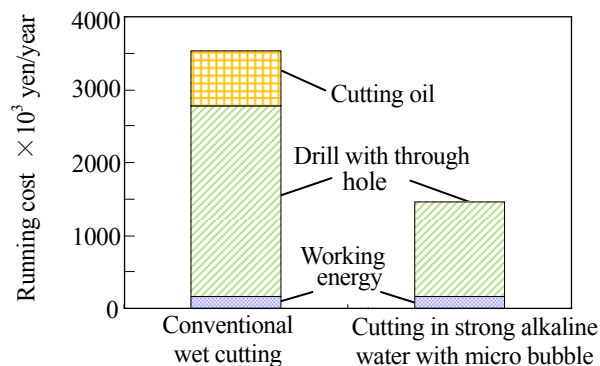


Fig. 14 Running fee for one year

で生じる CO₂を削減できるためである。

表 7 は切削油剤を使用した湿式切削の場合と、マイクロバブルを添加した強アルカリ水の強制冷却を使用した場合について、加工条件から計算した年間のランニングコストである。計算項目は、工作機械と装置の電力使用

料, 工具費用, 切削油剤の廃液処理費用の3つであり, 計算のための基本データは, 表5および表6を使用している. 計算は1日8時間, 1年250日稼働し, S45Cに $\phi 15$, 深さ30mmの穴を1時間で120個あけることを想定している. 表7のランニングコストの計算結果を整理して図14に示す. 湿式切削の場合は, 装置稼働電気料金のほかに多額の工具消耗費や切削油剤代金がかかるのに対して, マイクロバブルを添加した強アルカリ水の強制冷却を使用した場合は装置稼働電気料金のほかには水や空気を使用するのみであるため, ランニングコストが湿式切削のそれに比べて60%程度安価となっている.

このように, 本手法は切削油剤を使用せず, 加工後の洗浄も不要なため, 環境負荷の低減に有効であり, また, ランニングコストの低減効果もあり, 経済的でもある.

5. 結 言

本研究の結果をまとめると以下のとおりである.

- (1) マイクロバブルを添加した強アルカリ水は, マイクロバブルを添加しない場合に比較して大きな強制冷却効果があった.
- (2) マイクロバブルを添加した強アルカリ水をスルーホール付きドリルに供給したところ, 乾式切削に比べて温度上昇が70%程度改善, 加工面表面粗さは30%改善, 工具寿命が6.5倍にそれぞれ向上した.
- (3) マイクロバブルを添加した強アルカリ水の強制冷却効果は環境保全に効果があり, しかも, コスト低減にも効果があった.

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CO₂削減のために強アルカリ水中に工作機械を浸漬する技術の開発*田辺 郁男^{*1}, ジュニオール ライムンド ダ クルス^{*2}
坂口 暢也^{*2}, 金子 義幸^{*3}**Development of Technology Regarding Soaking Machine Tool in Strong Alkaline Water for Reduction of CO₂**Ikuo TANABE^{*1}, Junior Raimundo Da CRUZ,
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In the 21st century, as it is important to produce products with care for protecting the earth, a producer must be careful to conserve energy, save resources and reduce waste which pollutes environment. On the other hand, in case of a machine tool, much lubricating oil was used for smooth drive, electrical energy of forced cooling was used for high accuracy, and much cutting oil was also used for lubrication and cooling. This is large problem for protecting the earth. Therefore the soaking machine tool in strong alkaline water were developed and evaluated. Several elements of a machine tool were firstly investigated for alkali-proof. Then the bench lathe was remodeled and soaked in the vessel with strong alkaline water (pH12.5), thermal deformation between the spindle and the tool post was measured for evaluation of accuracy. And turning using the bench lathe was performed for investigating the effect of water evaporation in the strong alkaline water. It is concluded from the results that; (1) Alkali-proof regarding several elements of a machine tool were cleared in the experiment, (2) Thermal deformation of the bench lathe for bathing was very small in spite of no-forced cooling, (3) Accuracy of the machine tool was very good and the tool life was very long in spite of no-cutting oil, (4) The soaking machine tool in strong alkaline water was economical and eco-friendly.

Key Words : Forced Cooling, Machine Tool, Bathing, High Accuracy, Strong Alkaline Water, Cutting**1. 結 言**

高精度な加工のために多くの熱変形対策が工作機械に施されている^{(1), (2), (3)}。また、高精度化と生産性向上のために多くの切削発熱強制冷却技術も確立されている^{(4), (5), (6)}。これらの対策の多くが、複数台の冷凍機の強制冷却能力を利用し、発熱量を発熱箇所付近で効率よく除去し、工作機械構造や工具への熱影響を強制的に抑制する手法である。しかし、現在、地球環境保全に配慮したものづくり⁽⁷⁾がごく一般的に要求されるようになってきており、21世紀型加工技術として、高精度、高生産性、高信頼性に加えて、環境保全に配慮したものづくりが必要とされており、先の工作機械熱変形対策や工具強制冷却対策においても、省エネルギーと環境保全に十分に配慮した対策が要求され、それらに対してさらなる対策が必要になってきている。

そこで本研究では、鋼に対して耐食性のある強アルカリ水中に工作機械を浸漬した状態にして、その気化熱冷却効果によって工作機械の熱変形を抑制し、それと同時に浸漬状態になっている加工点付近でも、その気化熱冷却効果によって切削発熱を強制冷却する加工システムを開発する。具体的には、卓上旋盤を pH12.5 の強アルカリ水槽に浸漬状態にし、その機械構造の熱変形特性、加工精度、工具寿命を実験によって明らかにする。また、この技術を確認するために、機械要素の耐強アルカリ特性の解明、強アルカリ水へのマイクロバブルの添加による

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冷却能力向上の検討，本加工システムの環境保全特性の簡単な評価も行う．

2. 工作機械要素部品の耐強アルカリ特性

水の気化熱による冷却効果は，切削油剤のそれに比べてきわめて大きい⁽⁸⁾にも関わらず，現状において工場内の工作機械に適用されている例は少ない．それは，水が工作機械，工作物，その周辺の機械要素などの鋼製部品を腐食させるためである．しかし，腐食工学において平衡状態で金属イオン濃度 (mol/l) の対数値が -6 以下のときにその金属は腐食されないとみなされており，そのため，鋼の強アルカリ水に対する腐食特性⁽⁹⁾に関しては，pH 10 以上のアルカリ水中では腐食が起こらないことになる．よって pH12.5 を超える強アルカリ水は，前記の鋼製部品を腐食することはないと考えられる．また，同様に，鋼以外の工作物材料として，ニッケル基合金のベースとなるニッケルの場合は，pH 8.5～pH 13.0 の領域が化学的不動態領域である．さらに，チタン合金のベースとなるチタンの場合は，pH 13.0 以下領域で化学的不動態領域である．これらから，チタン合金やニッケル基合金などの工作物を強アルカリ水中に浸漬状態にして，水の気化熱によって強制冷却しながら，工具への熱影響の軽減を行う場合，その強アルカリ水の pH 値は，pH 10.0～pH 13.0 が適切と考えられる．しかも，強アルカリ水は界面浸透性，剥離分解能力，乳化・分離能力が大きいので，洗浄力が極めて大きく，除菌・腐敗防止作用もあるため，広域におよぶ洗浄剤として最近よく使用されている．また，強アルカリ水を大気中に放置し続けると，pH は 7.0 に漸進しアルカリ性を失いただの水になるため，環境保全を促進できる洗浄剤として注目されている．

ここでは，工作物や工具のほか，工作機械部品や工作機械関連の機械要素の耐強アルカリ特性を実験で明らかにする．表 1 に実験で使用する強アルカリ水を生成する装置の仕様を示す．小型の生成装置で，極めて容易に pH 12.5 の強アルカリ水を生成することができる．表 2 に示すように，加工関連材料のアルカリ水中における腐食特性を実験で確認した．工作機械構造材料，工作物，工具，工具のコーティング材料，工作機械要素部品，工作機械用電気部品，その他工作機械部品として利用されそうな素材，塗料の強アルカリ耐性を実験で確認するため表 2 に示すように，これらの材料（詳細は表 3 に示す）を pH 12.5 のアルカリ水の入った容器に入れ，温度 $20 \pm 1^\circ\text{C}$ ，湿度 60 %一定の恒温室に 2 カ月間放置した．アルカリ水は 1 週間に 1 度入れ替えをして pH 値を維持した．

耐強アルカリ特性の実験結果を表 3 に示す．金属では，アルミニウム，アルミニウム合金，銅，銅合金以外は，強アルカリ水中，および強アルカリ水面付近に 2 カ月間放置しても腐食しなかった．そのため，多くの工業材料を強アルカリ水中に浸漬状態にして，切削加工を行うことが可能であると考えられる．近年，工具のコーティング材料として，高硬度と低摩擦係数を特長とする TiAlN や TiAlCr が使用されているが，成分に Al が介在しているため腐食が促進し，とくに Al 含有量が多くなるとその腐食傾向は顕著に表れた．オイルシールは内部に設置されているバネ，排気クリーナは保護用のアルミニウム製金網，その他電気部品の端子台がそれぞれ腐食した．このように，機械要素部品と電気要素部品では組立や梱包等々に使用されているネジ，バネ，端子台等の部品に，アルミニウムや銅を合金材料として含有している場合があり，腐食や変色が起こるので注意が必要である．グリースが封入されている軸受やリニアガイドに関しては，油の流失もなく，強アルカリ水の浸漬前後で駆動特性（軸受は外輪に巻き付けた糸に荷重つけ回転速度測定，リニアガイドは傾斜板上の転がり速度測定）に変化はなかった．浸漬したサーボモータは，2 カ月後に乾燥させた後，NC 旋盤に組込み仕様通りの機能が出ることを確認した．DLC も耐強アルカリ特性があり，工作機械を強アルカリ水中に浸漬させたとき，その摺動面の固体潤滑剤として使用することが可能である．また，卓上旋盤（後述）を pH 12.5 のアルカリ水の入った容器に 2 カ月間浸漬させて継続的に実験を行ったところ，正常な稼働で，その後の目視観察では腐食・変色がなく，浸漬前と全く同等の正常な稼働を確認した．

Table 1 Specification of the system for making strong alkaline water

Method of generation	Closed generation type
Value of pH	pH 12.5
Quantity of generation	10 l/h
Voltage & Power	100 V & 300W
Size	495W×430D×1100H

Table 2 Condition of corrosion test

Medium in the vessel	Strong alkaline water (pH 12.5)
Ambient conditions	Room temp.: $20 \pm 1^\circ\text{C}$, Humidity: 60%
Period	Two months

Table 3 Results of the proof test for two month in alkaline water with pH12.5

Machine tool structure	S45C	○	Changeless condition	Machine element	Rubber bushing	○	Changeless condition
	SUS304	○	Changeless condition		Exhaust cleaner	×	Corrode and discoloration
	Cast iron	○	Changeless condition		Thinned cylinder	△	Only screw corroded
Work piece	Ti	○	Changeless condition	Machine element	Air chack	○	Changeless condition Same function
	Ti6Al4V	○	Changeless condition		Check valve	△	Only screw corroded
	Inconel 718	○	Changeless condition		Lubricator	○	Changeless condition Same function
	S45C	○	Changeless condition		Regulator	△	Only screw corroded
	Copper	△	Only discoloration		Push-button switch	△	Terminal corroded Screw corroded
	Brass	△	Only discoloration		Command switch	△	Terminal corroded Screw corroded
	Aluminum	×	Corrode		Optoelectronic switch amplifier	△	Terminal corroded Screw corroded
Tool	HSS	○	Changeless condition	Electrical element	Servomotor	△	Only screw corroded
	Carbide	○	Changeless condition		Box terminal	○	Changeless condition
	Cermet	○	Changeless condition		Electromagnetic contactor	×	Electromagnet corroded
	Diamond	○	Changeless condition		Solenoid valve	△	Only discoloration
	CBN	○	Changeless condition		Solenoid valve base	△	Only discoloration
	Ceramic	○	Changeless condition		Flat cable	○	Changeless condition
	DLC	○	Changeless condition		Cable connector	○	Changeless condition
Coating material of tool	Ti AlN	×	Discoloration	Electrical element	Direct acting two port solenoid valve	△	Only screw corroded and discoloration
	TiAlCr	×	Discoloration		Acrylic acid resin	○	Changeless condition
Machine element	V-belt	×	Small crack	Basic material	Vinyl chloride	○	Changeless condition
	Drive belt	○	Changeless condition Same function		Nylon	○	Changeless condition
	Timing belt	○	Changeless condition Same function		Polyurethane	○	Changeless condition
	O-ring	○	Changeless condition Same function		Polycarbonate	○	Changeless condition
	Bearing	○	Changeless condition		Nitrile rubber	○	Changeless condition
	Linear guide	○	Changeless condition Same function		Polyurethane rubber	○	Changeless condition
	Ball screw	○	Changeless condition Same function		Fluoro rubber	○	Changeless condition
	Oil seal	△	Spring corroded		Chloroprene rubber	○	Changeless condition
	Oil pump	×	Terminal corroded No work		Chlorosulfonated Polyethylene rubber,	○	Changeless condition
	Wire hose	○	Changeless condition		Oilproof vinyl mixture	○	Changeless condition
	Excel hose	○	Changeless condition		Urethane elastomer	○	Changeless condition
	Cap connector	△	Only screw corroded	Paint	Lacquer paint	○	Changeless condition
	Tube fitting	○	Changeless condition		Urethane resin paint	○	Changeless condition
	Oil level gauge	○	Changeless condition		Epoxy resin paint	○	Changeless condition

○ : Enable

△ : Only discoloration or only screw corroded

× : Disable

3. マイクロバブルを添加による強アルカリ水の見かけ上の熱伝達率の向上

ここでは、マイクロバブルを添加した強アルカリ水中の冷却特性を簡単な実験によって明らかにする。まず、マイクロバブルの基本特性として、水中に放出したマイクロバブルの水中における寿命を測定した。30 l の水槽に 8 l/min のマイクロバブル（マイクロバブルの粒径分布を図 1 に示す）を 10 分間供給し、白濁した強アルカリ水（pH12.5）が透明になるまでの時間を測定した。その際、同様に強アルカリ水に 10 l/min の気泡（1~2 mm と 3~5 mm）を供給した場合についても測定を行った。その結果、図 2 に示すとおり、マイクロバブルは強アルカリ水中で 5 分間程度保持されており、容器内の強アルカリ水にマイクロバブルを供給した後、各種工作機械に配管を通して搬送し、加工時の強制冷却に利用することが可能であることが明らかになった。しかし、1~2 mm もしくは 3~5 mm 程度のサイズの気泡になるとその形体は強アルカリ水中で数秒しか保持されず、1 台の工作機械において加工点まで数 mm の気泡入りの強アルカリ水を供給することは困難であると考えられる。

マイクロバブルを供給した強アルカリ水の強制冷却能力を把握するために、見かけ上の熱伝達率を測定した。図 3 に示すようなラバーヒータ（100×100×2mm）を 2 枚の鋼（SPCC, 100×100×1mm）で両側から挟み、それを強アルカリ水の入っている容器（L 1190×W 980×H 790 mm に卓上旋盤を浸漬させたときの水面高さを再現するために高さ 430 mm まで注入）の中央に宙づり状態で配置した。図 3 には示していないが、実験は図 6 に示す卓上旋盤を設置した状態で、主軸回転による対流の影響が上記センサーの両面に同等に作用するように、主軸と直角（X-Y 平面）の状態を設置した。ラバーヒータに電源を入れ（50W）、鋼表面に貼った熱電対の温度が定常状態になった段階で、鋼表面温度と水槽の平均水温から見かけ上の熱伝達率を測定した。実験は、強アルカリ水の自然

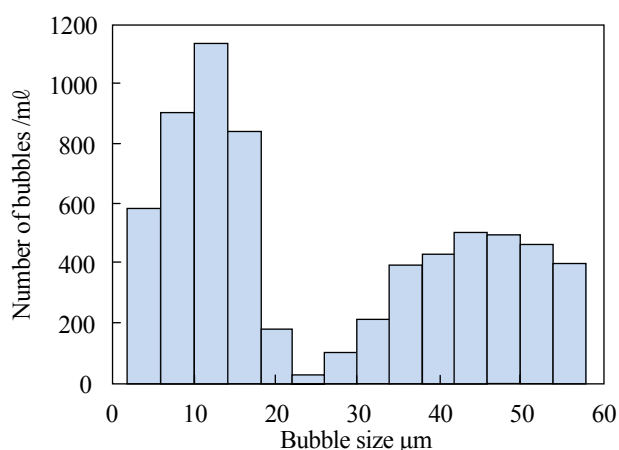


Fig. 1 Bubble size distribution of micro bubble ⁽¹⁰⁾

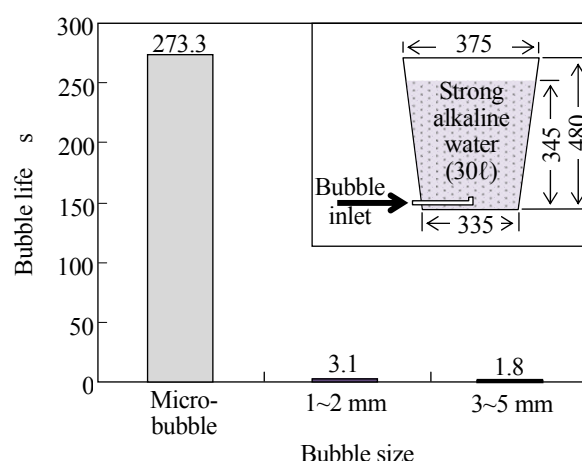


Fig. 2 Relation between bubble size and its life in strong alkaline water

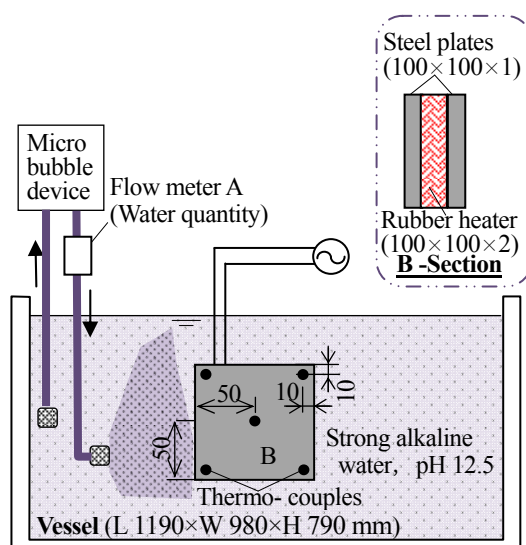


Fig.3 Experimental set-up for measuring heat transfer coefficient of alkaline water with bubbles

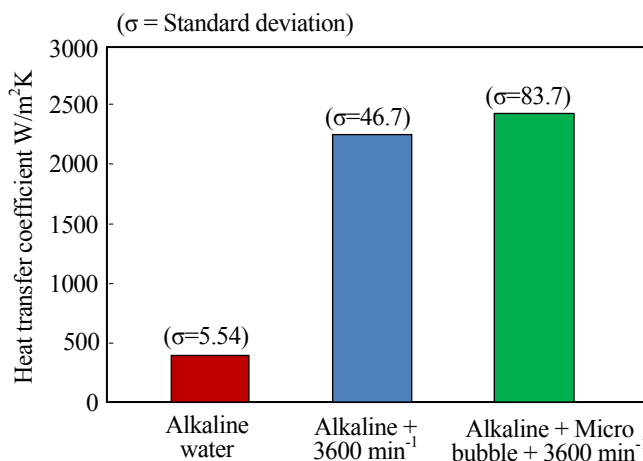


Fig. 4 Relationship between alkaline, micro bubble and 3600 min⁻¹ with the heat transfer coefficient

対流状態, 卓上旋盤の主軸回転 (3600min^{-1}) の追加, さらに卓上旋盤の主軸回転 (3600min^{-1}) にマイクロバブル供給 (8 l/min) の追加をパラメータとした.

図4に見かけ上の熱伝達率の測定結果を示す. 強アルカリ水の自然対流中に比べ, 主軸回転による対流の影響で5.5倍に, さらにマイクロバブルを追加すると6倍に熱伝達率が向上した. この結果より, 主軸回転による強制対流の効果が支配的であり, マイクロバブルを添加したときの熱伝達率の改善効果は8.5%程度 ($=2550/2350$, 10%弱) であった.

4. Soaking 卓上旋盤の熱変形特性と浸漬状態の加工特性

4・1 熱変形特性

表4のような仕様の卓上旋盤 (自作) を用い, それを図5の写真のようにマイクロバブルを添加した強アルカ

Table 4 Specification of the bench lathe in the experiment

Head stock	Height of center from bed	177 mm
	Height of center from floor	337 mm
	Spindle speed	Max. 3600 min^{-1}
Bed	Size (W×L×H)	$600\times 360\times 660$
Tool post	Stroke of Y axis	30 mm
Table	Stroke of Z axis	200 mm
Motor	Power	0.75 kW
	Speed control	Inverter
Mass		200 kg

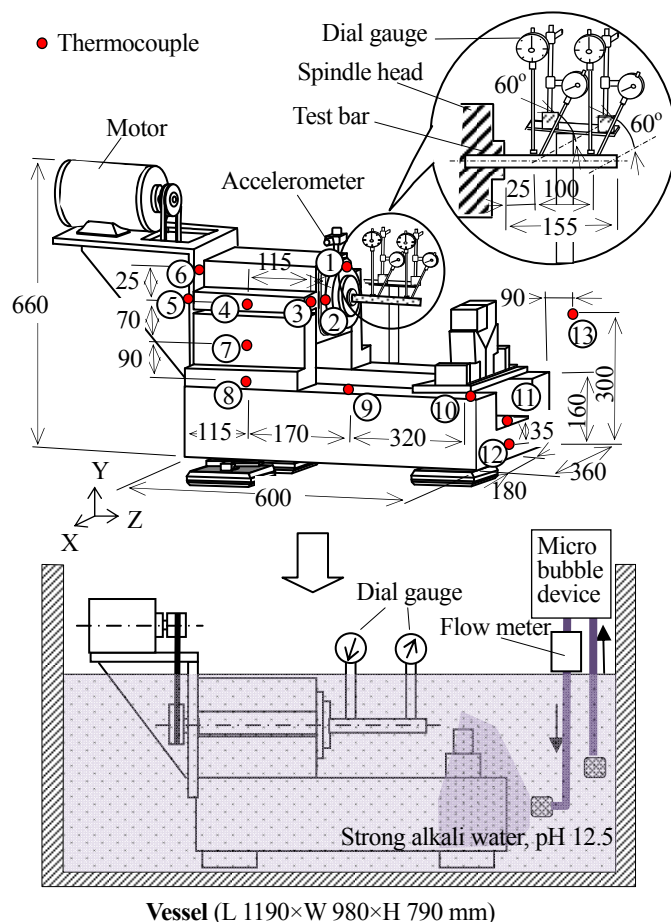
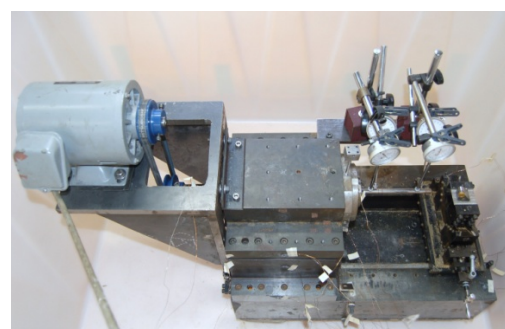
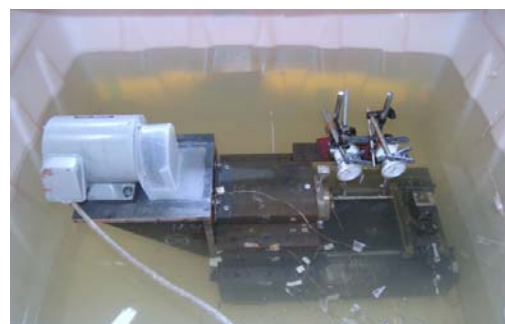


Fig. 6 Schematic view of the experiment using the bench lathe in strong alkali water with micro bubble



(a) Without strong alkali water



(b) With strong alkali water

Fig. 5 Photograph of the experimental set-up

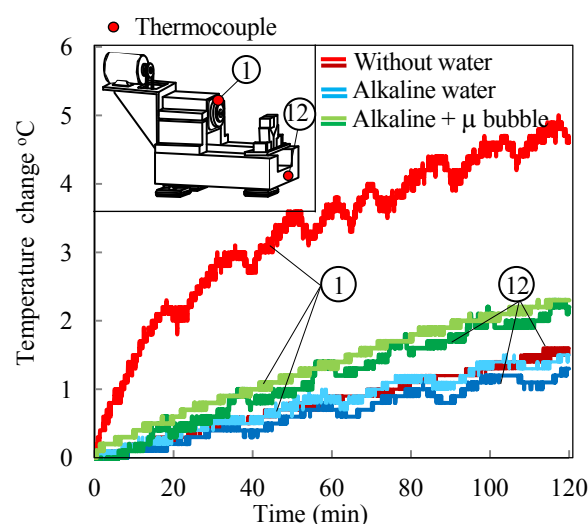


Fig. 7 Temperature change of the bench lathe in strong alkali water with micro bubble operated in 3600 min^{-1}

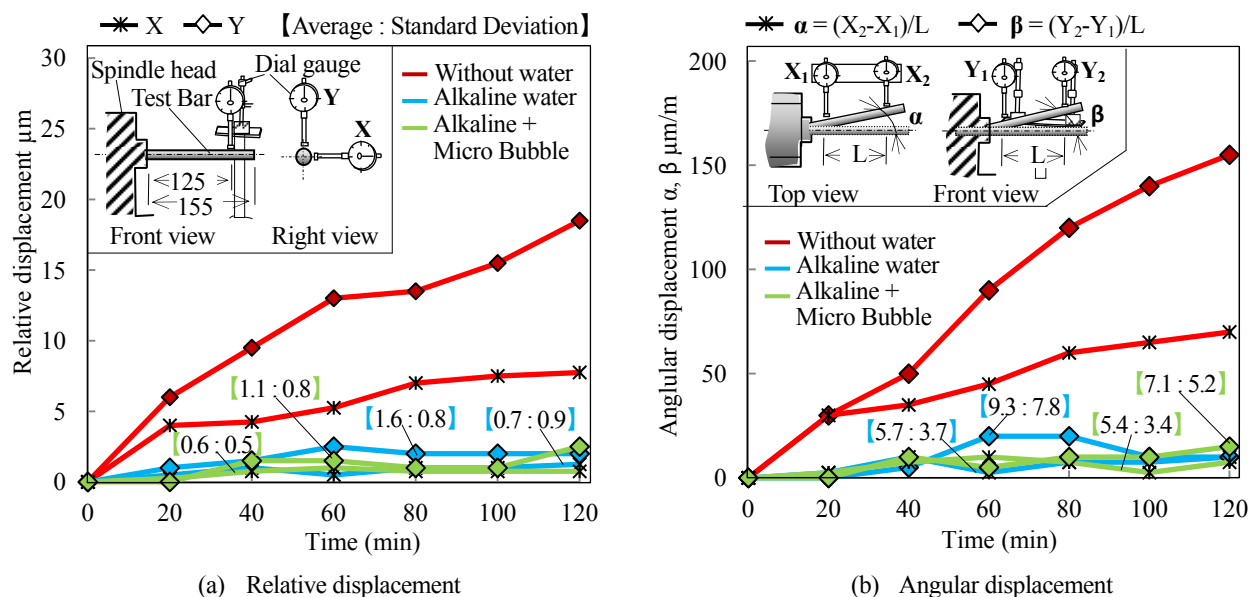


Fig. 8 Thermal deformation of the bench lathe in strong alkali water with micro bubble

リ水を入れた水槽中にモータ部のみを除いて浸漬状態にして、そのときの熱変形特性を実験で調べた。

図6に実験の概略を示す。L 1190×W 980×H 790 mm の容器内に卓上旋盤を搭載し、pH12.5の強アルカリ水 475 ℓを入れ、8 ℓ/minのマイクロバブルを連続的に供給し、アイドリング状態のまま主軸回転数 3600 min⁻¹で連続的に主軸を回転させ、テストバーのX、Y方向各2箇所(図中●印)の熱変形をダイヤルゲージで測定し、図中●印に取付けたT型熱電対で機械構造の温度を測定した。測定は2時間行った。また、比較のために強アルカリ水を注入しない場合、強アルカリ水を注入しマイクロバブルを供給しない場合についても実験を行った。

図7に工作機械(主軸端面①とベッドの端⑫)の温度上昇の測定結果を示す。加工精度に大きく影響する工作機械各部の温度上昇(定常状態の最大値(主軸軸端面①))が、乾式で5.0℃、主軸回転のみで1.4℃、さらにマイクロバブルを添加した強アルカリ水では2.2℃以内に抑制されており、この強制冷却効果によって熱変形がきわめて効果的に抑制できると考えられる。主軸回転のみの場合の温度上昇は主軸軸受の発熱が、また、マイクロバブルを添加した場合は主軸軸受とマイクロバブル発生装置の発熱がそれぞれ影響したものと考える。この2つの場合には機械構造内の温度分布がきわめて小さいと考えられる。

図8にテストバー先端の相対変位(X、Y方向)と相対的傾きの経時変化を示す。乾式では、相対変位が $\Delta X = 7.8 \mu\text{m}$ 、 $\Delta Y = 18.5 \mu\text{m}$ 、相対的傾きが $\alpha = 70 \mu\text{m/m}$ 、 $\beta = 155 \mu\text{m/m}$ に対して、主軸回転やマイクロバブルを添加した場合には、相対変位が2.5 μm 以下、相対的傾きが20 $\mu\text{m/m}$ 以下と熱変形が抑制されていた。主軸回転やマイクロバブルを添加した場合には、図中に20～120分の間の各6データの平均値と標準偏差が示されているが、主軸回転による対流の効果は大きく($\Delta X : 0.7 \mu\text{m}$ 、 $\Delta Y : 1.6 \mu\text{m}$ 、 $\alpha : 5.7 \mu\text{m/m}$ 、 $\beta : 9.3 \mu\text{m/m}$)、マイクロバブルの効果は多少($\Delta X : 0.7 \mu\text{m} \Rightarrow 0.6 \mu\text{m}$ 、 $\Delta Y : 1.6 \mu\text{m} \Rightarrow 1.1 \mu\text{m}$ 、 $\alpha : 5.7 \mu\text{m/m} \Rightarrow 5.4 \mu\text{m/m}$ 、 $\beta : 9.3 \mu\text{m/m} \Rightarrow 7.1 \mu\text{m/m}$)伺える。このように、卓上旋盤を強アルカリ水槽に浸漬状態にすることによって、機械構造の熱変形を効果的に抑制でき、機械の高精度な稼働を安定的に行うことができた。

なお、同様の実験を主軸回転数 996 min⁻¹と 3000 min⁻¹で行ったが、3600 min⁻¹の場合と定性的に同様の実験結果を得た。

4・2 浸漬状態の加工特性

これまで使用した卓上旋盤はZ方向の送りが手動のみであるため、加工後の表面粗さの測定結果に人的誤差が入る恐れがあるため、ここでは、図9に示すようにマシニングセンタを用い、加工関連付近のみを水槽で囲い、その中で強アルカリ水中切削を行った。そのため、卓上旋盤で強制対流源でもあり発熱源でもあった主軸の浸漬の影響因子が除外されことになり、これらの影響が、工具温度、工具寿命、工作物表面粗さの測定結果から除外

されている。ここでは、スローチップタイプのバイトを使用して表 5 に示す切削条件で加工したときの工具寿命、加工精度（表面粗さ）を測定し、本手法がどの程度の加工特性に効果を示すかを評価した。表 5 の加工条件は S45C 程度の鋼の中仕上げ切削の際によく使用されている加工条件であり、従来のドライ切削や湿式切削で工作物 Ti6Al4V を切削する場合は、工具にとって熱負荷が大き過ぎて不向きな条件である。パラメータとして、ドライ切削、一般的な湿式切削、マイクロバブルを添加した強アルカリ水中での切削の 3 種類の実験をした。工具寿命試験では逃げ面摩耗量が 0.3 mm になったときに寿命と判定した。また、表面粗さは寿命試験開始直後の切削面と寿命に至った際の切削面の 2 種類について、切削方向に対して直角に測定した。

図 10 にバイト先端温度の最大値の比較を示す。図 9 に示すように、バイトをバイスに固定し、工作物を回転させて切削を行い、バイト表面に取り付けた熱電対で温度測定を行い、FEM 解析によってバイト先端温度を外挿した。強アルカリ水中で切削した場合、ドライ切削に比べて 48% にバイト先端温度が低減していた。さらに、マイクロバブルを 8 l/min 混入した強アルカリ水中で切削した場合は、ドライ切削に比べて 39 % にバイト先端温度 (727℃) が低減していた。使用した超硬バイトの適正使用温度は 800℃ であり、本システムは実用的に使用できると考える。

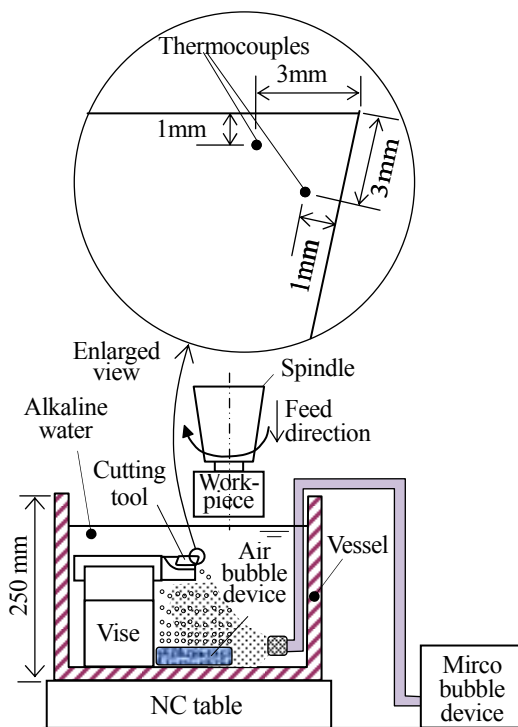


Fig. 9 Experimental set-up for measurement of tool temperature

Table 5 Cutting conditions

Cutting conditions		
Cutting speed 80 m/min	Feed speed 0.25 mm/rev	Depth of cut 0.4 mm
Work piece		
Material : Ti6Al4V	Specific cutting force : 3178 N/mm ²	
Tool		
Rake angle: 5°		Coated carbide

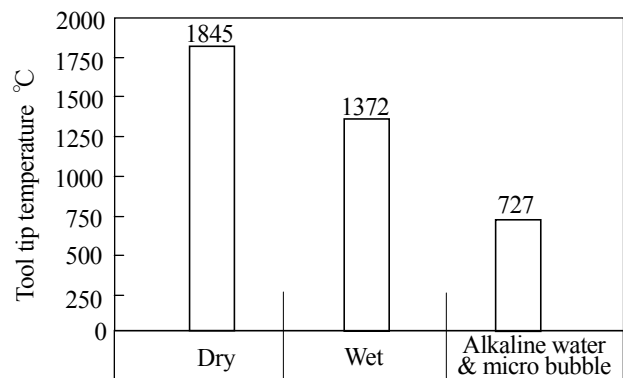


Fig. 10 Experimental results for tool tip temperature

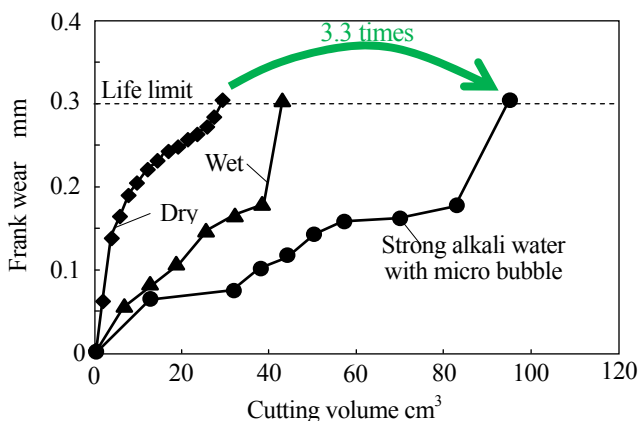


Fig. 11 Results of tool life test

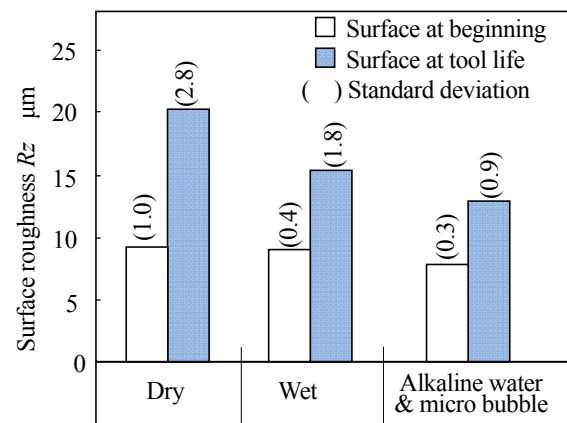


Fig. 12 Results of surface roughness

図 11 に工具寿命試験結果を示す。マイクロバブルを加えた強アルカリ水中切削の寿命は、ドライ切削に比べて工具寿命が 3.3 倍程度伸びている。また、湿式切削に比べて工具寿命が 2 倍程度伸びている。これは、マイクロバブルを含む強アルカリ水中切削が、難削材切削時に発生する熱を効率よく除去することができたためと考えられる。これは、本手法の強アルカリ水中切削を使用することによって、S45C 程度の中仕上げ切削条件が Ti6Al4V のような難削材の切削に対しても十分に対応可能な加工条件になったことを示しており、本システムは有効であったと考えられる。なお、工具顕微鏡を用いた観察の結果、チップ先端孔付近での割れやクラックの発生は観察されなかった。

図 12 に表面粗さ（最大高さ） R_z の測定結果を示す。強アルカリ水中切削した場合は、表面粗さ R_z がドライ切削や一般的な湿式切削のそれに比べてそれぞれ 70 %，89 %となっている。これは、本システムの冷却効果で工具温度上昇が抑制されたことにより、工具の熱変形が抑制されたのみではなく、工具の硬度の低下も抑制され工具剛性も維持されたことにより、工具先端位置の変動が抑制されたためと考えられる。

5. 環境保全特性と加工コストの簡単な考察

最後に、排出 CO₂ 量を検討することによって本手法の環境負荷に対する簡単な評価を行った。ここでは、基本的には使用したすべての装置・機器・工作機械の消費電力量を、電力会社が供給するために発電で排出してしまう CO₂ 量に換算して比較するが、さらに稼働中に消費した切削油剤の廃油処理によって排出される CO₂ 量もそこに加算して、従来の湿式切削の場合と本手法を適用した場合の排出 CO₂ 量を比較する。従来の方法では、稼働時における工作機械、オイルポンプ、冷凍機の各消費電力量と、廃油処理時の排出 CO₂ 量から合計排出量を算出した。また、本手法の場合はマイクロバブル発生装置、強アルカリ水生成装置、切屑除去用ポンプ稼働時の消費電力量をもとに排出 CO₂ 量を算出した。

表 6 に従来の湿式切削の排出 CO₂ 量の計算結果を示す。まず、従来の方法では、マシニングセンタ (3.6 kW)，オイルポンプ (1.2 kW)，冷凍機 (2.2 kW) の合計 7.0 kW の電力で、1 日 8 時間、1 年 250 日稼働させた場合を想定した。この場合算出される消費電力量は 14000 kWh (7.0 kW×8 h×250 days) となり、排出 CO₂ 量への換算係数

Table 6 CO₂ emission of conventional wet cutting

Machining center, Oil pump & Cooling unit			Waste oil disposal	
Power consumption	kW	7.0	Cutting oil amount	ℓ/year
Use condition	/year	8 h × 250 days	Refill oil amount	ℓ/year
Consumption electric quantity	kWh	14000		
CO ₂ emission	kg-CO ₂ /year	6552	CO ₂ emission	kg-CO ₂ /year
Total CO ₂ emission	kg-CO ₂ /year	9498		

Table 7 CO₂ emission of cutting in strong alkaline water

Calculation factors	Machining center	Micro bubble device	Pump for removing chip	Strong alkaline water generating unit
Power consumption	kW	3.6	0.56	0.0132
Electric quantity for strong alkaline water	kWh / ℓ			
Amount of strong alkaline water	ℓ	-	-	-
Use condition	/year	8 h × 250 days	8 h × 250 days	8 h × 250 days
Consumption electric quantity	kWh	7200	1120	26.4
CO ₂ emission	kg-CO ₂ /year	3370	524	12
Total CO ₂ emission	kg-CO ₂ /year	4822		

を 0.468 kg-CO₂/kWh とすると、推定される排出 CO₂ 量 CL_{CO_2} (kg-CO₂) は式(1)から求めることができる⁽¹¹⁾。

$$CL_{CO_2} = 0.468 \times W_E \quad (1)$$

ここで、 W_E は消費電力量 (kWh) であり、各装置で発生する消費電力量とする。これよりマシニングセンタ、オイルポンプ、冷凍機の稼働による排出 CO₂ 量は 6552 kg-CO₂ となる。

次に、廃油処理時の排出 CO₂ 量を計算した。ここではオイルタンク容量 340 ℓ を 1 年間で 2 回交換するとし、また 1 カ月に 1 回 30 ℓ を追加するとして 360 ℓ (30 ℓ × 12 month)、合計 1040 ℓ を処理する場合を想定した。推定される排出 CO₂ 量は式(2)から求めることができる^{(12),(13)}。

$$CO_2 \text{ 排出量 kg-CO}_2 = \text{廃油量 kℓ} \times \text{発熱量 GJ/kℓ} \times \text{炭素排出量 t-C/TJ} \times (44 \div 12) \quad (2)$$

ここで発熱量は 40.2 GJ / kℓ、炭素排出量は 19.22 t-C / TJ である^{(13),(14)}。式(2)を用いて廃油処理時の排出 CO₂ 量を求めると 2946.3 kg-CO₂ となる。以上より湿式切削による排出 CO₂ 量は合計 9498.3 kg-CO₂ となる。

表 7 に本手法を適用した場合の排出 CO₂ 量を示す。まず、本報の前半で使用した卓上旋盤ではなく、後半で使用したマシニングセンタを使用した場合について検討した。主電力 3.6 kW のマシニングセンタを 1 日 8 時間、1 年のうち 250 日稼働させた場合を想定した。この場合算出される消費電力量は 7200 kWh (3.6 kW × 8 h × 250 days) となり、排出 CO₂ 量への換算係数 0.468 kg -CO₂/kWh⁽¹¹⁾を用いて、式(1)と同様にして排出 CO₂ 量を求めると 3370 kg-CO₂ となる。同様にしてマイクロバブル発生装置、切屑除去用ポンプの排出 CO₂ 量を求めるとそれぞれ 524 kg-CO₂、12 kg-CO₂ となる。さらに、強アルカリ水生成装置による排出 CO₂ 量を検討する。強アルカリ水の容量は 26094 ℓ は、マシニングセンタの全容積 27000 ℓ (=W3000 mm × D3000 mm × H3000 mm × 10⁻⁶) から全機械部品の体積分 1026 ℓ (=機械全質量 8000 kg ÷ 鋼の密度 7800 kg/m³ × 10³) を引いた値 25974 ℓ を想定し、さらに、年間の強アルカリ水の補充量 120 ℓ (=10 ℓ / 月 × 12 カ月) を加算した値である。使用したアルカリ水生成装置は、電力 0.75 kW を使用し、1 時間で 10 ℓ の pH12.5 の強アルカリ水を生成することができるため、1 ℓ 当たりの強アルカリ水を生成するための消費電力量は 0.075 kWh / ℓ (0.75 kW × 1 h ÷ 10 ℓ) となる。使用したマシニングセンタを 1 年間 pH12.5 の強アルカリ水中に浸漬させるために必要な消費電力量は 1957 kWh となり、式(1)と同様に排出 CO₂ 量を求めると 916 kg-CO₂ となる。よって本手法適用後の排出 CO₂ 量は合計 4822 kg-CO₂ となる。

図 13 に排出 CO₂ 量の比較を示す。排出 CO₂ 量は今回の条件において 1 年間稼働した場合、4678 kg-CO₂ の削減効果 (49.2%削減) が得られることがわかる。これは、加工中に切削油剤を使用しないため、廃油処理で生じる CO₂ を削減できるためである。このように、本手法は切削発熱除去のための切削油剤を使用せず、また、加工精

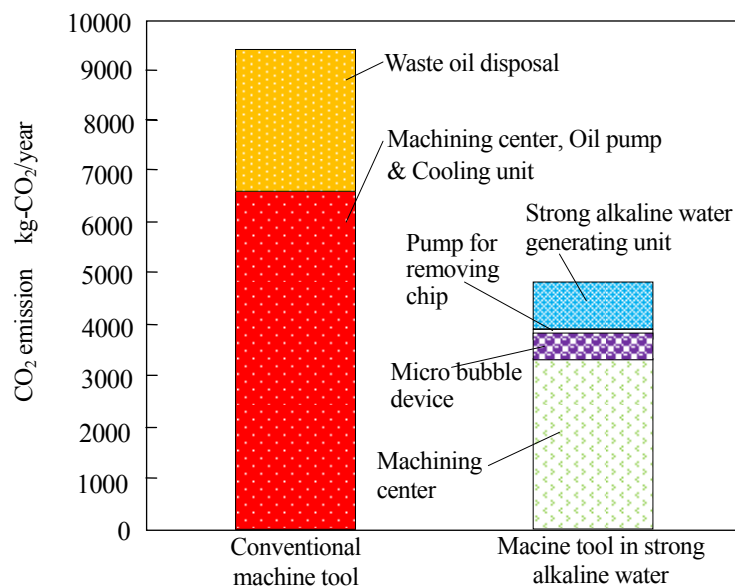


Fig. 13 Comparison of CO₂ emission

度維持のための冷凍機による強制冷却も使用することなく、さらに、加工後の洗浄も不要なため、環境負荷の低減に有効でありエコロジーであり、工業的にきわめて有効であると考ええる。

6. 結 言

本研究の結果をまとめると以下のとおりである。

- (1) 強アルカリ水中の熱伝達率が $400 \text{ W/m}^2\text{K}$, 3600min^{-1} で主軸回転を加えると熱伝達率が $2350 \text{ W/m}^2\text{K}$, さらにマイクロバブルを添加すると熱伝達率が $2550\text{W/m}^2\text{K}$ と大きくなり、冷却効率が向上した。
- (2) 強アルカリ水中に卓上旋盤を浸漬させることによって、乾式に比べて温度上昇が $1/2$, 相対的変位が $1/10$, 相対的傾きが $1/12$ にそれぞれ向上した。また、加工領域のみを強アルカリ水中に浸漬させることによって、工具寿命が 3.3 倍、表面粗さが $2/3$ にそれぞれ向上した。なお、工具寿命と表面粗さに関しては、強制対流源・発熱源でもあった主軸台は浸漬されておらず、その影響が除外されている。
- (3) マイクロバブルを添加した強アルカリ水中に工作機械を浸漬させることによって、切削油剤や冷凍機が不要となり、従来の工作機械に比べて年間の CO₂ 排出量を半部以下にすることができ、環境保全の効果があつた。

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6 章 強アルカリ水を使用した加工の環境インパクト

本章では，高精度なものづくりのために強アルカリ水を使用したことによる環境保全の効果を簡単な LCA によって明らかにする．

英論文中の本文では，この「強アルカリ水を使用した加工の環境インパクト」に関して 6 章で記述しているが，この付録 I では，3 章 工作機械の共振周波数を変更する技術の開発，4 章 マイクロバブルを混入した強アルカリ水を用いたドリル加工技術，5 章 CO₂ 削減のために強アルカリ水中に工作機械を浸漬する技術の開発の 3 つの章の後半に記述しているので，この章では省略する．

7 章 結 論

本研究では，加工に水を使用する技術を開発，評価した．ポリマ PEO を混入した水による工作機械の共振周波数の管理，マイクロバブルを混入した強アルカリ水を用いたドリル加工の強制冷却，工作機械を強アルカリ水中に完全浸漬させた加工方法を開発，評価した．

3 章 最適加工条件を維持するために，水を利用して共振周波数を制御する技術を開発した．機械の見かけ上の密度と見かけ上の剛性をコントロールした．これらの制御のためのパラメータは多数あるので，まず，CAE シミュレーションを使用し，それぞれの制御因子の中から最適対策のための制御因子を決定した．CAE シミュレーションの結果をもとに 3 つの対策の最適な組合せに関して実験によって評価した．提案した制御方法を使用して，工作機械の共振周波数は意図したようにシフトし，共振現象を避けることができた．それらの結論をまとめると以下のとおりである．

- (1) 工作機械の共振周波数を制御する手法が，機械の見かけ上の密度と見かけ上の剛性を変化させることを使用して，開発された．
- (2) 機械構造に 6wt% のポリマを混入した水を注入することによって，共振周波数を下げることが可能となり，しかも同時に振動高減衰化をすることも可能となった．
- (3) この手法を採用した実加工において，共振現象は完全に回避でき，最終加工時の表面粗さも改善された．

4 章 この章では，加工時の工具の熱影響を引き下げるために，強アルカリ水を使用した強制冷却技術が開発した．水を使用した場合，多く

の金属が腐食するため、その対策として強アルカリ水を使用し、加工現場に存在する金属の強アルカリ水中における耐食性試験を2か月間行った。また、強アルカリ水の pH の経時的変化を、水温をパラメータにして測定した。冷却効果を上げるために強アルカリ水にマイクロバブルを混入した。スルーホール付きドリルを使用してドリル加工実験が行われた。工具寿命と加工部の表面粗さ測定をして、本手法の評価をした。それらの結論をまとめると以下のとおりである。

- (1) 強アルカリ水にマイクロバブルを混入することによって、強制冷却能力が向上し、加工時の高熱伝達率 $2500\text{W/m}^2\text{K}$ を得た。
- (2) スルーホール付きドリルに、マイクロバブルを混入した強アルカリ水を供給したところ、工具先端の温度を 70% まで引き下げることができ、工作物の表面粗さは 30% に改善され、工具寿命は乾式の場合の 6.5 倍伸びた。
- (3) 強アルカリ水は、アルミニウム、銅、それらの合金を除く、金属を腐食することはない。

5 章 この章では、工作機械、加工システム、工具、工作物を完全に強アルカリ水内に浸漬させ、機械と加工領域の全域において、水の気化熱冷却による強制冷却を行った。さらに、加工熱の影響を効率よく引き下げるために、エアバブルとマイクロバブルを強アルカリ水に混入した。いくつかの金属の強アルカリ水に対する耐食性は 4 章で記述したとおりであり、ここではさまざまな工作機械部品、機械要素に関して耐食性を調査した。強アルカリ水に完全浸漬させた工作機械の評価として、熱変形と振動状況を測定した。さらに、工具寿命と工作物の表面粗さも実験で評価した。それらの結論をまとめると以下のとおりである。

- (1) 強アルカリ水を使用することによって、熱伝達率を $2350\text{ W/m}^2\text{K}$ に改善することができた。さらに、強アルカリ水にマイクロバブ

ルを混入することによって、熱伝達率 2550W/m²K まで向上させることができた。

(2) 強アルカリ水中に工作機械を完全浸漬することによって、工具先端の温度を 60%に引き下げることができ、工作機械の相対変位を 89%引き下げ、相対的傾きを 86%引き下げ、工具寿命を 3.6 倍に向上させ、工作物の表面粗さを乾式切削に比して 2/3 に改善できた。

(3) 強アルカリ水は、アルミニウム、銅、それらの合金を除く、金属を腐食することはない。

6 章 この章では、強アルカリ水を使用した場合の環境と作業員に対するインパクトを評価した。フライス加工、ドリル加工、旋削加工の 3 つの加工がアセスメントのために使用された。加工の際に使用する電気エネルギー使用と切削油剤や潤滑油などの油使用による排気 CO₂ をそれぞれ計算し、評価に使用した。さらに、強アルカリ水を強制冷却に使用した機械加工の効果を示し、従来の湿式加工と比較した。さらに、作業者の健康に対する評価も行った。それらの結論をまとめると以下のとおりである。

(1) 使用した強アルカリ水は環境と作業者に害を与えることはなかった。ただし、注意事項として肌への直接接触はさせるべきである。

(2) 強アルカリ水の使用は、地球温暖化のインパクトを 48%引き下げることができる。

(3) 強アルカリ水利用は、環境にやさしい加工を可能にできる。

このように、加工の際に水を使用することにはまだ制約が多々あったが、環境保全に配慮しながら、水を使用した高効率な生産のための研究を行った。まず、3 章では、工作機械の共振周波数制御技術が最適加工条件を維持するために開発された。この研究で、水は極めて容易で有用な制御媒体として有効利用された。さらに、振動を効率よく減衰させるために、水にポリマ PEO が混入された。それによって、極めて効率よく共振周波数を制御する手法を明らかにできた。加工条件を変えることなく共振現象を回避することはいままで困難であったが、提案した共振周波数制御方法では加工条件を変える必要はない。だから、加工精度や加工品位が低下することはない。また、最適加工条件を維持し続けることができるため、研削のようなきれいは表面加工が可能となり、加工プロセス数や加工コストをそれぞれ低減させることができる。4 章では、強アルカリ水を使用した新しい強制冷却方法を提案した。一般的な水では加工時に制限があるが、マイクロバブルを混入した強アルカリ水はそれらの制限がない。それは、アルミニウム、銅、それらの合金を除いて、その他の金属が強アルカリ水に対して耐食性があるためである。強アルカリ水にマイクロバブルを混入すると、その気化熱冷却効果が増大し、きわめて大きな冷却効果が得られる。この提案した手法を評価したところ、工具先端の大きな熱影響を引き下げることができ、加工精度が改善でき、表面粗さも改善された。5 章では、工作機械を強アルカリ水中に完全浸漬させた。ここでも、強アルカリ水の気化熱冷却効果が工具の熱影響を引き下げるために使用された。工作機械の熱変形と振動が測定された。難削材の加工に本手法を適用した。工作機械の熱変形は低減でき、工具寿命と表面粗さが改善できた。最後に、6 章では、環境と作業者に対して、加工で強アルカリ水を使用した場合のインパクトを調査した。加工の際に使用する電気エネルギー使用と切削油剤や潤滑油などの油使用による排気 CO₂ を評価に使用し、地球温暖化のインパクトを 48%引き

下げることができたことを確認した。さらに，強アルカリ水は 99%が水で構成されており，作業者の健康に対する安全性も確認した。

本研究「環境保全のために水を使用した高効率なものづくりに関する研究」で提案した各項目は，工業的に有効に利用可能であると考える。

Appendix II

(DISSERTATION IN TETUM VERSION)

Estudu Ba Akurasun Neebe Boot No Makinazen Neebe Eficiente Utiliza Bé Ho Kompostu Hodi Konserva Ambiente

Dizertasaun Doutoramentu nian

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KONTIÚDU

Kapítulu (1): INTRODUSAUN	A2-6
1.1 Importansia konservasaun ba iha ambiente.....	A2-6
1.2 Utilizasaun bé nian iha fabrikasaun.....	A2-7
1.3 Efeitu husi bé ba iha kualidale makinazen	A2-9
1.4 Metodu konvensionais hodi uza bé iha makinazen	A2-10
1.5 Objetivu husi estudu no kompozisaun teze nian.....	A2-12
Referênsia.....	A2-17
Kapítulu (2): PROPRIEDADES BÉ NIAN.....	A2-19
2.1 Propriedades jerál bé nian	A2-19
2.2 Propriedades bé nian neebe iha relasaun ba aplikasaun iha industria sira	A2-20
2.2.1 Agente de limpeza.....	A2-20
2.2.2 Calor espesífiku bé nian.....	A2-23
2.2.3 Resfriamentu evaporativu neebe aas.....	A2-24
2.2.4 Densidade.....	A2-24
2.2.5 Indúz korosaun.....	A2-25
2.3 Bé alkalina ba refrigerante.....	A2-27
2.4 Prosesu produsaun bé alkalina nian	A2-29
Referênsia.....	A2-30
Kapítulu (3): DEZEMVOLVEMENTU TÉKNIKU KONTROLU BA FREKUÊNSIA RESONÂNSIA IHA MÁKINA PRODUSAUN ATU ESTABELEZE KONDISAUN KOA NIAN NEEBE ÓTIMU.....	A2-34
3.1 Introdusaun	A2-34
3.1.1 Efeitu husi resonansia mákina nian ba iha prosesu koa nian	A2-36
3.1.2 Kontramedida konvensionais nian hodi prevene resonansia iha mákina produsaun.....	A2-37
3.1.3 Metodu kontrolu atu kontrola densidade, rigidez no posisaun suporta nian.....	A2-39
3.1.4 Metodu proposta hodi kontrola frekuensia resonansia	A2-40
3.2 Investigasaun uza CAE simulasaun ba fatór kontrolu sira (densidade, rigidez and suporta)	A2-45
3.2.1 Enxe bé atu hatun resonansia nia frekuensia	A2-47

3.2.2 Hamenus todan (densidade kiik) no reinforsa estrutura (rigidez a'as) hodi hasae frekuensia resonansia	A2-53
3.2.3 Muda suporta nia posisaun atu muda resonansia nia frekuensia	A2-59
3.3 Evaluasaun ho experimentasaun ba metodu kontrolu usa mákina torno de bancada.....	A2-61
3.3.1 Evaluasaun experimental ba metodu kontrolu uza mákina tornu.....	A2-63
3.3.1.1 Fatór kontrolu I.....	A2-63
3.3.1.2 Fatór kontrolu II	A2-66
3.3.1.3 Fatór kontrolu III.....	A2-69
3.3.2 Kombinasau neebe ótimu ba kontramedida tolu fátor kontrolu nian.....	A2-72
3.4 Evaluasaun koa nian	A2-74
3.5 Rezumu	A2-78
Referênsia.....	A2-79
Kapítulu (4): DEZENVOLVEMENTU TEKNOLOJIA RESFRIAMENTU FORSADU NIAN HODI BÉ ALKALINA NEEBE FORTE HO MICRO-BOLHAS IHA PERFURASAUN.....	
4.1 Introduction.....	A2-81
4.2 Espesifikasaun husi bé alkalina neebe forte ho micro-bolha	A2-82
4.2.1 Espesifikasaun husi bé alkalina	A2-82
4.2.2 Espesifikasaun husi micro-bolha.....	A2-86
4.3. Prosesu perfurasaun ho bé alkalina neebe forte kahur micro-bolha uza <i>through-hole</i> broca.....	A2-93
4.3.1 Broca nia temperatura	A2-93
4.3.2 Rugosidade da superfície (Surface roughness).....	A2-96
4.3.3 Vida broca nian	A2-100
4.4. Rezumu	A2-103
Referênsia.....	A2-104
Kapítulu (5): DESENVOLVEMENTU BA TEKNOLOJIA IMERSAUN MÁKINA PRODUSAUN IHA BÉ ALKALINA NEBE FORTE ATU REDÚS CO ₂	
5.1 Introdusaun	A2-106
5.1.1 Fundo estudu nian	A2-106
5.1.2 Proposta pesquisa nian.....	A2-107

5.2 Resistansia elementus sira mákina nian husi korosaun iha bé alkalina neebe forte	A2-108
5.3 Hasae koefisiente transferência calor nian husi bé alkalina neebe forte kahur ho micro-bolha	A2-115
5.4. Investigasaun ba vibrasaun no deformasaun térmika mákina torno nian no qualidade prosesaun uza metodu immersaun nian.....	A2-119
5.4.1 Investigasaun ba vibrasaun	A2-121
5.4.2 Investigasaun ba mudansa iha temperatura no deformasaun térmika	A2-124
5.4.3 Kualidade makinazen uza metodu imersaun nian	A2-133
5.4.3.1 Evaluasaun ba temperatura iha fermenta nia tutun	A2-134
5.4.3.2 Evaluasaun ba vida fermenta nian	A2-136
5.4.3.3 Evaluasaun ba rugosidade superfície peça nian	A2-137
5.5 Rezumu	A2-139
Referênsia.....	A2-139
Kapítulu (6): IMPAKTU BA AMBIENTE HUSI UTILIZASAUN REFRIGERANTE BÉ ALKALINA IHA MAKINAZEN.....	A2-141
6.1. Introdusaun.....	A2-141
6.2. Metodu estudu nian ba avaliasaun bé alkalina neebe forte	A2-142
6.2.1 Objetivu and eskopu estudu nian	A2-142
6.2.2 Metodu estudu nian.....	A2-143
6.2.3 Aproximasaun kalkulasi nian	A2-144
6.3 Avaliasaun simples ba makinazen uza bé alkalina neebe forte	A2-145
6.3.1 Inventário ba teknolojia koa nian iha bé alkalina neebe forte nia laran kahur micro-bolha.....	A2-145
6.3.2 Inventário ba teknolojia perfurasaun uza bé alkalina neebe forte kahur micro-bolha.....	148
6.3.3 Inventário ba imersaun mákina tornu bankada no halao operasaun iha bé alkalina nia laran atu redús CO ₂	A2-151
6.4 Análize impaktu makinazen uza resfriamentu bé alkalina neebe forte	A2-155
6.4.1 Impaktu ba ambiente.....	A2-155
6.4.2 Impaktu ba ema nia saude.....	A2-159
6.5 Rezumu	A2-161
Referênsia.....	A2-162
Kapítulu (7): KONKLUSAUN	A2-165

Kapítulu (1)

INTRODUSAUN

1.1 Importansia konservasaun ba iha ambiente

Iha tempo agora nian, qualidade fabrikasaun ne'ebe aas asosiadu ho konservasaun ba iha ambiente sai hanesan pedido ida nebe importante ba iha produsaun no fabrikasaun. Ho teknolojia ne'ebe avansadu ba dadaun, permiti ema atu dirigi operasaun ruma efisiente liu iha tempo agora nian kompara ba tempo uluk. Tan nee, konsiderasaun ba konservasaun meio ambiente sai hanesan fatór ida nebe importante tebes ba iha prosesu dezenho no fabrikasaun. Entretantu, prátika industria nian ba operasaun neebe seguru no mos konservasaun ba iha ambiente evolve makaas ona iha dekada ikus-ikus nee. Fonte barak energia nian mak deskobre tiha ona ^{[1-1], [1-2]}, makina barak ho presisaun neebe ótimu mak konstrui tiha ona ^{[1-3], [1-4]}, no mos produktu sira ho qualidade nebe aas prodúz tiha ona atu fó satisfasaun ba kosumedores sira. Maske nunee, pesqizadores sira tenke konsidera hotu hodi fó priorizasaun ba iha problema ambiente nian durante halo produsaun ou desenvolve makina ruma, metodu makinasaun nian, equipamentu makina nian, no mos produktu foun sira. Ho ida nee, bele hadiak teknolojia sem prejudika ita nia ambiente. No mos, ho presaan husi poluisaun no teknolojia, ambiente biofísiku komesa menus ba dau-daun ho tempo passa. Tanba nee, mosu konsiderasaun ba iha konservasaun ambiete nian atu nunee bele prevene poluisaun no kondisaun neebe prejudika ambiente. Nunee mos, ho *aquecimento global* neebe sai hanesan problema boot iha tinan ikus-ikus nee nia laran, konsiderasaun hodi fó prevensaun no seguransa

ba ambiente sai ona hanesan rekerimentu ida ba engenheiros no peskizadores sira atu kompleta wainhira halo produsaun ou fabrikasaun ba produktu foun.

Aprosimasaun barak mak usa tiha ona iha area oi-oin hodi halo konservasaun ba ambiente. ^{[1-5], [1-6]}. Iha area fabrikasaun no produsaun nian, protesaun ba ambiente bele halao liu husi dalan oi-oin hanesan *clean manufacturing* no *waste management* ou *pollution control* ^{[1-7], [1-8]}. *Clean manufacturing* mak metodu ida neebe atu hamenus, evita, ou halakon utilizasaun ba materiais, foer ou gastus industria nian, poluisaun, no emisaun neebe bele fo perigo ba ambiente no ema nia saude. *Waste management* ou *pollution control* mak proteksaun ba ambiente husi foer ou gastus, poluentes, no emisaun nebe prodús tiha ona husi fabrikasaun. Ho realidade katak bé mak substansia ida neebe fasil liu atu hetan iha rai, tanba nee, metodu *clean manufacturing* no *waste management* ou *pollution control* sei uza hanesan aprosimasaun atu bele alkansa kualidade produsaun neebe aas no mos prevensaun ba ambiente liu husi utilizasaun bé nian iha fabrikasaun.

1.2 Utilizasaun bé nian iha fabrikasaun

Bé mak substansia ida neebe importante liu iha rai tanba nia fó moris. Ita bele hetan bé iha fatin nebe deit no uza nia iha ita nia moris lor-loron nian. Iha area industria ho produsaun nian, bé sai nudar fonte importante ida neebe prontu atu utiliza. Industria neebe prodúz metal, ai, papel, produtos kímikus, gasolinas, olius, no mos produktu sira seluk, hot-hotu utiliza bé iha parte balun durante sira nia prosesu produsaun. Ho razaun ida nee, industria sira depende ba bé hanesan mos setór agrikultura ho uma laran depende ba bé. Industria uza bé kuaze iha nível hot-hotu industia nian. Bé bele uza nudar *agente de limpeza*, *solvente*, *refrigerante*, *agente de transporte*, no mos fonte energia nian. Dala barak, utilizasaun bé iha industriais relationa ba iha fabrikasaun. Tamba prosesu fabrikasaun produz kalór ou manas neebe barak husi friksaun no reasaun

kímiku, bé uza atu bele fó malirin ba ekipamentus no makina sira. Bé uza mos ba lubrifikasaun no limpeza. Dala ruma, bé inklui hotu iha produktu nia laran, hanesan iha produsaun hahan no bebida sira nian. Aplikasaun bé nian iha industia nee barak teb-tebes, tan nee ita sei labele mentiona sira hotu. Maibe, realidade mak produktu ida-idak neebe prodús tiha ona, sempre uza bé iha parte ida durante produsaun. Hó teknolojia neebe avansa ba bei-beik, kompania ho pesqizadores sira komesa realiza katak bé nudar fonte ida neebe importante liu iha setór industria nian. Tan nee, utilizaun bé nian iha setór industria komesa barak ona no sai diak ba bei-beik. Maibe, uza bé diretamente durante makinazen sei bandu iha area balun fabrikasaun nian. Bandu ba uza bé durante makinazen nee tamba bé sai kauza ba feruzu iha *peça* produktu nian.^{[1-9],[1-10]}. Maibe, ho razaun katak bé nudar elementu ida neebe fasil atu hetan, fasil atu transporte iha kuantidade neebe barak, no mos amizável ba meio ambiente, estudu ida nee halai liu ba iha desenvolvimento metodu foun hodi bele uza bé iha makinazen. Metodu no aprosimasaun barak uza bé nudar *refrigerante* hanesan fluidu kúa nian mak desenvolve tiha ona ^{[1-11], [1-12], [1-13]}, maibe, *refrigerante* barak mak inklui ho aditivu hodi bele prevene korosaun no hasae efisiensia *resfriamentu* nian. Tamba aditivu balun ladun diak ba ema nia saude no mos meio ambiente, metodu foun resfriamentu nian uza bé ho pH neebe boot apresenta iha estudu nee. Metodu ida nee bele uza ba hamenus temperatura neebe mosu iha *feramenta* no *peça* durante makinazen. Tamba interasaun entre nivel pH bé nian ho tipo materiais nee oin-oin, inventigasaun neebe klean presiza tebes hodi bele uza bé durante makinazen. Maske nune'e, ita bele espera katak uza bé ho pH neebe aas bele halo efeito *resfriamentu* nian sai diak liu, hamenus kustu prosesaun nian, no iha tempo nebe hanesan halo diak liu tan presisaun kúa nian no hanaruk vida *feramenta* nian. *Além de* nee, ambiente neebe saudável bele preserva, hodi nunee bele hadiak ekosistema, saude no *bem-estar*.

1.3 Efeitu husi bé ba iha kualidale makinazen

Esplika tiha ona iha sesaun uluk katak bé nudar element ida neebe importante no mos uza iha kuaze setór hotu-hotu industriais nian, maibe ema sei evita ninia utilizaun iha makinazen. Ho razaun ida nee, utilizaun bé durante fabrikasaun durante makinazen sei limitadu. Korosaun neebe kauza husi bé afeita produitu sira nia valór. Realidade katak korosaun ne prosesu natural ida, no mos nia akontese iha ambiente neebe bé existi. Hanesan bé suli ba fatin nebe badak, nunee mos prosesu natural hot-hotu nakfilak ba ida-idak nia kondisaun energia neebe kiik liu. Por ezemplo, *ferro* no *aço*, iha tendensia neebe naturais atu koliga ho elementus kímiku seluk hodi nakfilak ba sira nia kondisaun energia neebe kiik liu. Sira sempre koliga ho oxigente no bé, elemntu rua neebe prezente iha kuaze natural ambiente hot-hotu, hodi forma *hydrated iron oxides* neebe provoka feruzu atu mosu. Maske nunee, laós sira deit mak provoka korosaun, fatór sira seluk hanesan temperatura, kontiudu mineral nian wainhira nia dissolve, *calcium hardness*, alkalinidad, no pH bé nian mos sai kauza ida. *Além*, komportamentu korosaun materiais sira nian depende ba ambiente neebe sira iha, no mos korosivu ambiente nian depende ba materiais neebe expostu ba ambiente nee rasik.

Korosaun iha fabriku iha ninia impaktu negativu neebe barak. Wainhira metal ida feruzu, feruzu nee sei afeita ba iha presisaun produitu nian. Nia sei estraga no hatuun produitu nia valór iha merkadu. No mos, korosaun bele sai kauza ba mákina ho ekipamentu sira lakon sira nia pressisaun no effisiensia, failâ derepente deit, no mos redúz iha vida makina nian. Laós nee deit, konsekuensia seluk ba iha ambiente sempre existi. Polusaun rezulta durante feruzu neebe akontose ou husi produitu nee rasik bele aféita ema nia saude no mos integridade ekosistema aquátiku nian. Failansu derepenti husi mákina ou ekipamentu sira bele estraga mákina, hamosu ahi, bomba, no distribui veneno, neebe konsidera la

seguru ba ambiente. Korosaun mos bele afeita aspeitu ekonimiku, neebe bele kauza valór merkadu nian sai kiik.

Iha parte seluk, *além de* desvantajen husi bé nian neebe hamosu korosaun, iha vantajen barak neebe ita bele hetan husi bé se kuando fenómenu korosaun nee ita bele evita. Vantajen sira mak hanesan:

- Efeito resfriamento neebe aas
- Disponibilidade no fasil atu hetan
- Evita residuos no foer
- Kustu neebe kiik
- Fasil atu transpote
- Amizável ba ambiente

Ho vantajen sira nee, peskizadores barak mak komesa konsidera ona atu halao peskiza hodi prevene korosaun neebe kauza husi bé.

1.4 Metodu konvensionais hodi uza bé iha makinazen

To'o ohin lora, utilizaun bé iha makinazen sei uituan, maibe neneik ba neneik komesa atu sai barak. Iha metodu konvensionais balun nebe ema uza ona nudar resfriamentu. Metodu konvensionais sira balun mak hanesan:

[1] Resfriamentu uza refrigerante ho baze husi bé.

[2] Lubrifikasaun

[3] *Agente de limpeza*

Maibe, utilizaun bé nian uza metodu sira nee seidauk kontentável.

Iha faktu [1], maske resfriamentu uza refrigerante ho baze husi bé utiliza barak liu iha kuaze iha produsaun hotu-hotu, aditivu neebe inklui iha refrigerante sai hanesan desvantajen ida. Ho razaun katak aditivu balun dala ruma inklui ho

substansia kímiku sira neebe deskonêsidu, subtansia sira nee bele foo perigu ba ambiente no ema nia saude, nunee konsidera indesejável. ^{[1-14], [1-15]}. Nunee mos, refrigerante ninia presu merkado nian, transpote no mos soe nian aas los kuandu konsidera ba iha ekonomia agora nian. Pior liu tan, tamba refrigerante labele soe iha fatin nar-naran deit, presu soe nian sei bele aumenta aas liu tan. Tanba nee, pedidu atu hadiak kualidade refrigerante nian hodi nunee labele estraga ambiente, aumenta barak liu tan iha tinan ikus-ikus nee. Ho razaun nee, resfriamentu uza refrigerante ho baze husi bé seidauk konsidera óptimu no presiza hadiak liu tan.

Iha faktu [2], utilizasaun bé hanesan lubrifikasaun iha industia no fábriku sei menus ho razaun katak bé evapora lais liu fali oliu ou masa lubrifikante. Tan nee, oliu *miscível* prefere liu ba lubrifikasaun *do que* bé *miscível*. Além de evapora lais liu wainhira nia manas, bé mos provoka feruzu no estraga material metal sira neebe neneik sei kondúz ba possibilidade habadak vida mákina nian. Nunee mos, ninia *fluidez* difikulta nia atu hela metin iha fatin, tan nee presiza reaplika bei-beik. Maibe, konsidera ba problema ambiente nian no mos disponibilidade iha nia fonte, bé prefere liu se kuando fenomena korosaun nee bele prevene tiha. Too ohin loron, pesquizadores balun estuda ona kona ba utilizasaun fluido ho baze bé ba lubrifikasaun ^{[1-16], [1-17]}. Maske nunee, tanba metode sira nee seidauk satisfado, remodelasaun presiza tebes atu bele hadiak kualidade lubrifikasaun, hodi nunee bele prevene korosaun.

Iha faktu [3], *Agente de limpeza* ho baze bé uza barak tiha ona iha industria no fabrikasaun. Ba produktu neebe laós metal, fasil liu hamós uza bé, maibe ba produktu sira neebe metal, bé presiza aumenta ho additive ou solvente ruma atu bele evita korosaun ates uza hodi hamós. ^{[1-18], [1-19]} *Agentes de limpeza* ho baze bé balun uza bé alkaina ho pH 8.5 ba leten atu hamós masa, oliu, no *gorsuras* sira. Balun uza bé kahur additivu nudar refrigerante ba resfriamentu no *agente de limpeza* atu hamós no dudu sés restu kúa nian durante makinazen hanesan iha

prosesu *grinding* nian. Fora husi area fabrikasaun no makinazen nian, aplikasaun bé nian nudar *agente de limpeza* barak tebes kompara ho aplikasaun iha makinazen. Tamba nee, desenvolvimento ba iha utilizaun bé nian iha makinazen importante tebes atu bele hadiak fabrikasaun neebe kuida no amigável ba meio ambiente. Ho faktu sira nee no mos ho konsiderasaun katak aplikasaun bé nian iha makinazen sei menus liu, estudu ida nee halao atu desenvolve no introdúz utilizaun bé nian iha makinazen. Hodi nunee, bele konserva meio ambiente sem degrada qualidade no akurasaun husi rezultadu final produsaun nian.

1.5 Objetivu husi estudu no kompozisaun teze nian

Objetivu husi estudu nee mak atu desenvolve metodu foun uza bé hodi bele hasae efisiensia fabrikasaun nian no iha tempo neebe hanesan bele konserva meio ambiente. Uza bé ba resfriamentu durante makinazen bele aumenta efeitu resfriamentu nian, manas neebe prodús durante makinazen bele minimiza, no mos gastus koa nian bele hamenus. Efeitu resfriamentu neebe boot bele hatun manas iha *feramenta* no *peça* nian neebe bele hadiak rezultadu final koa nian sai kabér liu tan. No mos, redusaun husi lixo makinazen nian bele hamenus kustu soe ou disposisaun nian no redúz poluisaun husi emisaun gás sira neebe perigosu ba meio ambiente no ema nia saude. Aumenta liu tan, tamba ho ninia konveniênsia, disponibilidade no mos fluidez, fasil tebes atu maneja no transporte bé ba fatin nebe deit. Tamba nee, estudu ida nee halao atu defini aproximasaun hodi uza bé iha fabriku no industria sira. Prosesu no *fluxo* husi estudu nee hatudu iha Fig 1.1. Kapítulu (1) esplika kona ba konêsementu báziku, objetivu, no informasaun kona ba aprosimasaun uza bé iha makinazen iha pasadu no agora nian nudar introdusaun husi teze nee. Iha kapítulu (2), sei halo diskusaun kona ba propriedade bé nian no mos sei presente resistensia ba korosaun kauza husi bé ba materiál ho tipo oin-oin. Nunee mos, sei halo diskusaun

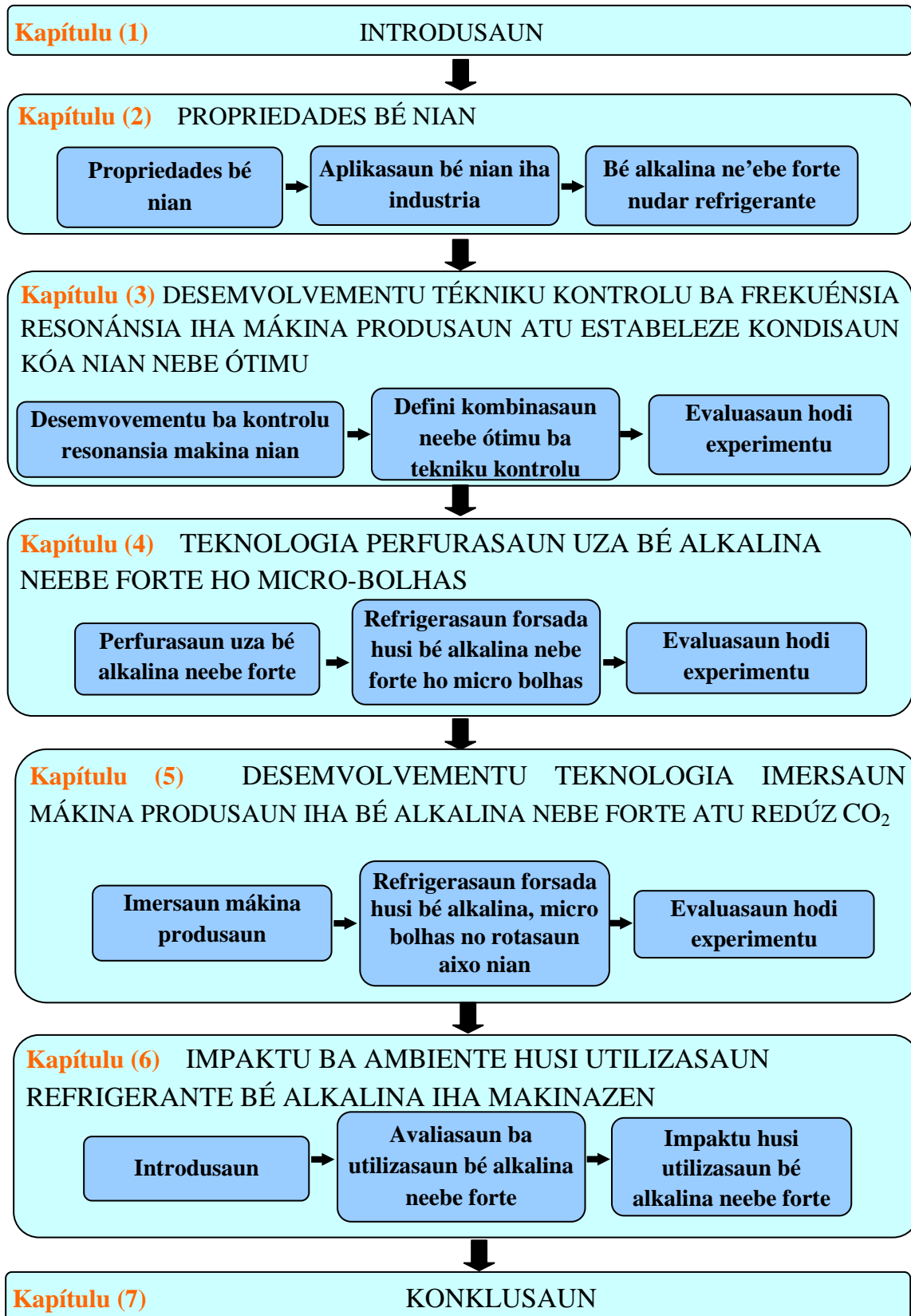


Fig.1.1 Fluxograma husi estudu ida nee

kona ba relasaun entre rezisténsia ba korosaun ho bé alkalina atu bele hadiak materiál sira nia rezisténsia ba fenómenu korosaun nian. Iha kapítulu (3), sei halao diskusaun kona ba metodu foun nebe propoin tiha ona atu bele halo kontrolu ba iha resonansia makina nian, hodi nunee bele estabeleze kondisaun koa nian neebe ótimu. Metodu foun nee sei apresenta, kombinasauun husi fatór kontrolu tolu sei avalia, no sei harii tekniku kontrolu neebe ótimu. Iha kapítulu (4), diskusaun no investigasaun kona ba perfurasaun uza bé alkalina neebe forte sei halao. Metodu ida atu hadiak efeitu refrigerasauun nian sei dezevolve iha sessauun nee. Investigasaun refrigerante forsada hodi bé alkalina nebe forte sei investiga uluk, hafoin *coeficiente de transferência térmica* no vida *feramenta* nian durante halao perfuramentu uza bé alkalina ho micro-bolhas sei avalia uza experimentu. Kapítulu (5) sei halao diskusaun kona ba immersauun mákina produsaun nian no halao makinazen iha bé alkalina forte nia laran. Rezisténsia husi elementus makina nian ba korosaun wainhira kona bé alkalina sei examina uluk. Hafoin, *torno de bancada* sei remodela no hatama iha bé alkalina nia laran. Evaluasaun atu hatene metodu nee nia akurasaun sei halao hosi sukat *deformação térmica* entre spindulu ho postu *freamenta* nian. Aumenta liu tan, makinazen uza *torno de bancada* sei halao atu investiga efeitu husi evaporasaun bé nian husi bé alkalina neebe forte. Kapítulu (6) sei apresenta *avaliação do ciclo de vida* uza bé. Impaktu husi estudu ida nee ba iha ambiente no saude ema nian sei identifika no evalua. Iha kapítulu ikus husi dizertasaun nee, kapítulu (7), sei apresenta konkluzauun ba estudu ida nee nian.

Konkretamente, estrutura husi estudu ida nee neebe kompostu ba iha kapítulu hitu sei espresa hanesan tuir mai nee:

Kapítulu (1), “INTRODUSAUN”: Kapítulu nee deskreve kona na konêsementu báziku, objetivu peskiza ida nee nian, no mos ninia relasaun ho metodu sira neebe iha tiha ona.

Kapítulu (2), “PROPRIEDADES BÉ NIAN”: Kapítulu nee sei deskreve kona ba propriedades bé nian, neebe sei uza hanesan konsiderasaun ba peskiza oin mai nudar baze teorítiku no faktus husi bé nian. Propriedades ba korosaun neebe kauza husi bé sei esplika iha kapítulu nee. Rezisténsia ba korosaun ba materiais ida-idak iha bé alkalina nia laran sei investiga no esklarese. Nunee mos, metodu oinsa atu prevene bé atu nunee labele kauza korosaun iha elementus sira makina nian sei esplika hotu.

Kapítulu (3), “DEZEMVOLVEMENTU TÉKNIKU KONTROLU BA FREKUÉNSIA RESONÁNSIA IHA MÁKINA PRODUSAUN ATU ESTABELEZE KONDISAUN KOA NIAN NEEBE ÓTIMU”. Iha kapítulu nee, sei halao diskusaun kona ba tékniku kontrolu ba frekuensia resonansia nian. Fatór kontrolu tolu sei define hodi uza atu kontrola resonansia makina nian no mos kontrolu neebe ótimu husi fatóres kontrolu ida-idak sei kombina hamutuk atu nunee bele hetan kombinasan kontrolu nian neebe ótimu. Enxe bé kahur ho polymer, reinforsa estrutura, no muda posisaun husi supporta makina nian mak fatór tolu neebe sei uza nudar tékniku kontrolu. Metodu atu hadiak *damping ratio* bé nian sei apresenta iha kapítulu nee. Simulasaun no analizaun uza sistema *Engenharia Auxiliada por Computador* ou *Computer Aided Engineering (CAE)* ba iha kontramedita oi-oin sei halao. Depois, fatóres kontrolu ótimu nian neebe hetan husi simulasaun sei evalua fali uza experimentu atu bele hetan kombinasan kontrolu neebe ótimu. Ikus liu, efisiensia husi metodu nee sei evalua uza prosesu makinazen hodi halao experimentu koa nian uza makina *torno de bancada*. Komparaun ho metodu sira neebe iha tiha ona sei halao hodi sukat no kompara *rugosidade da superfície peça* nian.

Kapítulu (4), “TEKNOLOJIA PERFURASAUN UZA BÉ ALKALINA NEEBE FORTE HO MICRO-BOLHAS”: Iha kapítulu nee, tecnologia perfirasaun uza bé alkalina neebe forte sei desenvolve no esklarese. *Broca* ho

kuak iha nia klaran sei uza iha estudu ida nee. Efeitu refrigerante husi bé alkalina ho micro-bolhas sei investiga uluk hodi experimentu. Hafoin, *coeficiente de transferência térmica broca* nian sei evalua atu hatene kapasitasaun refrigeraun nian. Depois, evaluaun ho experimentu makinazen ba peça Ti6Al4V sei halao. Ti6Al4V mak material neebe ninia kondutividade térmika nee kiik, tan nee difícil atu koa ou fura. Efetividade husi metodu nee sei investiga klean liu tan hodi sukat no kompara vida *broca* nian.

Kapítulu (5), “DEZEMVOLVEMENTU BA TEKNOLOJIA KONA BA IMERSAUN MÁKINA PRODUSAUN IHA BÉ ALKALINA NEBE FORTE ATU REDÚZ CO₂”: Iha kapítulu nee, imersaun makina produsaun no halao makinazen iha bé alkalina neebe forte nia laran sei evalua no esklarese. Rezisténsia korosaun nian husi materiais oi-oin sei investiga. Modifikasaun no remodelasaun ba makina *torno de bancada* sei halao no esplika iha estudu ida nee. No mos, deformasaun térmika entre espidulu no postu feramenta nian sei sukat no evalua ba akuramentu metodu nee nian. Aumenta liu tan, operaun uza makina *torno de bancada* sei halao hodi investiga efeito evaporasaun husi bé alkalina neebe forte.

Kapítulu (6), “IMPAKTU BA AMBIENTE HUSI UTILIZASAUN REFRIGERANTE BÉ ALKALINA IHA MAKINAZEN”: Iha kapítulu nee, avaliasaun neebe simples sei halao hodi kolekta no kalkula impaktu husi utilizaun bé alkalina neebe forte ba iha meio ambiente no saude ema nian. Mákina tolu sei usa ba avaliasaun iha estudu ida nee. Karbonu neebe emitte durante halao makinazen no disposaun ba oliu nian sei komputa. Nunee mos, total husi emisaun CO₂ husi makinazen ho metodu konvensional no uza bé alkalina neebe forte sei apresenta no kompara ba malu.

Kapítulu (7), “KONKLUSAUN”: Ikus liu, konklusaun husi estudu nee sei apresenta iha kapítulu ida nee.

Ho arranjementu husi kapitulu hitu iha leten, “Estudu ba Akurasun neebe Boot no Fabrikasaun neebe Eficiente Utiliza Bé ho Kompostu atu Konserva Ambiente” mak halao tiha ona nee, no aplikasaun husi teknolojia neebe dezenvelope tiha ona konsidera aplikavel ba iha produsaun no industia sira.

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Kapítulu (2)

PROPRIEDADES BÉ NIAN

2.1 Propriedades jerál bé nian

Buat ida neebe halo ita nia planeta especial tebes mak prezensa bé nian. Bé importante liu ba moris. La ho bé, buat moris hotu sei mate. Bé okupa kuaze 71% husi superfície mundo nian no kuaze 65-75% iha ita nia isin. Tamba nee mak kuaze 82% husi ita nia ran nee bé ^{[2-1],[2-2], [2-3]}. Bé, ho ninia formula kímiku H_2O , preseve hanesan substansia ida neebe transparente, la iis, *insipido*, no *ubíquo*. Ligasaun entre átomo *hidrogênio* rua ho *oxigênio* ida halo bé konhesidu hanesan komposisaun ida neebe simples liu husi elemetus reativu neebe hetan iha rai. Uniku liu, bé mak substansia natural ida mesak neebe existi iha kondisaun físiu tolu – sólidu, líquidu, no gás – iha temperatura neeba hetan iha rai. Substansia sira seluk tenke *super-heated* ou *super-cooled* hodi bele muda sira nia kondisaun físiu. ^{[2-4],[2-5]}. Gás mak iha konsidaun ida neebe kuando bé evapora. Kondisaun nee ita bele hetan iha atmosfera. Kondisaun líquidu ne *ubíquo*, katak ita bele hetan iha neebe deit, iha mota, lago, no tasi. Kondisaun sólidu husi bé mak iha forma gelo fatuk. Tan nee mak bé substansia ida neebe uniku.

Bé iha propriedade neebe especial se haree ba oinsa *hidrogênio* ho *oxigênio* liga ba malu hodi forma molékula bé. Bé mos espesial iha wainhira ninia molékula sira reazen ba malu. Wainhira substância polar ida hatama ba iha bé laran, manifestasaun entre polares rua neebe diferente husi bé no substansia polar neebe atrai ba malu sei akontese. Tan nee mak fasil ba bé dizolve substância polar sira. No mos, atrasaun nee halo molekula husi substansia foun kahur ho molekula bé nian, tamba nee mak bé bele dizolve substansia barak liu duque líquido sira seluk. Tanba nee mak bé hanaran “solvente universal” ^[2-7].

Kapasidade dizolve bé nian halo nia sai importante liu tan, tanba bele suporta buat moris iha rai. Nia dizolve no lori mineral, kímikus, no *nutrients* ba neebe deit, tan nee mak importante tebes ba buat moris sira. Ho ninia polaridade, molekula sira bé nian atrai metin ba malu nunee kria tensaun *superficial* neebe boot ^[2-8]. Molekula sira bé nian kombina ba malu hodi forma revestimento iha bé leten, nunee iha forsa atu bele suporta buat ruma neebe kamaan. Por ezemplu, insektu balun bele lao iha bé leten tamba prezensa husi tensaun *superficial*. Tensaun nee halo bé forma sirkulu hamutuk wainhira nia fakar, doque espalha fali sai *camada* neebe mihis. Nia mos halo bé bele nani tuir aihoris nia abut no *vaso sanguíneo* iha ita nia isin.

Alem de propriedade bé nian neebe esplika ona iha leten, sei iha tan propriedades oi-oin bé nian. Tamba ita labele mentiona hotu propriedade ida-idak, teze nee sei fo atensaun liu no halao diskusaun kona ba propriedades bé nian neebe iha relasaun ba ninia aplikasaun iha industria sira.

2.2 Propriedades bé nian neebe iha relasaun ba aplikasaun iha industria sira

2.2.1 Agente de limpeza

Bé nudar *agente de limpeza* neebe popular tebes no uza tiha ona durante tinan barak iha area oin-oin husi industriais no fabrikasaun sira atu hamos foer sira. Hanesan esplika tiha ona iha leten, bé iha propriedade ida hanaran tensaun *superficial* neebe diak tebes nudar limpador. Maibe, propriedade nee limita bé nia abilidade atu sai hanesan *agente de limpeza* neebe excelente. Tan, laós foer hot-hotu bele hamos uza bé. Iha bé laran, molekula bé nian haleu no atrai ba molekula ida-idak iha ninia sor-sorin. Maibe, iha bé leten, molekula sira nee haleu molekula bé nian iha ninia ninin deit. Desde tensaun neebe kria iha bé leten dada molekula bé nian tama ba iha bé laran, bé nakfera waihira fakar iha buat ruma leten, nunee minimiza prosesu habokon nian. *Conseqüentemente*, prosesu

limpeza nian sai ladun diak. Tan nee, presiza hamenus tensaun *superficial* hodi nunee bé bele espalha no habokon area ruma hodi bele hal prosesu limpeza nian sai diak liu tan. ^{[2-9], [2-10]}. Bé mos ajuda prevene foer husi area neebe moos tiha ona hodi nunee fasil atu bele hamos sai moos liu tan iha limpeza final. Bé mos servisu hanesan agente anti-redepozisaun nian, katak nia bele penetra ba iha foer laran, iha kapasidade atu bele destrui foer ba iha particular neebe kiik, bele hamos partikular sira nee, no bele prevene restu foer nian neebe atu hafoer fali area neebe hamos tiha ona. ^[2-11]

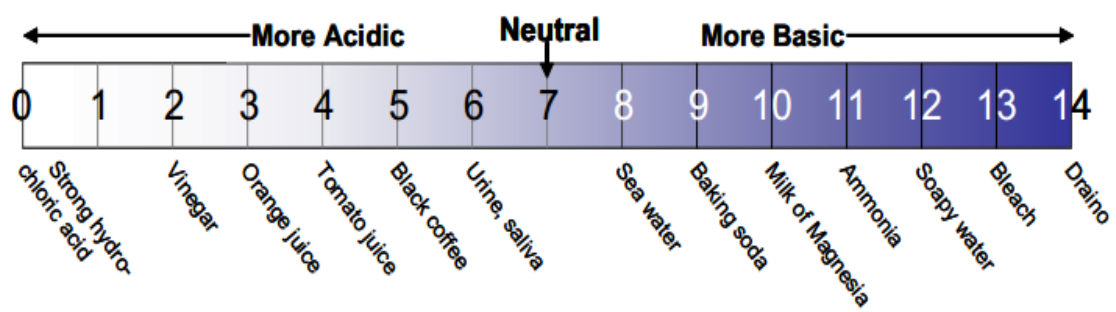


Fig. 2.1 Escala pH no ezemplu husi solusaun iha pH ida-idak

Além de redúz tensaun superfisiais atu bele hadiak prosesu limpeza nian, uza bé ho partikular pH bele mos hadiak liu tan prosesu limpeza nian. Tamba bé nee solvete neebe universal, geralmente nia iha pH neebe oi-oin. Tamba nee mak agente limpeza nian bai-bain prodúz husi bé neebe bele acido, alkalina ou neutral, depende ba ninia uzu. Escala pH nian no ezemplo husi solusaun iha pH ida-idak hatudu iha Fig.2.1. pH 7 mak neutron, menus liu pH 7 mak acido no boot liu pH 7 mak alkalina.

a. Agente de limpeza alkalina

Agente de limpeza alkalina mak agente limpeza ida neebe ninia pH 7 ba leten. Detergente alkalina mak detergente ida neebe efetivo liu wainhira hamos foer orgniku hanesa oliu, mina, protein no karbohidro sira neebe hetan iha industria.

Aumentasaun alalinidade ba iha detergente barak mak atu bele hadia liu tan detergente ninia efisiênsia limpeza nian. Servisu husi detergente nee mak hanesan uniaun husi peptide hidrólize uluk tiha, depois proteína boot neebe susar atu hamos sobu ba elemetus neebe kiik hafoin bele hamos ^[2-12]. Uza Agente de limpeza ida nee, efisiênsia limpeza nian bele hetan husi dalan rua. Primeiro mak aumenta alalinidade. Iha kondisaun nee, foer acidu bele neutraliza, nunee fácil atu hamos. Foer seluk hanesan mina, olio ho protein sira emulsionado ou peptizadas uluk hafoin bele hamos. Segundo, komponente detergente nian diak bele mos ajuda atu evita kressimentu husi microorganismu no kímiku restu sira.

b. Agente de limpeza acidu

Limpador acidu dala barak uza atu halakon no hamos metal sira no mos efetivo wainhira hamos depositu mineral nian ou oxidasau husi *superficies*. ^[2-13] Geralmente, limpador acidu ideal ba hamos amido, karbonato, no *hidróxidos insolúveis*. Maibe, limpador nee bai-bain uza depois de uza detergente alkalina tamba foer makaas, olio, no glucana sira difisil tebes atu hamos uza detergente acidu. ^[2-12] Detergente acidu konsisti husi *ácidos orgânicos* no *inorgânicos*. *Ácidos inorgânicos* mak hanesan *fosfórico, nítrico, sulfâmico, sulfato ácido de sódio* no *ácido clorídrico*. *Ácidos orgânicos* mak hanesan *hidroxiacético, ácido cítrico*, no *ácido glucónico* ^[2-14]. Detergente acidu uza mos hanesan prevensaun ba óxido alumínio nian. Maibe, detergente acidu efetivo liu wainhira uza kontra bakteria doque detergente alkalina. No mos, asaun husi limpador acidu nian bele sai diak liu tan wainhira aumenta ho *acid-sTabela surfactant* ^[2-15], neebe bele penetra tama ba iha foer depositu nia laran no mos asisti ba iha prosesu lavazem nian iha prosesu ikus limpeza nian.

c. Agente de limpeza neutral

Agente de limpeza neutral mak limpador ho pH neutral entre pH 6.5 - 7.5. Nia konsisti husi mistura proprietária husi surfactantes non-iónicos no

ingredientes husi organiku seluk neebe dispersa foer ho tipo neebe la hanesan. Limpador nee uza elementus kímiku seluk hanesan surfcante (*Agentes activos de superficie*), neebe demola tensaun superficial husi likuido hodi nune bele uza ba hamoos foer. ^[2-16]

2.2.2 Calor espesífiku bé nian

Bé iha kapasidade calor neebe aas, *cerca de* 4.18 J/g°C, katak nia bele resisti mudansa husi temperatura wainhira nia absorve ou husik calor. Kapasidade calor nian defini husi relasaun entre kapasidade calor substansia ida nian ho kapasidade calor bé nian. Calor espesífiko, escala husi kapasidade calor, mak calor ida neebe presiza atu hasae temperatura husi 1 grama bé ho temperatura 1°C. Ho kapasidade calor neebe aas, mudansa iha temperatura neneik liu kompara ho kompostu sira selu neebe simu ou lakon energia.

Calor espesífiko bé nian resulta husi ninia uniaun entre hidrogenio estrutura nian. Maske uniaun hidrogenio nee fraku, sira nia efeitu kombinasan enorme tebes. ^[2-17] Tamba nee mak presiza calor neebe boot atu bele hasae ou hatun temperatura 1°C. Uniaun entre hidrogenio presiza calor atu bele haketak. Wainhira aumenta calor ba bé, energia calor nian hafahe uluk uniaun hidrigenio, hafoin permiti molekula bé nian atu desloca ho livre. Deslokasaun nee aumenta ba lalais wainhira aumenta ninia temperatura. Tamba calor barak mak uza tiha ba hafahe uniaun hidrogenio nian, restu calor neebe hela la suficiente atu hasae temperatura bé nian. Tamba nee mak difisil tebes atu hasae bé nia temperatura. Tan temperatura nudar medida husi média energia kinético molekula sira nian (wainhira sira desloka), bé nia temperatura aumenta uituan-uituan ho aumentasaun husi calor. Wainhira bé nia temperatura menus uituan, uniaun hidrogenio barak mak forma no husik energia neebe notável sai calor. ^[2-18]

Ho razaun katak bé bele absorve calor neebe barak ho mudansa neebe uituan iha ninia temperatura, nia sai hanesan *tampão térmico*. Iha eskalaun neebe kiik hanesan iha ita nia sélula, bé bele absorve calor barak ho mudansa kiik iha temperatura. Iha eskalaun neebe boot hanesan iha tasi, nia sai hanesan *tampão térmico* ba rai, resisti mudansa ba iha temperatura, no kria ambiente neebe amizável ba moris. [2-19], [2-20]

2.2.3 Resfriamentu evaporativu neebe aas

Bé iha vaporizasaun calor ne'ebe a'as, tan nee mak nia resisti evaporasaun [2-21]. Atu molékula bé nian bele evapora husi liquido ba gas, uniaun hidrogenio tenke hafahe uluk. Tan nee, presiza energia husi calor. Tamba energia neebe presiza atu hafahe uniaun hydrogenio kaer metin bé nia molékula ba ninia vizinho, energia barak mak presiza atu bele evapora bé kompara ho substansia sira seluk. Atu bele evapora bé grama ida iha temperatura ambiente, presiza kuaze 580 caloria. Caloria nee quaze duplo husi quantidade neebe presiza atu bele evapora grama ida álcool ou amônia. Bé relativamente iha vaporizasaun calor neebe a'as iha *ponto ebulição* nian (540 cal/g or 2260 J/g; Joule = 0.239 cal). Entre liquidos sira, bé iha *calor latente* vaporizasaun neebe aas liu (334 J/g). *Calor latente* nee conhecido mos ho naran *calor de fusão* ou energia neebe presiza atu muda substansia ho grama ida husi solido ba liquido (ou *vice-versa*) sem muda ninia temperatura. [2-22],[2-23]

2.2.4 Densidade

Densidade bé nian úniku tebes se haree ba oinsa temperatura afeita ninia densidade. [2-24] Densidade nee prevene bé atu konzela husi okos ba leten. Substansia barak mak aumenta iha sira nia densidade wainhira temperatura redús, tamba molékula sira kria substansia no komesa disloka neneik ba neneik too sira besik malu, nunee hasae densidade. Densidade bé nian aumenta sai boot kuandu

nia malirin too 4°C. Maibe ninia densidade komesa redús fali wainhira temperatura tun too 0°C (*ponto de congelamento*). Wainhira besik ba *ponto de congelamento*, uniaun hidrogenio sira para metin hodi forma *estrutura cristalina* neebe hadook molékula sira ba malu kompara ba iha liquido bé. ^[2-25]

2.2.5 Indúz korosaun

Razaun jerál tamba saida mak bé la uza ba resfriamentu iha industria balun, hanesan iha fabrikasaun no makinazen, tamba nia sai kauza ba feruzu iha peça no produsaun metal sira seluk. Korosaun nee prosesu natural ida neebe involve ba iha degradasaun kímika ou elétriku metal sira nian wainhira kona bé. Quantidade korosaun nee variadu, depende ba acidez bé nian, ninia condutividade elétrica, concentrasun husi oxigênio, no temperatura. ^{[2-26], [2-27]}. Geralmente, ferruzen mosu tamba reasaun husi oxigênio nebe dissolve iha bé laran ho ferro. Ferruzen nee termo ida nebe jerál wainhira deskreve óxidos ne'ebe diferente hanesan: *Ferrous hidróxido* Fe(OH)₂, *Hidróxido de óxido* Fe(OH)₃, *Férrico Oxy-Hidróxido* FeO(OH), *Amarelo óxido de ferro* Fe₂O₃.H₂O, neebe forma wainhira ferro sai ferruzen^[2-28]. Forma jerál ferruzen nian neebe konêsido mak korosaun mean: Fe₂O₃. Oxigênio iha atmosfera dizolve iha bé no kauza ferruzen atu forma. Reasaun kímika prosesu korosaun nian fahe ba rua hanesan:

1) Dissolusaun anódika metal nian (ferro) iha solusaun nia laran (bé)

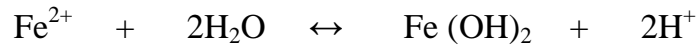
Dissolusaun anódika metal nian bele hakerek kímikamente hanesan:

Ferro elementar → Ferrous ferro + Elétrons



Reasaun nee prodús *ferrous ferro* no elétron rua. Elétron nee depois nani husi metal ba kátodu. Iha parte seluk, *ferrous ferro* reaze ho bé (eletrólito) iha metal hodi kria ferruzen no ion hidrogênio.

Ferrous ferro + bé \leftrightarrow Ferrous hidróxido + Íon hidrogênio

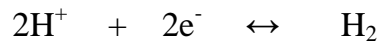


Ferruzen cria revestimento iha anódiu nia leten. *Ferrous hidróxido* bele mos halo reasaun ho bé neebe ho quantidade neebe barak atu forma ferruzen seluk ho naran *hidróxido férrico* ($\text{Fe}(\text{OH})_3$).

2) Redusaun katódiku oxigênio neebe dizolve ba iha bé laran

Iha redusaun katódiku, elétron husi dissolusaun anódiku nian husik hela metal no tama fali ba bé laran, depois reazen ho íon hidrogênio sira hodi forma gas hidrogênio. Reasaun nee bele expresa hanesan:

Íon hidrogênio + Elétrons \leftrightarrow Gas hidrogênio

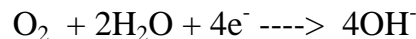


Dissolve oxigênio ba iha bé laran bele reazen ho gas hidrogênio iha katódiku nia sor-sorin.

Gas hidrogênio + Oxigênio \leftrightarrow bé (água)

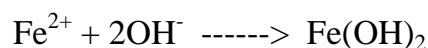


Enquanto bé reazen fali ho oxigênio no íon elétron hodi forma íon hidróxido.



Iha reasaun ikus, ferrous reazen fali ho íon hidróxido (OH^-) atu forma korosaun $\text{Fe}(\text{OH})_2$.

Reasaun final mak:

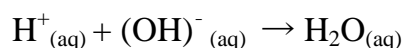


Óxido ida nee sei bele halo reasaun liu tan ho oxigênio hodi forma produktu korosaun mean: $\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$. Tan nee mak katalisador principal atu kria prosessu ferruzen mak bé. Estrutura husi ferro no aço bele solido, maibe molékula bé nian bele penetra tama ba ferro no aço laran se koak ou fenda kiik existi iha metal nebe exposto. Átomo hidrogênio neebe existi iha molékula bé nia laran bele kombina ho elementus sira seluk hodi forma acido, neebe sei halo matriál barak mak feruzu lais.

2.3 Bé alkalina ba refrigerante

Esplika tiha ona iha sesaun liu ba katak ho evaporasaun resfriamentu neebe boot, bé sai hanesan média neebe diak ba resfriamento. Maibe tamba bé neebe natural konsidera neutral iha ninia pH, nune nia indúz korosaun. Tan nee mak atu bele uza bé ba halo malirin metal ruma, nia presiza ionizadu uluk ba pH neebe aas. Ho prosesu nee, ita bele prevene korosaun iha metal wainhira uza bé.

Bé alkalina mak bé ida neebe ho kuantidade íon hidrogênio $[\text{H}^+]$ neebe uituan no konêsidu hanesan bé ionizado ho eskala pH boot liu pH 7.0. Hanesan esplika tiha ona katak, pH mak eskala acido ou alkalina husi solusaun ruma. Konsentrasaun husi íon hidrogênio iha solusaun ruma nia laran mak determina escala ba pH. Bé alkalina sei la prevene korosaun se nia iha kondutividade elétrika neebe boot. Wainhira metal rua neebe diferente hanesan aço no broze halo kontaktu ho solusaun, sei kondúz eletrisidade no *célula galvanic* sei estabeleze. Iha kondisaun nee, metal ida sei feruzu atu nune bele fo balansu ba *célula galvanic* neebe gradu. Tan bé inklui íon H^+ no mos OH^- , se kuantidade husi H^+ sai boot liu fali OH^- , bé sei sai acido. Iha parte seluk, se íon OH^- mak barak liu fali H^+ , bé sei sai alkalina. Bé neebe pura, ida neebe iha kuantidade íon rua neebe hanesan, konsidera neutral. Ekuasaun kímika ba formasaun bé pura (*pure water*) mak hanesan:



Grau husi acidez ou alcalinidade iha eskala pH nian váriu entre 0 too 14. Hanesan hatudu ona iha Fig. 2.1 katak solusaun neebe acido iha pH menus husi 7, solusaun alkalina iha pH boot liu 7. Bé pura, hanesan bé neutral, ninia pH mak pH 7. Ba mudansa 1-uniaun iha pH, konsentrasaun husi íon hidrogênio muda dékuplu. Por ezemplu, se pH mak 8, signifika katak íon OH^- atus ida barak liu fali íon H^+ (se $[\text{H}^+] = 10^{-8}$, $[\text{OH}^-] = 10^{-6}$).

Matematikamente bele expresa nudar:

$$\text{pH} = -\log [\text{H}^+]$$

Expresaun nee bele mos deskreve ho liafuan seluk hanesan, pH nia valór mak elevadu negativu atu hasae valór 10 hodi nune bele sai hanesan ho konsentrasaun íon hidrogênio. Wainhira bé sai alkalina neebe forte, íon hidrogênio iha bé laran sai menus, nune atraza korosaun. Bazeia ba propriedades korosaun bé alkalina neebe forte ^[2-29], ba aço materiais, korosaun sei la akontese kuandu pH boot liu pH 10.0. Materiais balun hanesan níquel no níquel ho baze *alloys*, sira nia pasividade kímika entre pH 8.5 ~ pH 13.0. Pasividade kímika mak karakterístika metal nian ida neebe la afeita husi fatór ambiente nian hanesan bé no anin. Iha parte korosaun nian, pasividade kímika material ida nian mak kondisaun ida neeba wainhira bé ou anin la afeita ba material atu estabeleze korosaun. Pasividade resulta husi acumulasaun *camada metal óxido* neebe estável no forte iha metal nia leten. *Camada óxido* nee forma husi korosaun iha metal nia superfície neebe mo'os, iha neeba produktu korosaun insolúvel iha particular ambiente ida neebe metal iha ba. Kuando *camada* nee forma tiha ona, nia sai hanesan parede ida neebe hafahe *superfície* metal nian husi ambiente, nune, estabezementu korosaun nian redús ou para total.

Materiais seluk hanesan titânio ho titânio alloy, sira nia pasividade kímika mak pH 13.0 ba kraik. Tamba nee mak geralmente, pH entre 8.0-13.0 la halo feruzu ba mateiais industria sira nian.

2.4 Prosesu produsaun bé alkalina nian

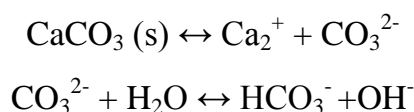
Hanesan esplika tiha ona iha sesaun liu ba, alkalinidade mak medida husi kapasidade bé ou solusaun ida nian atu netraliza acido. Kompostu bé nian neebe importante liu hodi determina alkalinidade mak íon karbonatu (CO_3^{2-}) no bikarbonatu (HCO_3^-). Íon karbonatu bele halo reasaun no netraliza íon hidrogênio (H^+) rua no bikarbonatu bele netraliza H^+ ou íon hidróxido (OH^-) neebe existi iha bé laran. Tabela 2.1 hatudu kompostu sira neebe importate ba produsaun alkalina.

Tabela 2.1. Kompostu sira neebe importate ba alkalinidade

H^+	Íon hidrogênio (acido)
OH^-	Íon hidróxido (baze)
H_2CO_3	Ácido carbônico
HCO_3^-	Íon bicarbonato
CO_3^{2-}	Íon carbonato
CaCO_3	Cálcio carbonato (calcite)
$\text{CaMg}(\text{CO}_3)_2$	Calcário dolomítico
K_2CO_3	Potássio carbonato

Fonte ida alkalinidade nian mak kálsio karbonatu (CaCO_3). Alkalinidade bele hasae pH nia eskala (halo bé sai báziku liu), kuandu alkalinidade nee mai husi fonte mineral nian hanesan kálsio karbonatu (CaCO_3). Kuando CaCO_3 dizolve

iha bé laran, karbonatu (CO_3^{2-}) reazen ho bé hodi forma bikarbonatu (HCO_3^-), ida neebe prodús hidróxido (OH^-):



Íon hidróxido (OH^-) mak baze neebe forte, nunee aumentasaun iha OH^- nia konsentrasaun sei hasae pH nia eskala.

Iha estudu nee, kompostu husi potássio karbonatu K_2CO_3 mak uza atu halo bé alkalina neebe forte. Tamba 0.1 % husi bé alkalina neebe uza iha estudu nee mak iôniko husi potássio karbonatu K_2CO_3 , enkuantu quaze restu 99.9 % nee bé. Nunee, bele konsidera katak bé alkalina neebe forte nee seguro ba meio ambiente. Tan nee mak “Estudu ba Hasae Efisiensia Fabrikasaun Nian uza Bé Hodi fó Konservasaun ba Ambiente” halao no evalua.

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Kapítulu (3)

DEZEMVOLVEMENTU TÉKNIKU KONTROLU BA FREKUÉNSIA RESONÁNSIA IHA MÁKINA PRODUSAUN ATU ESTABELEZE KONDISAUN KOA NIAN NEEBE ÓTIMU

3.1 Introdusaun

Iha tempo agora nian, tamba teknolojia husi mákina produsaun presija atu uza ba produtividade neebe aas, estabelezementu metodu kontrolu nian ba frekuensia resonansia atu estabeleze kondisaun ótimu husi koa nian nesesáriu tebes ba hadiak qualidade husi produsaun no fabrikasaun. Atu hasae produtividade, kondisaun koa nian ho parametru hanesan velocidade espindulu, velocidade koa nian, alimentasaun ho klean husi koa nian tenke iha kondisaun nebé ótimu atu nunee rezultadu nebe ita hetan bele mos ótimu hodi la prosesu hó mákina seluk tan. Wainhira uza kondisaun koa nian neebe ótimu, óras makina nia bele habadak, kustu makina nian bele hamenus no resulta produtividade neebe aas nunee bele hasae benevisiu ba produsaun sira. Tan nee, selesaun kondisaun koa nian hola parte importante ba rendimentu no gastu industria nian. ^{[3-1], [3-14]}

Iha parte seluk, vibrasaun iha mákina produsaun nian sei sai hanesan problema jerák iha makinasaun. Natural ba estrutura ida atu nakdoko, maibe kondisaun nee aseitadu se kuandu osilasaun la liu nivél neebe toleravel. ^{[3-7], [3-13]} Maske mákina sira ho sira nia kondisaun operasaun nebe diak liu mos, sei iha vibrasaun uituan nebe afeita husi defeitu nebe kiik. Maibe, kuando vibrasaun mákina nian sai aas no makaas, failansu mekánika nian sei mosu. ^[3-2] Vibrasaun la sai boot no makaas la ho razaun ida. Kondisaun hanesan dezbalansementu, dezalinamentu, *engrenagem* ou *rolamentu erodida* no *folgado* mak halo vibrasaun sai boot no makaas. Iha kazu seluk, kondisaun nee bele prevene ho

fasil wainhira mákina iha nia kondisaun nebe ótimu. Maibe, resonansia mákina nian mak ida nebe difisil liu atu prevene se la halo mudansa ba iha sistema mákina nian. Resonansia bele deseja no bele mos la deseja. Tamba, konsidera bai-bain se kuandu mákina ida iha frekuensia resonansia nebe barak, nunez kondisaun resonansia sei akontese nafatin iha mákina sira wainhira forsa husi rotasaun ou estrutura husi mákina nian halo nakdoko iha ninia natural frekuensia ida.

Frekuensia resonansia mákina nian determina husi mákina nia estrutura, ninia modelu, medida, propriedade materiais sira nia (*young's modulus* no densidade) no metode suporta nian. Iha parte seluk, kondisaun ótimu koa nian determina husi produktu dezenho, material husi peça, tipu kondisaun koa nian ho ninia materiál. Maibe, wainhira halo operasaun ho kondisaun ótimu koa nian nebe hili ona, iha parte ida, fórza frekuensia husi parte nebe movél koincide ho frekuensia resonansia mákina nian, vibrasaun makaas sei akontese. Iha situasaun nee, kondisaun koa nian tenke muda atu munez bele prevene vibrasaun, maibe presisaun geometria, vida feramenta nian, no *rugosidade* sei la ótimu. Kuandu kondisaun nee akontese, sei afeita prosesu koa nian no *rugosidade* ikus peça nian. Kondisaun ida nee konsidera hanesan problema ba produtividade iha produsaun masal.^{[3-1],[3-2],[3-3],[3-4]}

Tamba nee, iha estudu nee, dezvoltamentu tékniku kontrolu atu kontrola frekuensia resonansia mákina nian dezvoltolve hodi simpliza no modifika mákina nia estrutura hodi; (1) Kontrola densidade mákina nian hodi halo kamaan mákina nia estrutura, (2) Kontrola rigidez mákina nian hodi kuadru reinforça ho kuak iha ba, (3) Kontrola suporta hodi muda kombinasan posisaun husi mákina nian. Ho aplikasaun husi fatór kontrolu 3 nee, teknolojia atu kontrola frekuensia resonansia mákina nian dezvoltolve no mos evaluasaun ho ekperimentu ba metodu neebe proposta halao uza mákina *torno de bancada*.

3.1.1 Efeitu husi resonansia mákina nian ba iha prosesu koa nian

Kondisaun resonansia iha mákina produsaun nian, bele afeita prosesu koa nian iha fábrica no produsaun. Hanesan esplika tiha ona iha leten, kuando mákina halo operasaun iha distansia resonansia nian, maske uza mákina ho kualidade nebe diak mos, kondisaun no rezutadu koa nian sei la dun diak hanesan ita espera. Alem de afeita prosesu koa nian no nia rezultadu, problema seluk hanesan mákina fáila, se lae hakanek operador bele mos akontese wainhira osilasaun kontinua ba tempo naruk. Iha situaun nee, frekuensia resonansia presiza atu muda hodi nune bele prevene erro no problema tuir mai.

Rezultadu ikus mákina nian nebe ladun diak bele afeta produtividade iha produitu barak.^[3-8] Ho prezensa resonansia iha mákina, kondisaun ótimu koa nian difisil atu aplika wainhira velocidade spindulu nebe ita hili koinside ho frekuensia resonansia mákina nian. Wainhira kondisaun nee akontese, mákina sei nakdoko ho makaas, no vibraun nebe boot sei afeita presisaun medida no modelu peça nian. Presisaun nebe ladun diak no mos defeito husi peça, sei presiza prosesu kontinuasaun atu nune bele hadiak nia kualidade, nune konsidera hanesan demora ida nebe hamenus produtividade. Tamba nee, iha situaun hanesan nee, presiza desidi kondisaun seluk ho diferensia iha nia velocidade spindulu atu bele prevene vibraun nebe boot.

Máquina produsaun barak mak desenho tiha ona atu prevene nia frekuensia resonansia hodi hasae mákina nian rigidity no desidi velocidade spindulu nebe konstanta hodi uza. Maibe, tamba resonansia iha mákina kiik no naton sempre akontese iha frekuensia 100 Hz ba kraik^[3-3], difisil atu prevene resonansia kuandu uza mákina ho spindulu oin-oin. Tamba nee, prevene spindulu nebe coinsida ho mákina nia resonansia hodi muda spindulu ba velocidade seluk sei uza barak liu iha fabrikasaun. Muda velocidade spindulu nian bele prevene resonansia maibe, ho mudansa iha kondisaun koa nian, rezultadu koa nian sei la ótimu. Nune, kondisaun

nee konsidera hanesan problema ba produtividade.^[3-3~3-6] Ho razaun nee, iha peskiza ida nee, tekniku kontrolu ba frekuensia resonansia iha mákina produsaun nian konsidera atu halao invesigasaun no desenvolvimento hodi estabeleze kondisaun koa nian nebe ótimo.

3.1.2 Kontramedida konvensionais nian hodi prevene resonansia iha mákina produsaun

Iha kontramedida konvensionais barak neebe uza ona atu prevene frekuensia resonansia iha mákina produsaun hanesan;

[1] Muda kondisaun koa nian hodi muda velocidade husi espindulu

[2] Uza *damper* atu minimiza amplitudu vibrasaun nian

[3] Hasae rigidez hodi haboot mákina nia medida no nia todan

Maibe kontramedida sira nee seidauk kontentavel nafatin.

Ba razaun [1], muda kondisaun koa nian hodi muda velocidade spindulu nian atu sés husi frekuensia resonansia, geralmente uza barak durante fabrikasaun iha industria ho fabrika sira. Maibe, mudansa iha spindulu sei modifika kondisaun koa nian, tan nee, rezultadu ikus koa nian sei la ótimo. No mos, kondisaun ida nee la desejavél iha produsaun nebe barak ^{[3-5], [3-6], [3-12]}

Ba razaun [2], uza *damper* atu redús amplitudu vibrasaun nian uza barak ona iha industria no servisu privadu sira iha ohin loron nee.^{[3-9], [3-10], [3-11]} Uza *damper* no suspensaun, efetivu liu hodi redús amplitudu vibrasaun nian. Maibe, tamba mákina nebe komplezo normalmente iha frekuensia resonansia nebe barak, *damper* no suspensaun sei difisil wainhira uza iha frekuensia resonansia nebe barak ^[3-1]. No mos, presiza kustu neebe aas ba instalasaun no modifikasaun ba iha mákina. Tan nee, kontrolu nebe fasil no kustu kiik mak prefere liu.

Ba razaun [3], hasae rigidez hodi haboot medida no todan mákina produsaun nian bele hasae frekuensia resonansia. Maibe, medida mákina nian no todan nebe boot sai karu liu wainhira halao transportasaun, no mos presiza fatin nebe luan

atu tau mákina ba. Aumenta liu tan, konsidera ba iha produtividade iha produsaun masal, mákina kiik barak presiza liu atu halo produsaun nebe barak dala ida deit duque mákina boot ida. Ho ida nee, mákina nia medida no todan nebe boot ladun presiza iha produsaun masal.

Antes defini metodu atu kontrola resonansia, análise komputacional presiza atu halao uluk. *Torno de bancada* remodela uluk, hafoin análise uza CAE. Resposta frekuensia husi vibraisaun livre kalkula no ezamina. Modus lima frekuensia resonansia nian imprimi ho sira ninia rezultadu hatudu iha Fig. 3.1. Iha rezultadu nee ita bele haree katak vibraisaun boot mosu iha mákina niaulun no baze motor nian. Rezultadu frekuensia resonansia konsektivamente husi kalkulasaun mak 16.197 Hz, 26.129 Hz, 49.71Hz, 90.726 Hz and 125.48 Hz. Modus tolu primeiro mak

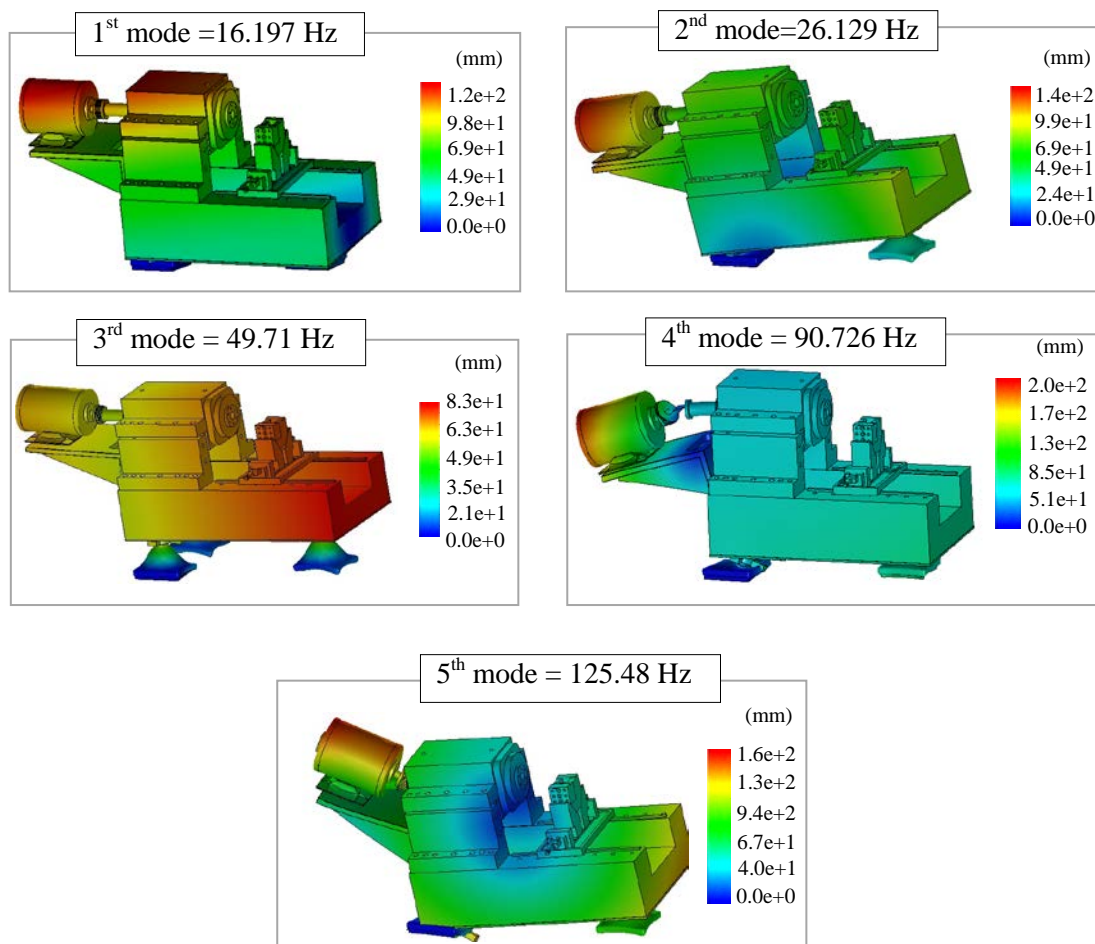


Fig. 3.1 Modu vibraisaun mákina tornu nian analiza iha vibraisaun livre

resonansia vibraisaun nian husi *torno de bancada* tui-tuir malu iha X, Z and Y áxis. Modu 4 no 5 mak kombinasau husi vibraisaun iha Z-X and Z-Y axis, konsekutivamente. Bazeia ba rezultadu nee, peskiza nee halao atu investiga no harii metodu kontrolu neebe bele uza atu evita frekuensia resonansia sira nee.

3.1.3 Metodu kontrolu atu kontrola densidade, rigidez no posisaun suporta nian

Hodi bele desenvolve metodu kontrolu nian atu kontrola frekuensia resonansia, parametru no kontamedida oi-oin mak konsidera iha estudu nee atu bele defini metodu ida nebe efetivu liu. Konsiderasaun husi metodu kontrolu nian atu kontrola densidade, rigidez no posisaun suporta nian hatudu iha Fig. 3.2. Husi fasil no operasaun lalais nia pontu de vista; (1) Muda *apparent* densidade, (2) Muda rigidez, no (3) Muda posisaun suporta nia pontu sira hodi muda modu vibraisaun nian hanesan fatór 3 nebe konsidera atu hodi halao investigasaun ba.

Atu kontrola *appearance density* husi mákina produsaun hanesan mensiona iha (1); ① troka *Espessura* estrutura mákina nian, ② uza materiais ho *densidade*

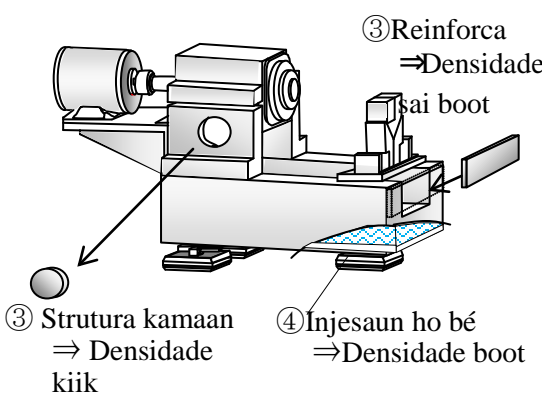
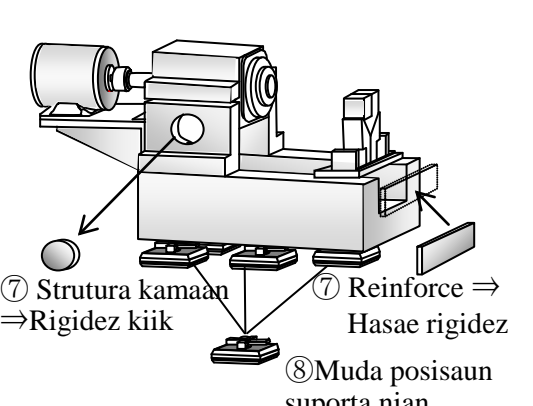
Atu kontrola densidade iha makina produsaun	Atu kontrola rigidez iha makina produsaun
<p>① Mudansa iha klean (Espessura ⇒ densidade sai boot)</p> <p>② Mudansa iha materiais ba densidade</p>  <p>③ Reinforca ⇒ Densidade sai boot</p> <p>③ Strutura kamaan ⇒ Densidade kiik</p> <p>④ Injesaun ho bé ⇒ Densidade boot</p>	<p>⑤ Mudansa iha klean (Espessura ⇒ Rigidez sai boot)</p> <p>⑥ Mudansa iha materiais ba rigidez</p>  <p>⑦ Strutura kamaan ⇒ Rigidez kiik</p> <p>⑦ Reinforce ⇒ Hasae rigidez</p> <p>⑧ Muda posisaun suporta nian</p>

Fig. 3.2 Skemátiku tekniku sira nebe mak bele uza atu kontrola densidade no rigidez iha mákina produsaun nian

neebe diferente, ③ Aumenta ou hasai parte balun husi estrutura mákina nian, no ④ Fui bé ba iha mákina nia base no fatin seluk iha mákina nia estrutura hanesan posivilidade sira neebe foti ba konsiderasaun. Tamba ①, ②, no ③ laós deit kontrola densidade mas bele mos afeta ba rigidez tomak mákina nian, presiza fo atensaun didiak wainhira halao modifikasaun. Nunee mos, tamba ① no ② presiza modifikasaun neebe boot ba iha mákina no désde kontrola nebé fasil mak prefere liu, metodu rua nee sei la aplika iha estudu ida nee. Tamba nee, ③ no ④ deit mak sei aplika atu kontrola densidade iha mákina produsaun.

Atu kontrola rigidez tomak mákina nian hanesan mensiona iha (2); ⑤ Muda espessura husi estrutura mákina nian, ⑥ uza *young's modulus* husi materiais nebe la diferente, ⑦Aumenta ou hasai parte balun husi estrutura mákina nian mak possibilidade 3 nebe foti nudar konsiderasaun. Henesan ho konsiderasaun halo hodi muda densidade, ⑤ no ⑥ presiza modifikasaun boot tan nee la adequa ba kontrolu nebé simples no sei la uza iha jornal nee. Tamba nee, metodu ⑦ deit mak konsidera atu aplika hodi muda rigidez estrutura nian.

Atu kontrola no muda modu vibraisaun husi mákina produsaun nian hodi troka no muda posisaun suporta nian hanesan mensiona iha (3); ⑧ posisaun pontu suporta mákina produsaun nian (posisaun husi bolt pocket) konsidera uza atu muda no altera frekuensia resonansia. Kuando suporta barak uza ba iha sistema, sei rezulta mudansa iha modu vibraisaun sistema nian, tan nee bele kontrola frekuensia resonansia. No mos, distansia entre suporta ida-idak bele mos konsidera hodi uza atu desloka frekuensia resonansia mákina nian.

3.1.4 Metodu proposta hodi kontrola frekuensia resonansia

Ho konsiderasaun oin-oin ezamina ona iha sesaun 3.1.3, metodu proposta ba kontrolu nebe fasil no lalais atu kontrola frekuensia resonansia desidi ona. Tau bé ba *vessel* iha mákina nia ulun no baze, aumenta no hasai parte balun husi mákina

nia estrutura, no muda posisaun suporta mákina nian hanesan proposta ba kontramedidas. Hanesan rezumu ba konsiderasaun husi metodu kontrolu nian nebe esplika ona iha sesaun uluk, esplikasaun ba parametru tolu atu defini metodu neebe proposta ba kontrola resonansia nian hatudu iha Tabela 3.1. Iha tabela nee, metodu kontrolu sei defini detailu liu tan no esplikasaun ba razaun tan saida mak hili tékniku kontrolu sira nee. Bazeia ba Fig. 3.2, kontramedida ③, ④, ⑦, no ⑧ hili nudar kontramedida ba tekniku kontrolu. Atu halo kamaan estrutura hodi hamenus densidade no hatodan estrutura ba densidade neebe aas, bele uza kontramedida ③. Maibe, tamba prefere liu densidade nebe kiik, hili deit kontramedida nebe mak bele halo kamaan mákina.

Kontramedida ④ uza atu kontrola densidade hodi tau bé no aumenta todan atu hasae densidade mákina nian, maibe tamba estrutur neebe kamaan no operasaun nebe facil prefere liu, hili deit mak uza bé para hasae densidade iha mákina produsaun. Ba kazu atu hasae rigidez, kontramedida ⑦ hili tamba

Tabela 3.1 Esplikasaun ba parametru tolu hodi kontrola frekuensia resonansia

Kontramedida	Kontextu ho detalha	Kontramedida nebe hili
③ (Haré Fig. 3.3)	Estrutura nebe kamaan ho densidade nebe kiik & structure todan ba density nebe a'as	Estrutura nebe kamaan deit ho densidade nebe kiik
④ (Haré Fig. 3.3)	Tau be no aumenta todan ba hasae densidade makina produsaun nia estrutura	Tau deit be atu hasae densidade iha makina produsaun nia estrutura
⑦ (Haré Fig. 3.3)	Hasae rigidez uza reinforsa & hamenus rigidez hodi hasai estrutur ida (Nee hanesan ho ③)	Rigidez nebe a'as deit uza reinforsu
⑧ Suporta	Kontrola posisaun husi suporta nian atu muda frekuensia resonansia no nia <i>mode shape</i>	Kontrola posisaun husi suporta

kontramedida nee bele uza atu hasae rigidez hodi reinfora mákina nia estrutura no bele mos hamenus rigidez hodi hasai estrutura mákina nian balun. Kontramedida nee hanesan ho kontramedida ③, maibe tamba rigidez nebé aas prefere liu, nunee hili deit mak kontramedida nebe hasae rigidez. Finalmente, kontramedida ⑧ mos hili ho razaun kuandu muda posisaun husi suporta no uza pontu suporta nian neebe diferente, bele muda frekuensia resonansia no ninia modu vibraasaun.

Bazeia ba kontramedida neebe hili tiha ona, metodu propostu atu kontrola frekuensia resonansia define tuir kontrolu ninia fasil, simples, no efektivu. Esplikasaun ba parametru no kontramedida sira hodi kontrola frekuensia resonansia husi mákina produsaun nian hatudu iha Fig. 3.3. Metodu kontrolu 3 nudar fatór kontrolu nebe define nudar metodu kontrolu. Fatór kontrolu I hodi tau bé, fatór kontrolu II hodi reinfora estrutura mákina nian, no fatór kontrolu III hodi muda quantidade suporta nian no nia posisaun. Espesífiku liu, esplikaun ba parametru konfigurasaun nian ba kontrola frekuensia resonansia ilustra iha Fig. 3.3. Metodu propostu sei esplika hodi foti ezemplu ba iha mákina tornu kiik nebe uza iha experimentu. Primeiru, aumenta todan hodi tau bé ba iha mákina nia estrutura nunee hamenus frekuensia resonansia (hasae densidade) neebe define nudar fatór kontrolu I. ho kontrolu nee, frekuensia resonansia sei redús maibe, ho *damping ratio* nebe kiik, bé halo boot fali vibraasaun. Tan nee, ba efetividade nebé aas, mistura husi bé no polimer mos sei performa. Tuir mai, ho akordansia ba iha rezultasu análise preliminaru nia, modu vibraasaun primerio no segundu boot besik motor nia baze, tamba nee, hasae frekuensia resonansia hodi reinfora baze motor nian no hamenus todan (densidade kiik) atu hadiak liu tan rigidez husi mákina define nudar fatór kontrolu II. Ikus mai, hodi muda posisaun no numeru husi pontu suporta nian iha mákina produsaun, bele iha possibilidade atu muda frekuensia resonansia ho ninia modu vibraasaun. Metodu kontrolu ida nee

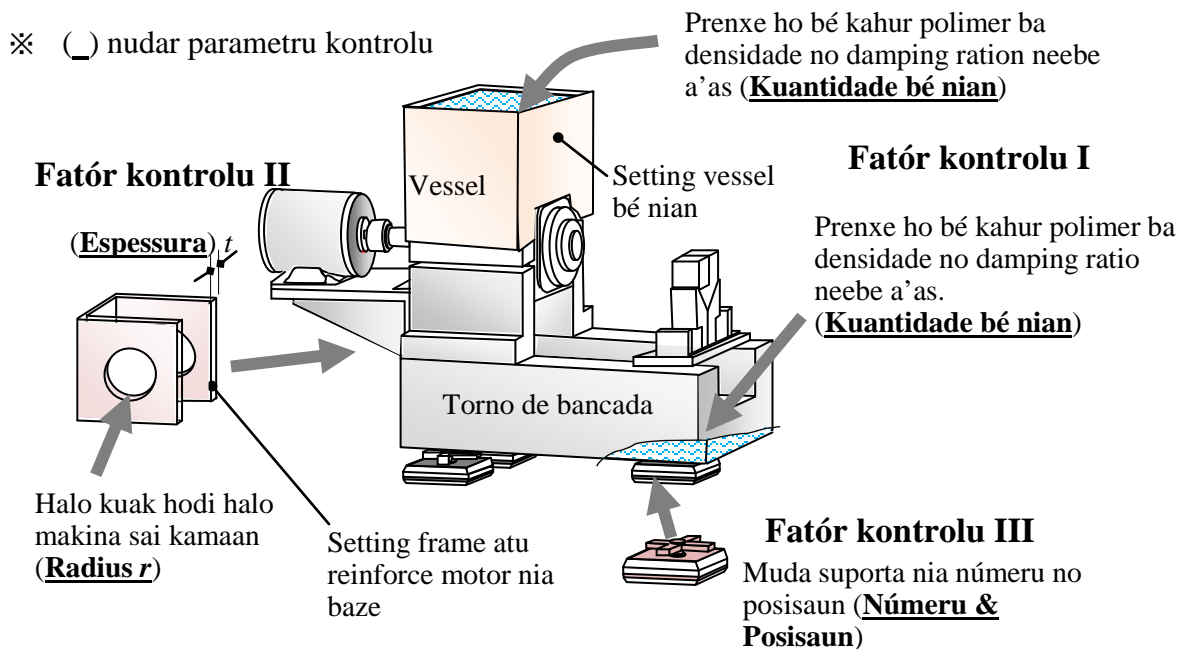


Fig. 3.3 Esplikasaun ba parametru no kontramedida sira hodi kontrola frekuensia resonansia iha mákina produsaun

defini hanesan fatór kontrolu III. Metodu sira iha leten bele aplika ho adjustamentu nebe facil, tan nee konsidera bele fo kontribusaun nebe boot ba iha aplikasaun pratiku nian. No mos, iha estudu nee, metodu kontrolu sira nee konsidera atu uza ba iha distansia frekuensia resonansia husi 100 Hz ba kraik ^[3-1] neebe iha influensia boot ba iha presisaun prosesu koa nian. Iha metodu nebe uza bé iha fatór kontrolu I, *viscosity* bé nian halo boot liu tan atu hasae *damping ratio*. Iha nee, bé kahur ho polimer PEO (Polyethylene oxide) no nivél *damping ratio* nian sei investiga liu husi experimetu. Figura 3.4 hatudu tubu besi ho naruk $\ell = 300$ mm no klean $t = 2$ mm, enxe ho bé kahur polimer PEO no tara uza fiu iha $\ell/3$ husi parte rua tubu nia sorin. Parte klaran husi tubu nee baku uza *impact hammer*, depois sukat nia vibrasaun uza acelerômetro nebe monta iha parte opostu husi pontu baku nian. *Damping ratio* sura uza *logarithmic decrement* husi resposta exitasaun nian. Tamba *damping ratio* nebe sukat liu husi experimentu kahur mos ho karakterístika tubu besi nian, analize inverse FEM nian sei halao atu buka

damping ratio nebe lós husi bé ho polimer mesak deit hodi uza metode *curve fitting* entre rezultadu husi experimentu ho FEM hatudu iha Fig. 3.5.

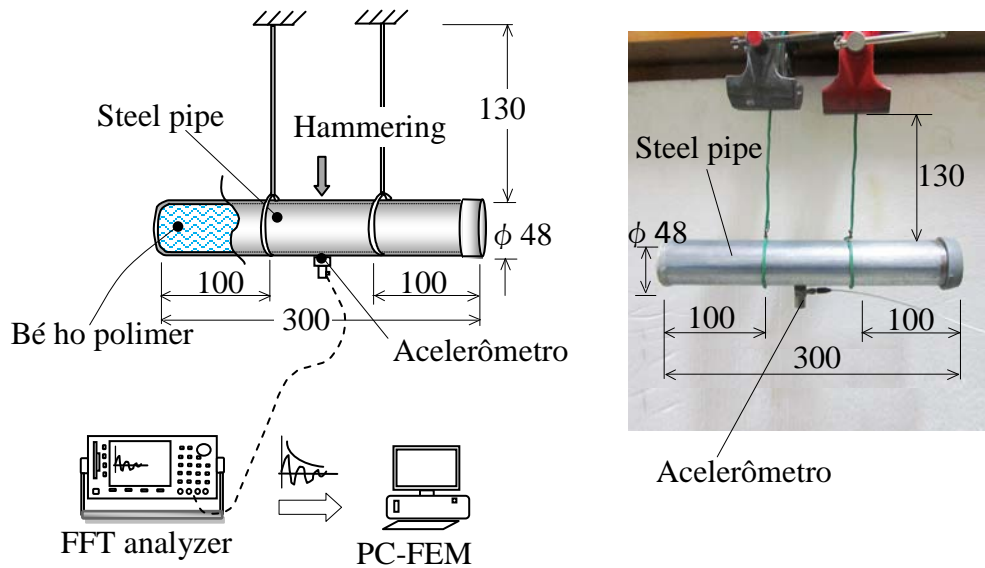


Fig. 3.4 Konfigurasaun experimentu nian no fotografia husi metodu atu sura *damping ratio* husi bé no polymer

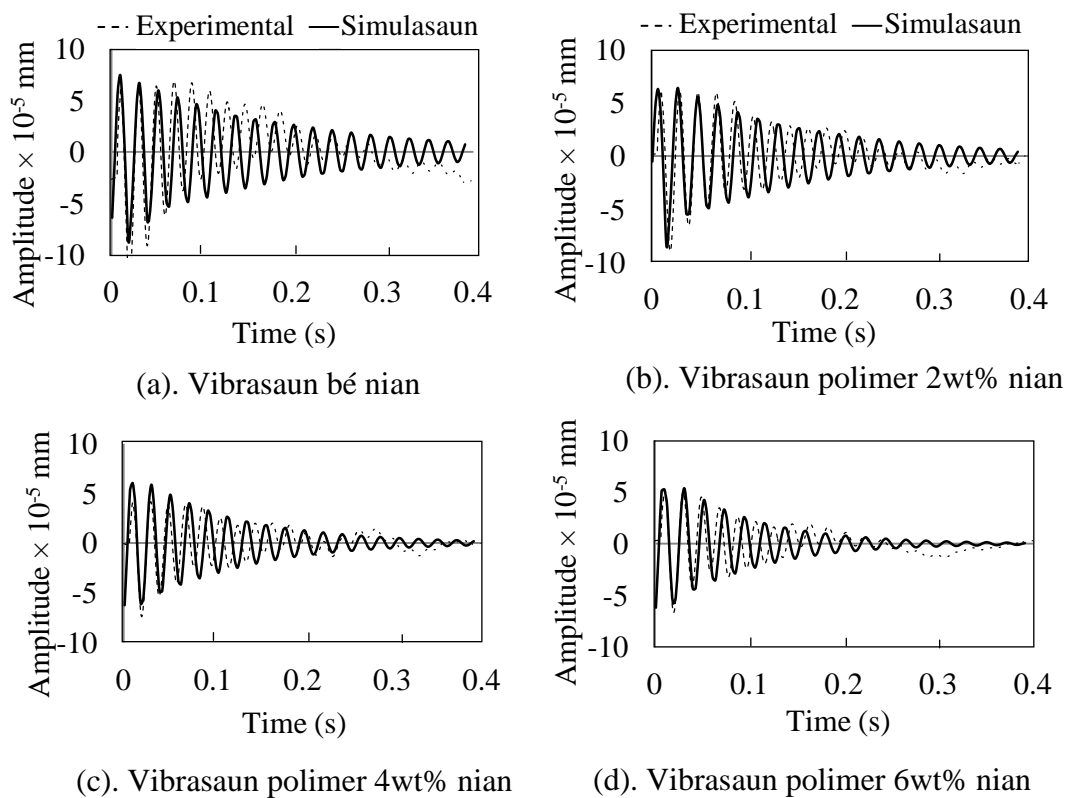


Fig. 3.5 *Curve fit* husi medisaun *damping ratio* nian entre experimental ho simulasaun

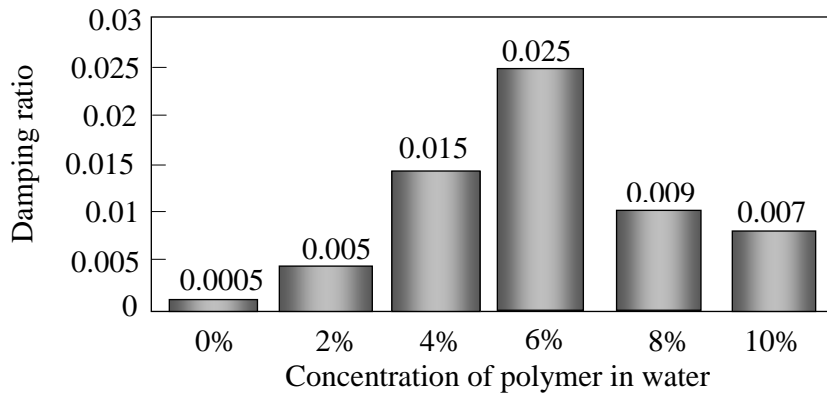


Fig. 3.6 Relasaun entre percentazen polimer nian ho *damping ratio* (Resultadu husi experimentu)

Relasaun entre percentazen husi polimer ho *damping ratio* husi rezultadu experimentu nian hatudu iha Fig. 3.6. Bainhira *apparent* densidade bé nian hasae iha tempu kahur ho polimer, *damping ratio* mos aumenta. Tamba nee, konsidera hanesan kontrolu neebe suficiente ba hamenus frekuensia resonansia no amplitudu vibraisaun nian. Hodi hasae polimer nia konsentrasaun, ninia efetividade mos aumenta, maibe, desde *viscosity* mos sai boot liu tan, prosesu enxe no hasai bé sai difisil liu tan wainhira konsentrasaun polimer nian boot liu 6 wt%. Tamba nee mak konsentrasaun polimer nian limite too deit 6 wt%.

3.2 Investigasaun uza CAE simulasaun ba fatór kontrolu sira (densidade, rigidez and supporta)

Modelu elementu finito neebe uza iha simulasaun nee hatudu iha Fig. 3.7. Modelu nee sei aplika iha investigasaun ba metodu; (1) hamenus frekuensia resonansia hodi enxe bé iha mákina nia estrutura hodi aumenta nia mákina nia todan (densidade boot), (2) Hasae frekuensia resonansia hodi redús todan (hamenus densidade) no reinforce estrutura (hasae rigidez), (3) Muda posisaun suporta nian atu muda frekuensia resonansia ho ninia modu vibraisaun. Iha analize nee, modelu husi finite elementu construi no pinta bazeia ba mákina tornu de bancada neebe los nian. Ho modelu komputasaun

nee, analize uza mákina tornu bancada neebe modifika ona bele halao tamba bele fornese dados foun kona ba sistema nebe difisil no imposivel atu hetan wainhira uza instrumentu nebe ordinariu. Ho CAE simulasaun nee, modelu husi *torno de bancada* nee konstrui bazeia ba metodu propostadu, neebe define tiha ona iha kapítulu liu ba. Análize halao ba metodu kontrolu ida-idak no sumariu husi kondisaun ótimu neebe defini ona husi analize sei avalia uza avaliasaun experimentu nian nebe sei esplika iha kapítulu tuir mai.

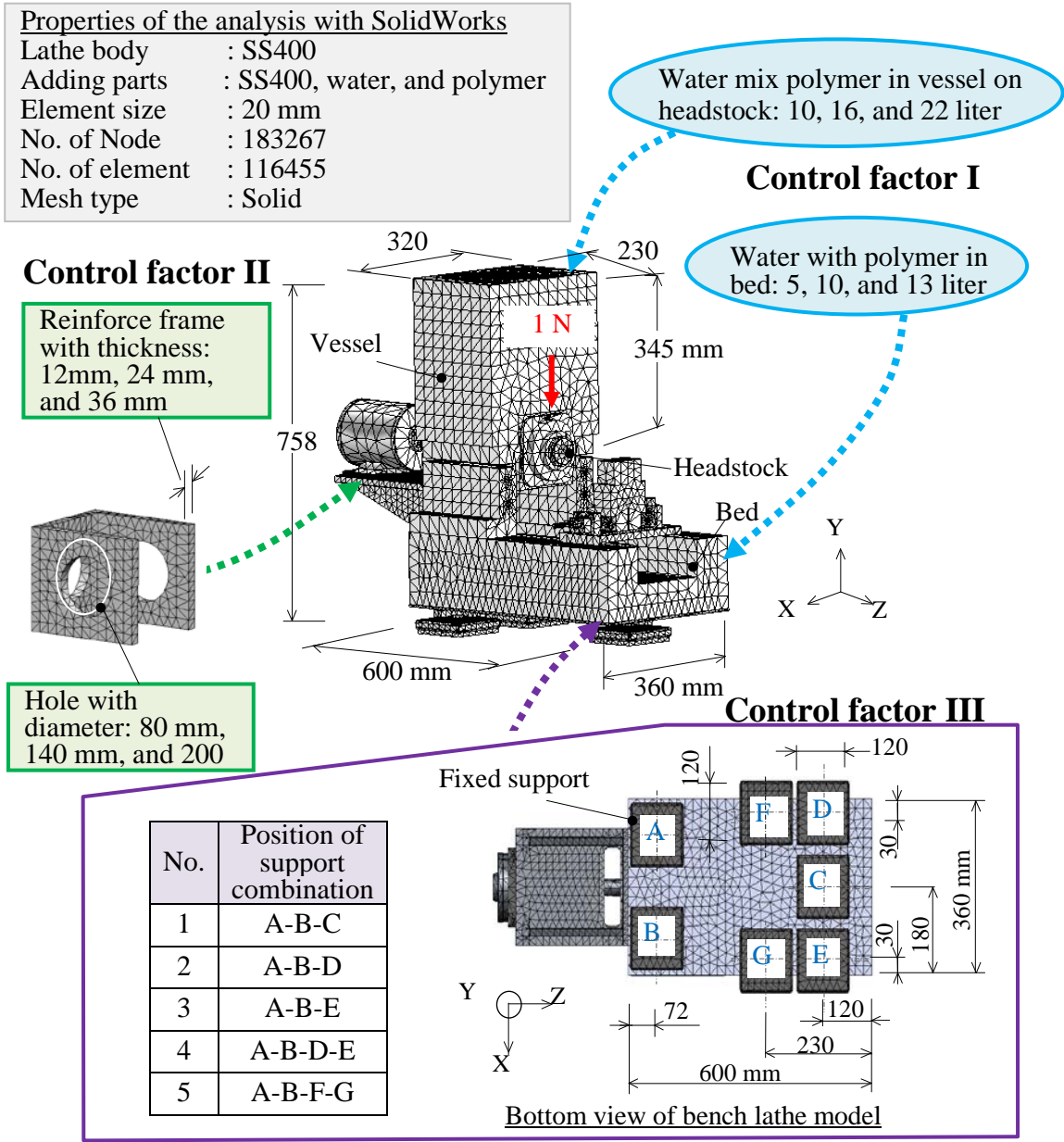


Fig.3.7. Modelu FEM nian ba investigasaun influensia husi densidade, rigidez, no suporta

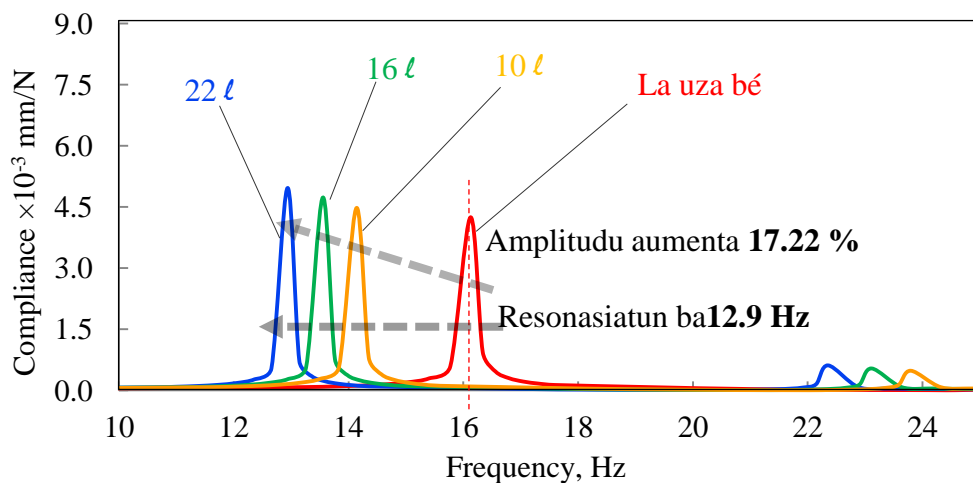
Modelu nebe uza ba invetigasaun husi fatóres kontrolu 3 mak modelu husi: densidade, rigidez and suporta. Investigasaun halao uza metodu 3 nee ho;

- (1) Fatór kontrolu I; Hamenus frekuensia resonansia hodi tau bé ba uha estrutura mákina nian atu hasae mákina nia toda (densidade boot).
- (2) Fatór kontrolu II; Haasae frekuensia resonansia hodi hamenus todan (hatun densidade) no reinfora estrutura (hasae rigidez).
- (3) Fatór kontrolu III; Muda posisaun suporta nian atu bele muda frekuensia resonansia ho ninia *mode shapes*.

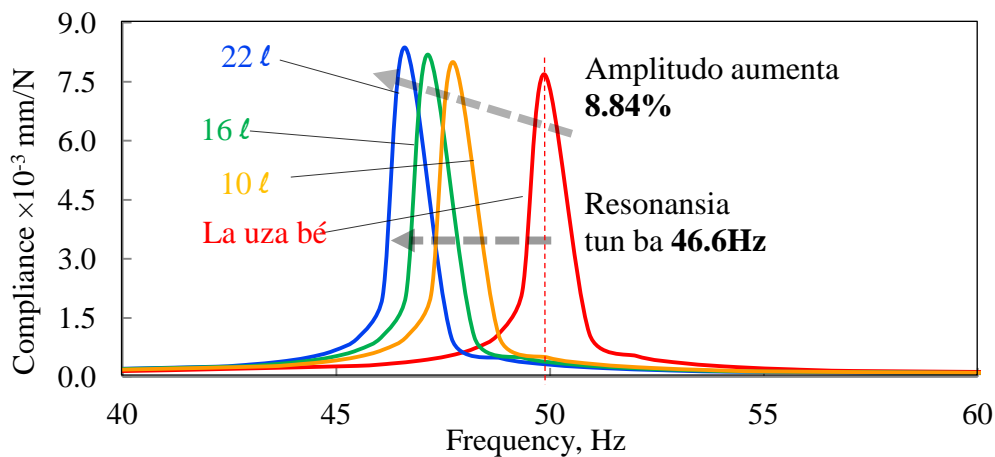
3.2.1 Enxe bé atu hatun resonansia nia frekuensia

Injesaun bé ba iha fatin nebe mamuk iha estrutura mákina nian sei aumenta mákina nia todan no halo densidade mákina nian sai aas liu tan, hodi nune, afeita frekuensia resonansia atu muda sés husi ninia frekuensia original. Iha kalkulasaun frekuensia resonansia kona ba aumentasaun bé nian, mákina tornu bancada kiik simplifika tiha ba iha modelu komputasional uza programa SolidWorks. Analize no kalkulasaun influensa bé nian ba iha frekuensia resonansia halao hotu. Atu halo kiik frekuensia resonansia, bé fui ba iha fatin 2; *vessel* iha mákina nia ulun no mákina nia baze. *Young modulus* bé nian konsidera hanesan 1×10^{-6} GPa ba iha numeru nebe kiik liu husi elementu nebe solidu. Numeru nee foti ho suposisaun katak iha element solidu neebe kiik liu iha bé laran. Valór *damping* nian nebe uza iha analize nee hetan husi rezultadu experimentu preliminaru nian (Fig. 3.4). Ba komparasaun nian, kontramedita seluk hodi aumenta polimer ho konsentrasaun 2wt%, 4wt% and 6wt% mos konsidera hotu. Investigasaun hodi kahur bé ho polimer PEO (Polyethylene-oxide) atu sai hanesan jelly, nune bele hasae *damping ratio* halao hotu. Valór *damping ratio* nian hetan husi rezultadu experimentu iha Fig.3.6. Iha analize nee, posisaun suporta nian uza suporta (A-B-C) hanesan hatudu iha Fig.3.7. Evaluasaun ba vibraun livre nian komputa no

analiza uluk, depois analizasaun ba vibraasaun forsada halao hodi fó impaktu ho forsa 1N ba iha parte leten husi mákina niaulun (*headstock*) husi dirasaun Y-áxis. Y-áxis mak dirasaun koa nian husi feramenta (*bite*). Rezultadu análise husi resposta frekuensia nian hatudu iha Fig. 3.8 ho áxis vertikulu nudar *compliance* vibraasaun nian neebe iha influencia makaas ba iha rugosidade peça nian. *Compliance* neebe boot liu sei halo rugosidade sai aat liu tan. Maibe, kuandu *compliance* sai kiik, *peça* sei sai kabér liu tan. Tamba nee, analize nee halao atu buka rezultadu neebe ótimu ho *compliance* neebe kiik liu.

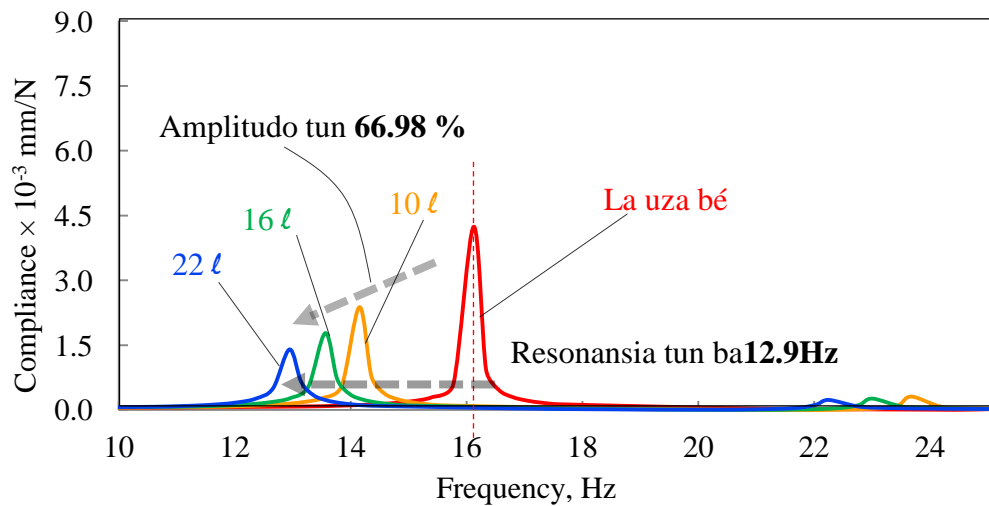


(a) Injesaun bé ba vessel iha headstock (áxis X)

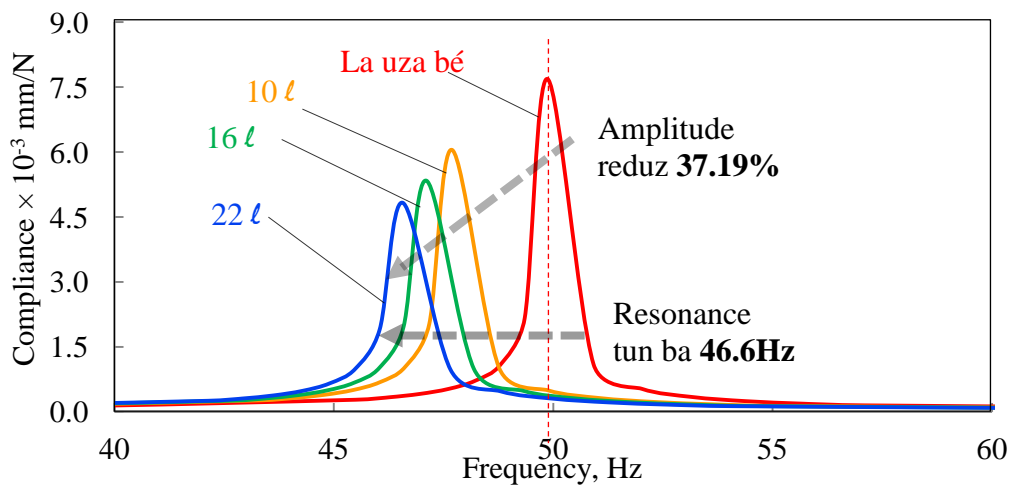


(b) Injesaun bé ba vessel iha headstock (áxis Y)

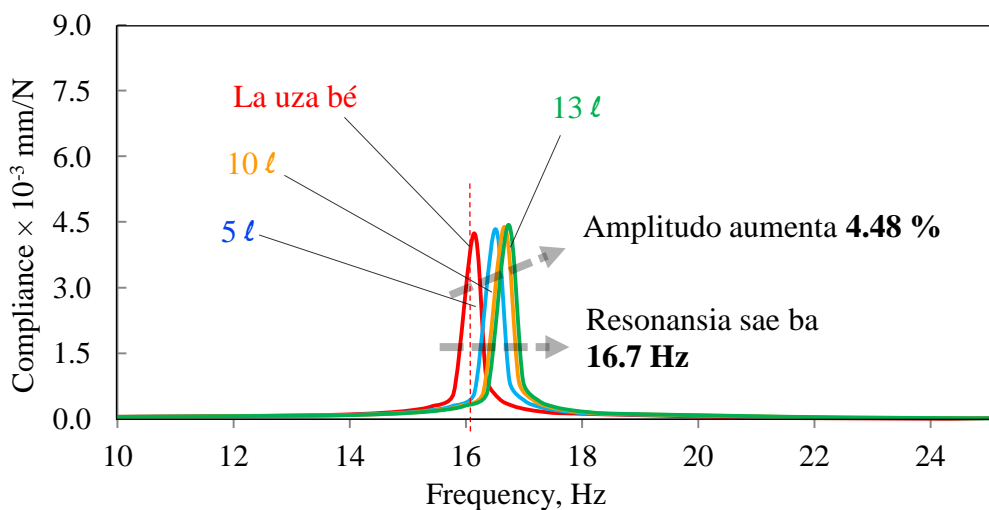
Fig. 3.8 Resposta frekuensia nian husi makina torno de bancada ho densidade oin-oin (Kalkulasaun uza FEM)



(c) Injesaun bé ho polimer ba vessel iha headstock (áxis X)

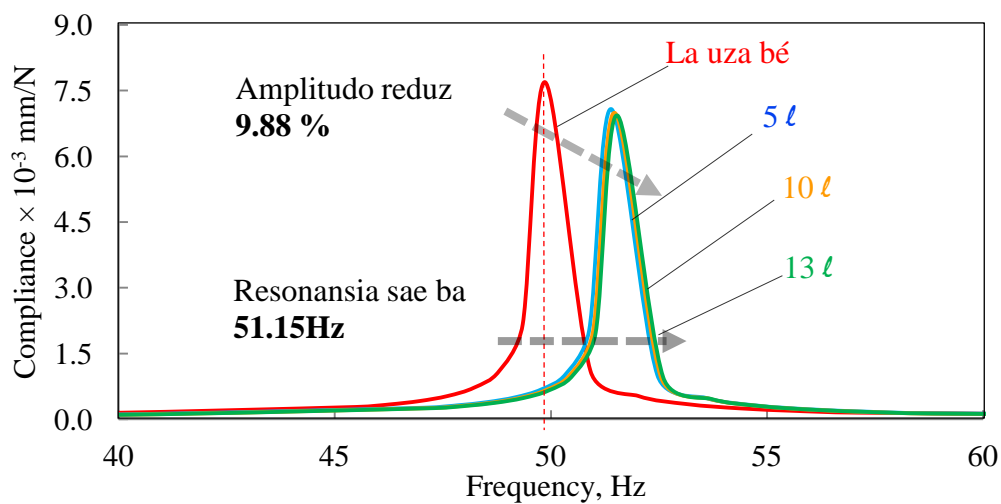


(d) Injesaun bé ho polimer ba vessel iha headstock (áxis Y)

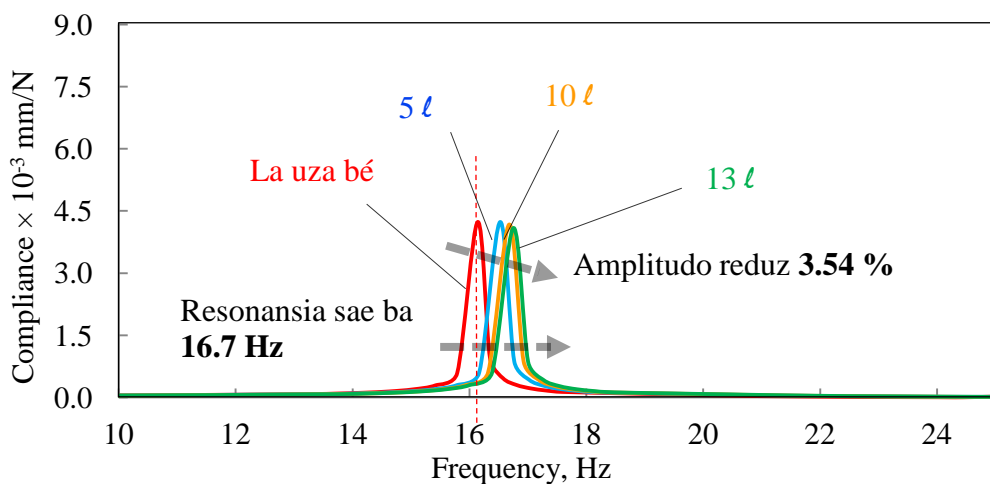


(e) Injesaun bé ba makina nia baze (áxis X)

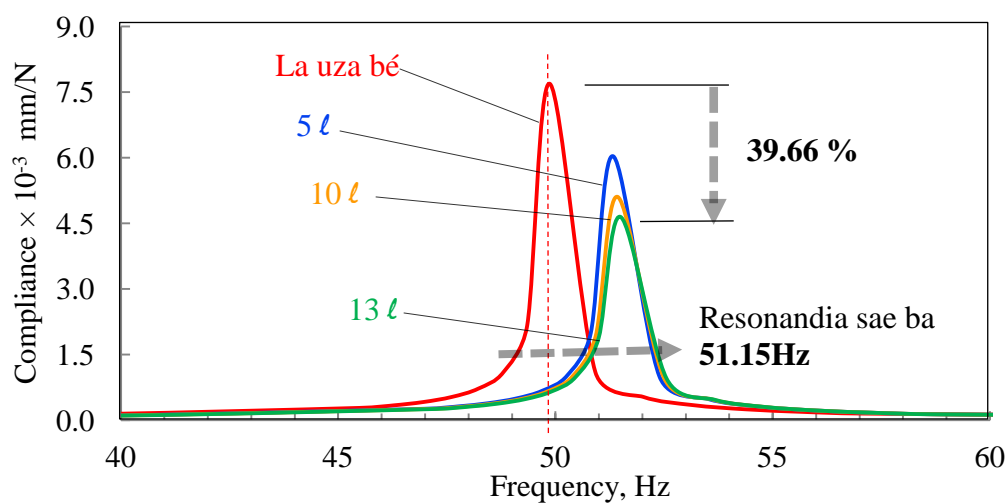
Fig.3.8 Resposta frekuensi nian husi makina torno de bancada ho densidade oin-oin (Kalkulasaun uza FEM)



(f) Injesaun bé ba makina nia baze (áxis Y)



(g) Injesaun bé ho polimer ba makina nia baze (áxis X)



(h) Injesaun bé ho polimer ba makina nia baze (áxis Y)

Fig. 3.8 Resposta frekuensi nian husi makina torno de bancada ho densidade oin-oín (Kalkulasaun uza FEM)

Influensia husi injesaun bé kahur ho polimer ba iha *headstock* hatudu katak iha possibilidade atu redús frekuensi resonansia kuaze 10 Hz. Fig. 3.8a), b), c), no d) fo hatudu rezultadu frekuensi nia resposta husi modelu komputerizada mákina tornu nian neebe enxe ho bé kahur polimer ba iha mákina nia *headstock*. Fig. 3.8e), f), g), and h) representa rezultadu husi resposta frekuensi hodi injeta bé kahur polimer ba iha baze mákina nian. Depois, reasaun avalia husi áxis X no áxis Y mákina *torno* nian.

Hodi injeta bé ba *vessel* neebe prepara ona iha mákina niaulun, frekuensi resonansia sai kiik kuaze 12.9 Hz iha áxis X (Fig. 3.8a). Husi rezultadu mos hatudu katak, hodi enxe bé too litru 22, bele kontrola frekuensi resonansia too 12.9 Hz iha diresaun horizontal nian. Iha áxis Y (Fig. 3.8b), frekuensi resonansia tun too kuaze 46.6 Hz wainhira uza bé ho litru 22. Nune'e, wainhira enxe bé barak liu tan, frekuensi sei tun ho número nebe boot. Maibe, se uza bé barak liu fali mos, vibraisaun nia amplitudu sei aumenta makaas. Rezultadu resposta frekuensi nian hatudu iha Fig. 3.8(a) no 3.7(b) uza bé litru 22. Rezultadu hatudu katak vibraisaun nia amplitudu aumenta tui-tuir malu kuaze 17.22% ho 8.84% iha áxis X ho áxis Y. Ho rezultadu ida nee, ita bele hateten katak bé efetivu tebes ba kontrola frekuensi resonansia maibe, ladun efetivu iha kontrolasaun ba vibraisaun nia amplitudu.

Tan bé efetivu atu hatun frekuensi resonansia, maibe bé sempre haboot vibraisaun nia amplitudu, tan nee, ami konsidera no analiza metode kahur bé ho polimer PEO atu bele redús amplitudu husi vibraisaun. Hanesan esplika ona iha kapitulu anterior, bé kahur ho polimer 6wt% iha valór *damping ratio* neebe diak liu, tan nee, ami desidi atu uza polimer 6wt% hodi kahur ba bé ho montante litru 10, litru 16 no litru 22 hodi uza ba iha simulasaun. Rezultadu resposta frekuensi nian iha diresaun X no Y wainhira enxe bé kahur konsentrasaun 6wt% husi polimer hatudu tuir malu iha Fig. 3.8(c) no 3.8(d).

Fig. 3.8(c) nudar resposta frekuensia iha áxis X hodi injeta bé kahur polimer ba iha *vessel* iha *headstock* mákina nian. Figura nee hatudu katak, amplitudu husi vibraasaun bele hatun too kuaze 66.96%, maibe frekuensia resonansia la muda no hanesan nafatin ida uza bé deit nee. Haree ba vibraasaun iha axis Y (Fig. 3.8d), amplitudu vibraasaun nian bele hatun too 37.19%, mas laiha mudansa iha ninia frekuensia resonansia.

Rezultadu seluk hodi injeta bé kahur polimer ba iha mákina nia baze hatudu iha Fig. 3.8(e), f), g), no h). Bé ho kuantidade litru 5, litru 10, no litru 13 uza nudar parametru. Resposta frekuensia nian kalkula husi áxis X no áxis Y hodi enxe mákina nia baze ho bé hatudu iha Fig. 3.8(e) no 3.8(f) tui-tuir malu. Iha parte seluk, resposta frekuesia iha diresaun X no Y hodi preence bé kahur ho polimer 6wt% ba iha mákina nia baze hatudu iha Fig. 3.8(g) no 3.8(h). Rezultadu sira nee hatudu katak, wainhira uza deit mak bé, vibraasaun nia amplitudu iha áxis X aumenta 4.48% no mos frekuensia resonansia sae too 16.7 Hz. Enquanto, iha diresaun Y nian, amplitudu tun kuaze 9.88% ho frekuensia resonansia sae too kuaze 51.5 Hz. Wainhira bé kahur tiha ho polimer ho konsentrasaun 6%, amplitudu husi vibraasaun tun kuaze 3.54 % no 39.66 % iha diresaun X ho Y, maibe frekuensia resonansia nafatin deit.

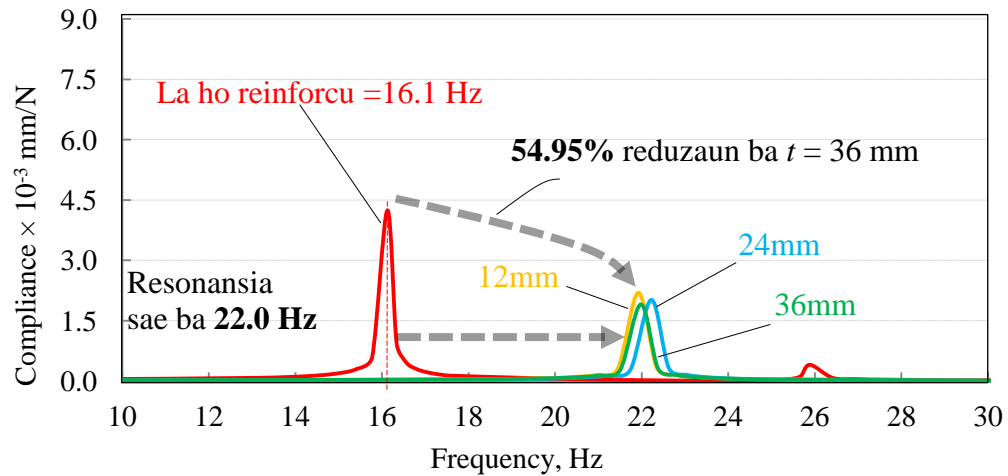
Nudar rezumu ba análise nee, wainhira aumenta uza bé, mákina nia masa mos aumenta hodi nune muda frekuensia resonansia. Iha parte seluk, tamba bé senpre haboot vibraasaun nia amplitudu, tan nee investigasaun atu redús vibraasaun hodi aumenta bé nia *damping ratio* mos performa hotu. Hodi kahur bé ho polimer sai hanesan bé jelly, *damping ratio* sai diak liu tan. Tamba nee, iha estudu nee, ami desidi atu uza bé kahur ho polimer nudar kontrolu frekuensia resonansia nian nebe óptimu. Kontrariu fali, wainhira injeta bé ba mákina nia baze, frekuensia aumenta deit 2~3 Hz. Nee tamba aumento iha mákina nia todan halo mákina nia baze sai forte liu tan, nuneé hasae *rigidez* no frekuensia resonansia. Nune mos,

ho inkrementu nebe kiik iha frekuensia resonansia wainhira injeta bé ba iha mákina nia baze, kontramedida nee sei uza deit hanesan konfirmasaun husi experimentu nian, tan nee sei la uza ba aplikasaun hanesan tekniku kontrolu ida iha peskiza nee. Maibe, ami sugere katak injesaun bé ba iha mákina nia baze sei efetivu liu se kuandu iha fatin mamuk no luan iha mákina, nune bele preenxe ho kuantidade bé nebe barak. Hodi dalan nee, bé nia efeito ba iha frekuensia resonansia konsidera bele sai diak liu tan.

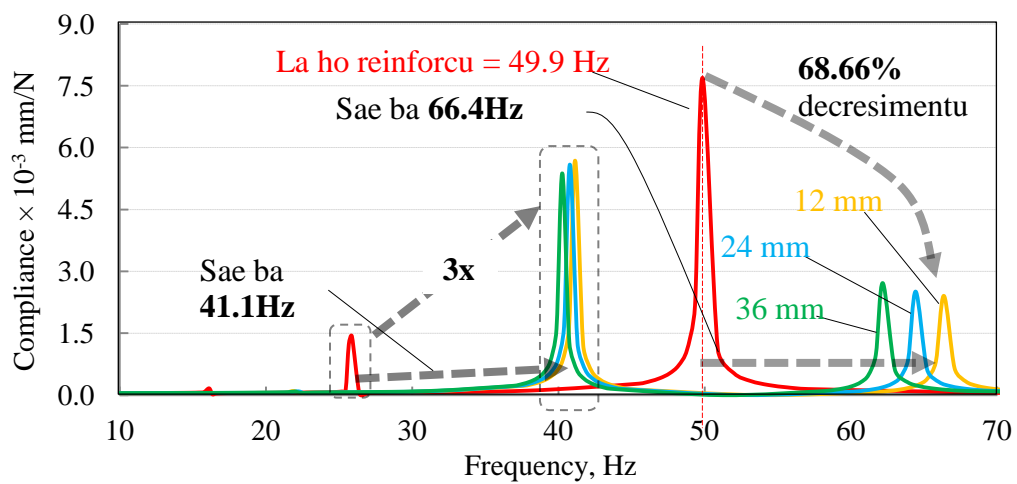
3.2.2 Hamenus todan (densidade kiik) no reinforsa estrutura (rigidez aas) hodi hasae frekuensia resonansia

Bazeia ba analize vibrasaun livre nian (Fig. 3.1), tamba modu vibrasaun nian neebe kiik liu mosu besik ba part husi motor nian, tan nee mak prosesu atu reinforsa desidi tiha ona hodi aplika ba iha parte okos baze motor nian, nune hasae rigidez parte neebe mamar husi baze motor nian. Hodi reinforsa parte neebe mamar ou ladun forsa husi motor nia baze, parte sira nee sei sai toos liu tan no frekuensia resonansia mos sei sai boot liu tan.

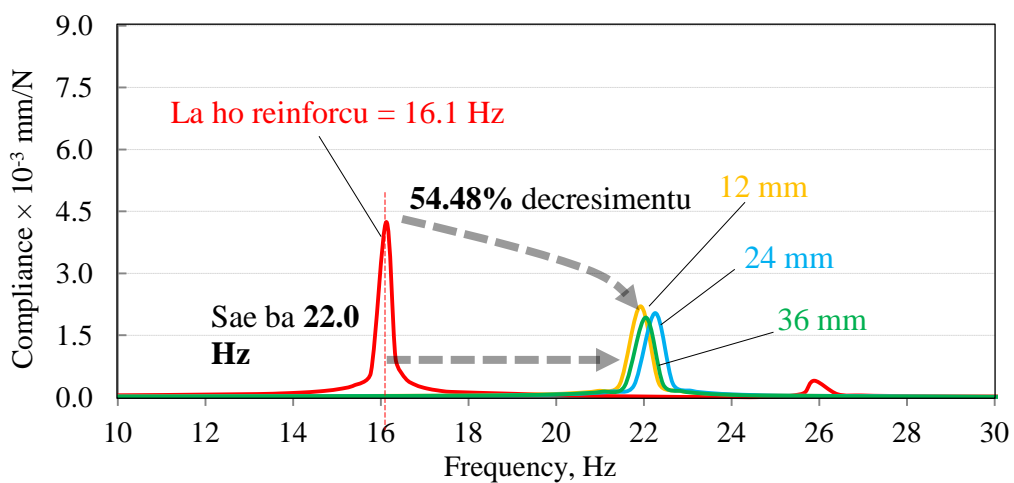
Análize halao uza chapa reinforsu (*reinforce frame*) ida-idak ho ninia klean nebe diferente hanesan; 12 mm. 24 mm no 36 mm. Atu halo kamaan chapa (hatun nia densidade), kuak ho diamentru hanesan; 80 mm, 140 mm, no 200 mm halo ba iha parte centru husi chapa nia sorin-sorin. Depois, analize halao ho kondisaun konfigurasaun nebe hanesan ho sessaun liu ba. Vibrasaun livre kalkula uluk tiha ho mákina suporta iha pontu (A-B-C), depois vibrasaun forsada analiza tuir hodi fo impaktu ho forsa 1N ba iha parte leten spindulu nian iha mákina nia ulun. Rezultadu kalkulasaun nian husi resposta frekuensia nian hatudu iha Fig. 3.9. Fig. 3.9(a) no (b) nudar resuldatu husi resposta frekuensia nian nebe kalkula iha diresaun X no Y la ho kuak iha chapa, enkuantu Fig. 3.9(c) no (d) nudar resposta frekuensia nian neebe uza chapa reinforsa ho diamentru 80 mm.



a) Reinforca la ho kuak (áxis X)

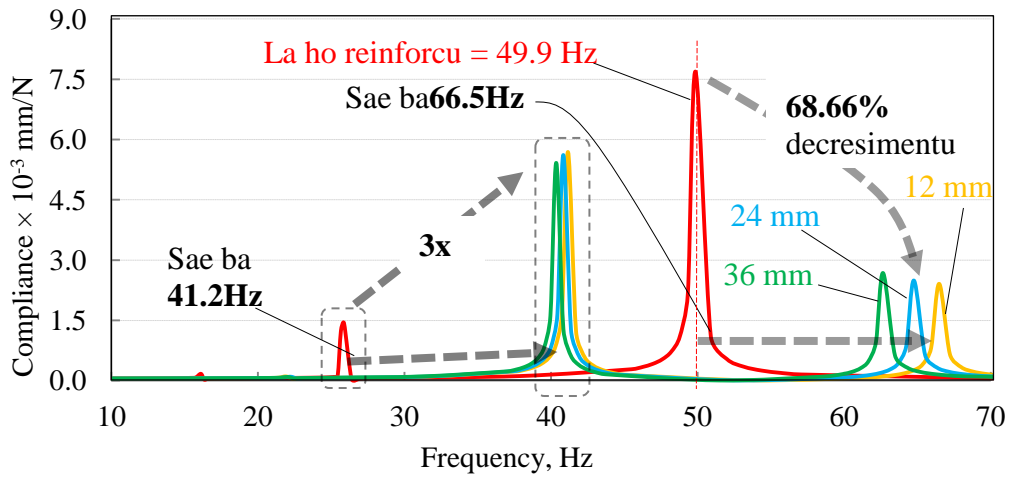


b) Reinforca la ho kuak (áxis Y)

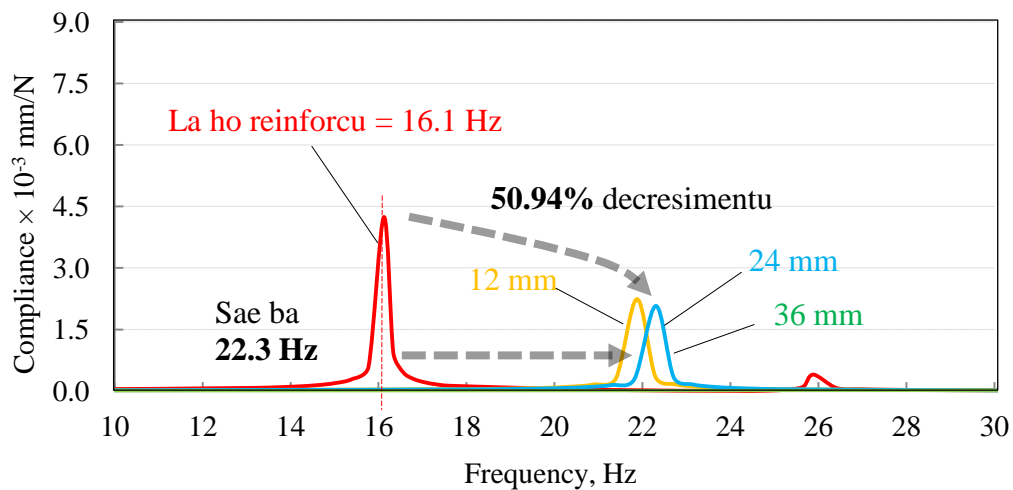


c) Reinforca ho kuak Ø 80 mm (áxis X)

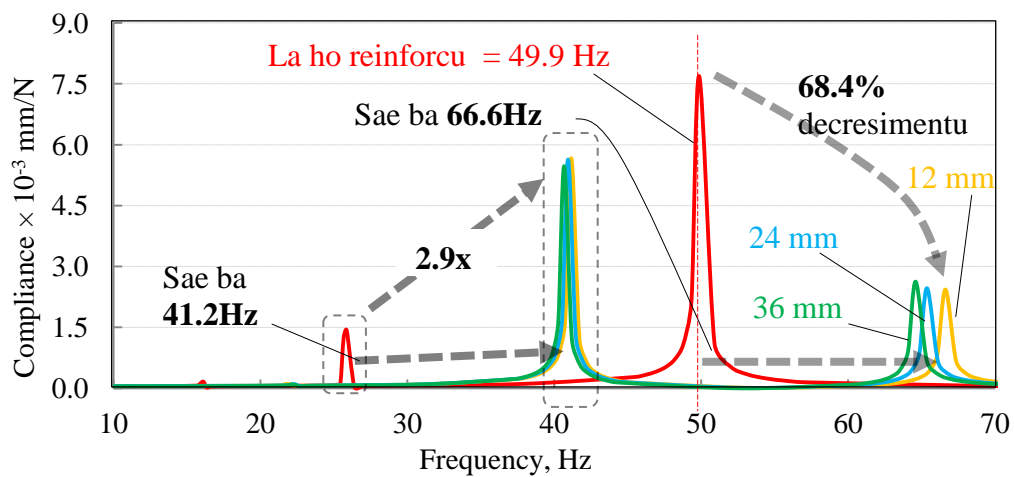
Fig. 3.9 Resposta frekuensia nian husi makina tornu de bancada ho stiffness oin-oin (Kalkulasaun uza FEM)



d) Reinforca ho kuak Ø 80 mm (áxis Y)

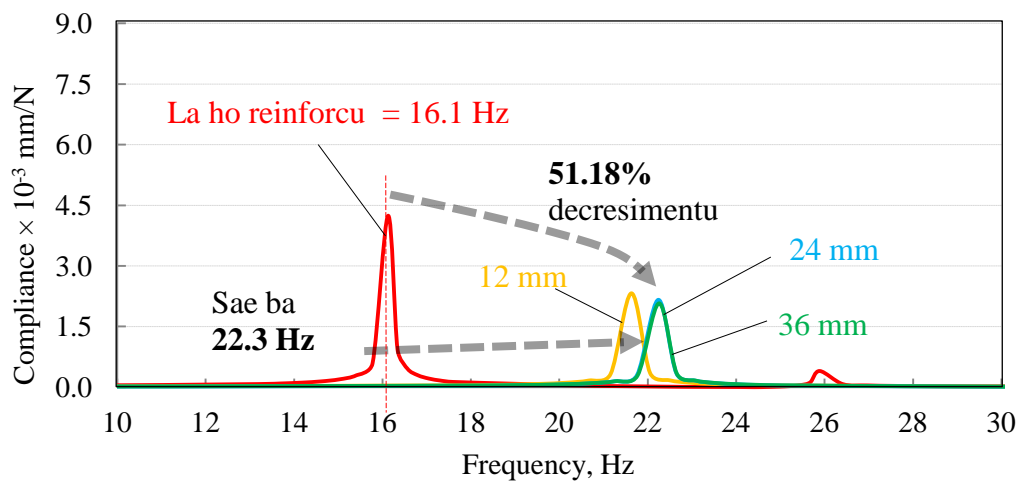


e) Reinforca ho kuak Ø 140 mm (áxis X)

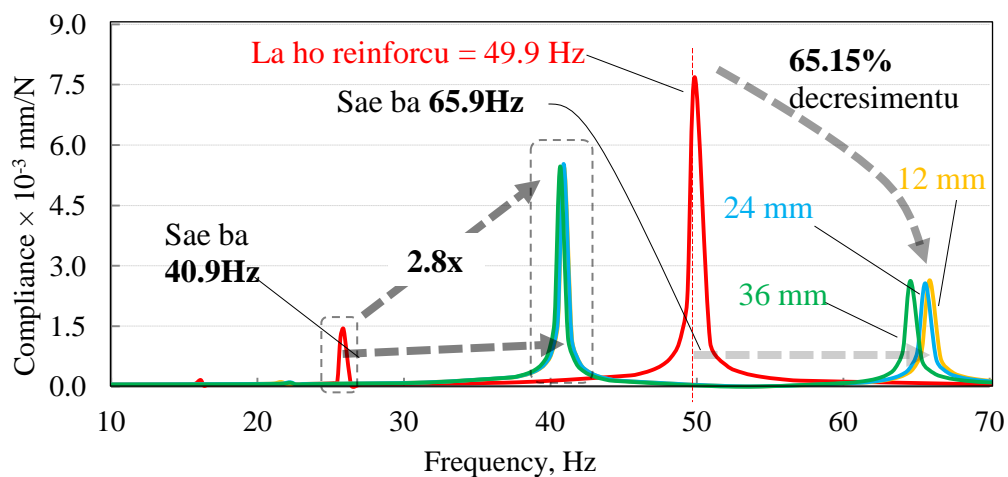


f) Reinforca ho kuak Ø 140 mm (áxis Y)

Fig. 3.9 Resposta frekuensia nian husi makina tornu de bancada ho stiffness oin-oin (Kalkulasaun uza FEM)



g) Reinforca ho kuak Ø 200 mm (áxis X)



h) Reinforca ho kuak Ø 200 mm (áxis Y)

Fig. 3.9 Resposta frekuensia nian husi makina tornu de bancada ho stiffness oin-oin (Kalkulasaun uza FEM)

Rezultadu resposta frekuensia nian kalkula husi diresaun X no Y tui-tuir malu hatudu iha Fig. 3.9(e) no (f) ba chapa reinforca nebe uza kuak ho diamentru 140 mm no mos iha Fig. 3.9(g) ho (h) ba chapa reinforca nebe uza kuak diamentru 200 mm. Rezultadu sira nee hatudu katak, frekuensia resonansia aumenta quaze 10 Hz too 15 Hz wainhira reinforca mákina nia estrutura. Iha modu 1, maske frekuensia resonansia aumenta, *compliance* mos aumenta.

Kuandu la halo kuak ida iha chapa, frekuensia resonansia aumenta too 22 Hz no

amplitudu husi vibrasaun tun too quaze 54.95% wainhira uza chapa reinfora ho klean $t = 36$ mm. Ida nee rezultadu neebe kalkula husi diresaun X. Husi diresaun Y nian, resonansia aumenta too 66.4 Hz husi ninia original frekuensia resonansia 49.9 Hz, enquanto nia amplitudu tun quaze 68.8 %. Iha parte seluk, hodi reinfora baze motor nian, frekuensia resonansia seluk iha mode 2° (24.5 Hz) sae too 41.1 Hz no ninia amplitudu mos aumenta boot too dala 3. Desde prosesu kontrol ba resonansia nia objetivu mak atu muda sés frekuensia resonansia husi ninia original frekuensia no se 1° , 2° , ou resonansia seluk la koresponde ba frekuensia tuir mai, kondisaun nee aseitavel. Compara ho frame nia klean neebe la halo kuak, frame tolu seluk bele muda frekuensia resonansia too quaze 22 Hz iha diresaun X nian. Maibe, chapa ho klean 36 mm mesak deit mak bele redús vibrasaun too 54.95 % compara ba frame seluk. No mos, chapa ho klean 12 mm diak liu wainhira uza atu muda frekuensia resonansia no redús vibrasaun nia amplitudu iha diresaun Y nian.

Wainhira uza chapa reinfora ho diamentru kuak $\varnothing 80$ mm, frekuensia resonansia aumenta ba 22 Hz no 66.5 Hz iha diresaun X no Y nian tui-tuir malu (Fig. 3.9c no d) no mos amplitudu vibrasaun nian tun too quaze 54.48 % iha diresaun X no 68.66 % iha diresaun Y nian. Frekuensia resonansia primeiru iha diresaun Y nia aumenta too 41.2 Hz no magnifika amplitudu sai boot dala tolu. Hanesan esplika tiha ona, tamba mudansa husi frekuensia resonansia primeiru iha diresaun Y nian la koincide ho frekuensia resonansia neebe tuir mai, nune konsidera aseitavel. Parametru ida nee mos konsidera ba iha rezultadu uza chapa reinfora ho diamentru kuak $\varnothing 140$ mm no $\varnothing 200$ mm.

Amplitude vibrasaun nian redús kuaze 50.94 % iha diresaun X no 68.4 % iha diresaun Y ba chapa reinfora ho diamentru kuak $\varnothing 140$ mm hole. Ho chapa nee, frekuensia resonansia mos aumenta too 22.3 Hz no 66.6 Hz tui-tuir malu iha diresaun X no Y. Enquanto, chapa reinfora ho kuak $\varnothing 200$ mm, muda frekuensia ba too 22.4 Hz iha diresaun X no 65.9 Hz iha diresaun Y no mos amplitudu

vibrasaun nian redús consecutivu ba 51.18% no 65.15 % iha diresaun X no Y.

Husi resuluatu hotu chapa reinforsu ho klean no kuak nebe diferente, ita bele haré katak, compara incrementu iha frekuensia resonansia entre rezultadu ida-idak, iha diresaun X, reforsa uza kuak Ø 140 mm no Ø 200 mm bele muda sés frekuensia diak liu fali duque la uza kua no uza kuak Ø 80 mm. Maibe iha diresaun Y, uza chapa reinfora la ho kuak no ho kuak Ø 80 mm efetivu liu fali. Iha caso atu redús amplitudu husi vibrasaun, chapa la ho kuak bele redús vibrasaun diak liu fali iha diresaun X duque chapa seluk, enquanto chapa la ho kuak no ho kuak Ø 80 mm bele redús amplitudu vibrasaun nian diak liu iha diresaun Y nian. Tamba reinforsu la ho kuak bele redús amplitude vibrasaun nian diak liu iha diresaun X no Y compara ba sira seluk, tan nee, metodu reinforsu nee konsidera atu uza ba iha evaluasaun experimentu nian neebe bazaia ba ninia rezultadu neebe ótimu. Konsidera ba chapa nia klean, chapa ho klean 36 mm bele redús vibrasaun diak liu iha diresaun X, enquanto chapa 12 mm redús vibrasaun sai kiik liu iha diresaun Y nian. Tamba experimentu ba koa nian sei performa husi diresaun Y nian, tan nee, ami desidi atu uza chapa 12 mm. Ba mákina produsaun seluk neebe koa husi diresaun X nian, chapa 36 mm mak diak liu hodi uza atu controla frekuensia resonansia no amplitude vibrasaun nian.

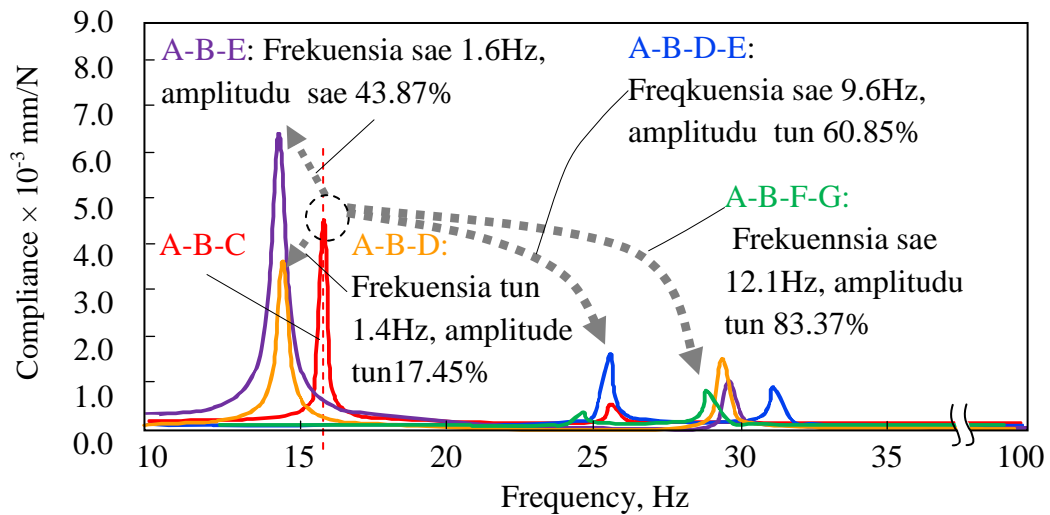
Atu sumariza, rezultadu husi kalkulasaun hatudu katak frekuensia resonansia bele hasae ba 10 Hz too 15 Hz wainhira halo reinfora. Iha modu primeiro, maske frekuensia resonansia aumenta, *compliance* mos aumenta. Nee konsidera aceitavel se kuandu mudansa frekuensia nian husi resonansia primeiru la koincide ho fonte resonansia boot neebe mosu iha frekuensia 50 Hz no iha tempu hanesan, *compliance* tun iha segundu modu. Tan nee, maske kontrolu nee efetivu liu ba hasae frekuensia resonansia, presiza atu tau konsiderasaun wainhira frekuensia resonansia rua ka tolu sae hamutuk

enquantu koko atu evita frekuensia resonansia ida, neebe resulta resonansia mode tuir mai bele sai problema fali. Ho ida nee, husi rezultadu sira iha leten, chapa ho klean 12 mm konsidera sufisiente ba kontrola frekuensia resonansia. Instalasaun chapa reinforsa nian iha parte okos husi motor nia baze bele halao iha tempo nebe badak ho instalasaun neebe fasil uza *chapa ferro*, no mos bele espera ninia efeito neebe boot.

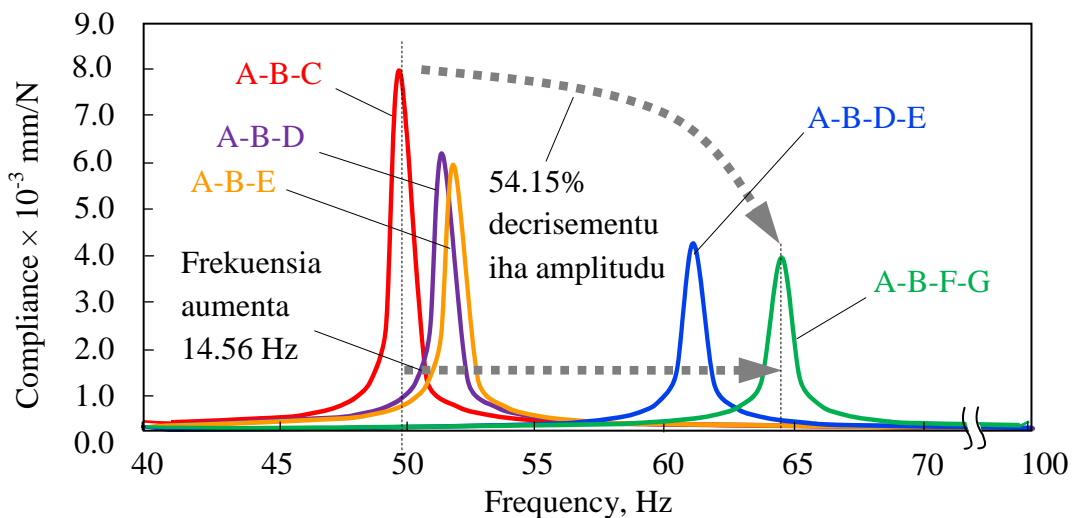
3.2.3 Muda suporta nia posisaun atu muda resonansia nia frekuensia

Muda posisaun suporta nian konsidera hanesan terseiru parametru hodi kontrola frekuensia resonansia. Iha simulasaun ba metodu nee, posisaun suporta nian neebe uza atu suporta mákina produsaun hatudu iha figura husi modelu simulasaun nian liu ba (Fig. 3.7 ba Kontrol fatór III). Modelu komputador husi simplifikasaun mákina tornu nian konstrui ba kalkulasaun nebe fasil no lalais. Kondisaun analize nian ba simulasaun hanesan ho kondisaun neebe uza ba iha metodu 2 liu ba. Vibrasaun livre performa uluk tiha, hafoin vibrasaun forsada ho forsa 1N aplika ba iha spindulu nia leten. Ikus mai, rezultadu kalkulasaun nia fotu husi pontu rua husi iha *headstock* atu detekta vibrasaun iha diresaun X no Y. Vibrasuan livre nee uza atu observa mudansa iha mákina nia estrutura antes analiza ho vibrasaun forsada ba iha kontramedida hodi muda posisaun suporta nian.

Iha simulasaun nee, kombinasun 5 posisaun suporta nian neebe diferente konsidera atu uza nudar kontramedida. Analize ba resposta frekuensia nian halao hodi evalua kontramedida ida-idak, depois rezultadu analize neebe hetan ona sei kompara ba malu. Rezultadu resposta nian husi kontramedida ida neebe diak liu sei uza ba iha evaluasaun experimental nian. Rezultadu kalkulasaun nian hatudu iha Fig. 3.10 tuir mai nee. Rezultadu leten nee hatudu katak, frekuensia resonansia bele muda sés uza posisaun suporta nian ho tipu oin-oin. Husi rezultadu nee, wainhira la uza kontramedida ida (suporta basico deit),



a) Frekuensi resonansia iha áxis X



b) Frekuensi resonansia iha áxis Y

Fig. 3.10 Resposta frekuensi nian husi makina tornu ho suporta oin-oin (Kalkulasaun uza FEM)

frekuensi resonansia husi mákina tornu nian mak 16.1 Hz no 49.9 Hz iha áxis X no Y, tui-tuir malu. Wainhira uza kontramedida, frekuensi resonansia husi mákina tornu nian muda tuir mudansa suporta nia posisaun. Posisaun suporta A-B-D no A-B-E muda tun frekuensi resonansia iha áxis X, enquanto muda sae hertz balun iha áxis Y nian. Maske suporta ho posisaun A-B-D no A-B-E muda tun frekuensi iha diresaun X, maibe iha parte amplitudu vibraisaun nian,

suporta ho posisaun A-B-E haboot amplitudu quaze 43.86%, enkuantu posisaun suporta A-B-D hamenus vibraisaun ho aproximasaun 17.45%. Kuandu uza suporta ho kombinasau A-B-E, magnifikasau boot iha amplitudu akontese tamba rotasau spindulu nian halo mákina tornu (iha parte neebe laiha suporta) magnifika ho osilasaun nebe boot. Diferente fali husi kombinasau suporta ho posisaun A-B-D no A-B-E, suporta ho posisaun A-B-D-E ho A-B-F-G bele hasae frekuensia resonansia too 12.1 Hz iha diresaun X no 14.56 Hz iha diresaun Y nian. Laós deit aumentu iha frekuensia, maibe amplitudu vibraisaun nian mos redús too 83.37 % ho 54.15% tui-tuir malu iha diresaun X no Y nian. Husi rezultadu resposta kalkulasaun nian, suporta ho kombinasau A-B-F-G diak liu atu uza hodi kontrola frekuensia resonansia ba hamenus amplitudu vibraisaun nian.

Hanesan resumu, hodi uza kombinasau neebe la hanesan husi pontu suporta nian, frekuensia resonansia bele muda entre 10 Hz too 20 Hz. Hanesan mos modu vibraisaun nian muda enkuantu uza metode suporta nian, valór *compliance* nian mos muda hotu, tan nee mak metode nee efetivu atu uza ba kontrola resonansia iha mákina sira.

3.3 Evaluasaun ho experimentasaun ba metodu kontrolu usa mákina torno de bancada

Evaluasaun experimentu nian ba metodu kontrolu hodi kontrola frekuensia resonansia halao uza mákina tornu bancada. Suporta báziku nebe uza iha mákina tornu nee ba evaluasaun metodu kontrolu nian mak suporta A-B-C hanesan hatudu Fig 3.11. Iha prepassaraun nee, inversor uza hodi kontrola rotasau motor mákina nian durante halao medisaun. Epesifikasau husi mákina tornu nebe uza iha experimentu bele haree iha Tabela 3.2. Motor elétriku diretamente dulas espindulu husi mákina tornu, nune velocidade maximu husi spindulu mak 3600 rpm ho frekuensia 60 Hz wainhira uza inversor. Atu estuda vibraisaun, ami monta

accelerometru (●) rua iha parte leten mákina nia ulun husi diresaun X no Y atu detekta accelerasaun vibrasaun nian husi mákina tornu no analiza uza analizador FFT. Hodi uza basiku konfigurasaun experimentu nee, configurasaun ba evaluasaun metodu kontrolu ba fatór kontrolu ida-idak estabeleze no evalua.

Tabela 3.2 Espesifikasaun makina tornu nian

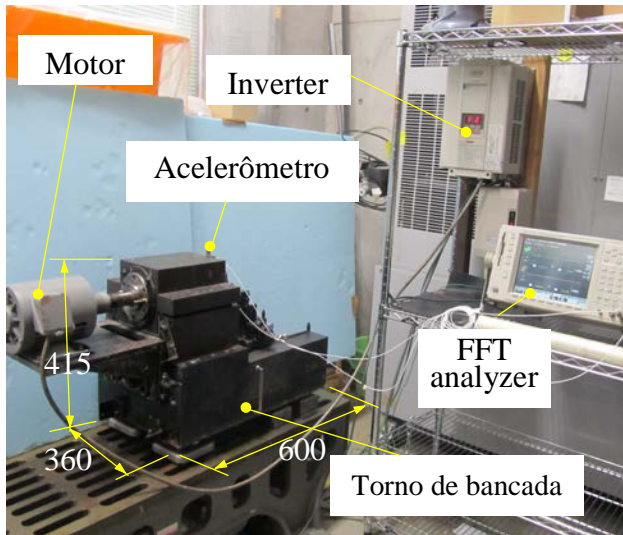


Fig. 3.11 Fotografia no configurasaun experimentu nian

Head stock	Height of center from bed	177 mm
	Height of center from floor	337 mm
	Spindle speed	Max.3600 min ⁻¹
	Front bearing	50BNC10TY DBB
	Rear bearing	45BN10TYD B
Bed	Size	600×360×160 mm
Tool post	Stroke of Y axis	30 mm
Table	Stroke of Z axis	200 mm
Motor	Power	0.75 kW
	Speed	Inverter control
Weight		200 N

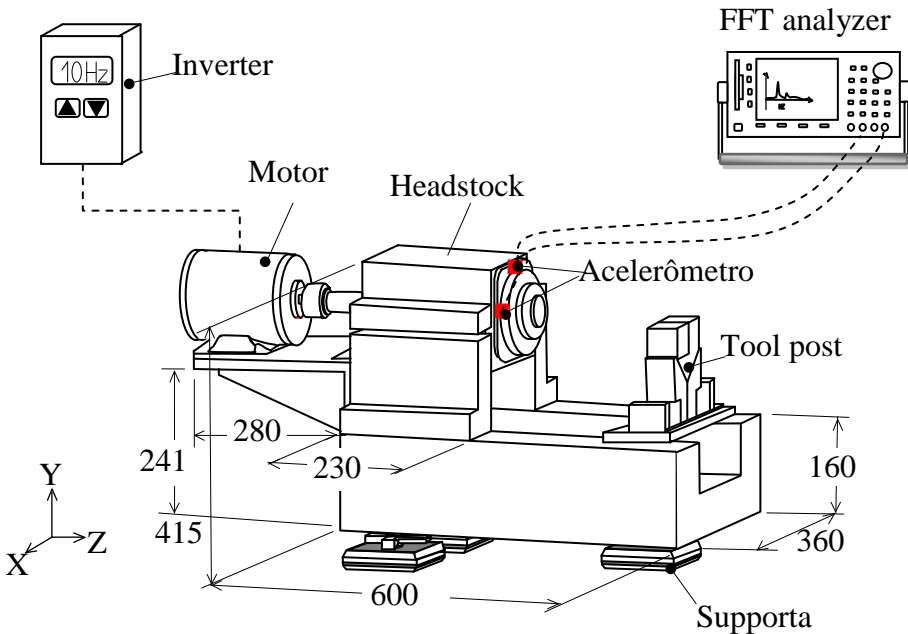


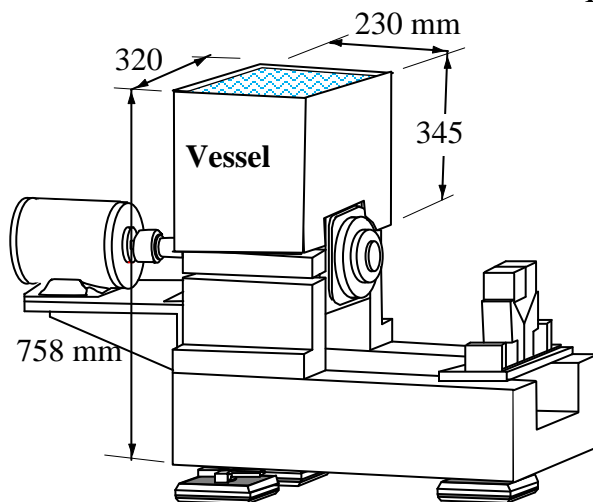
Fig. 3.12 Configurasaun experimentu nian no modelu husi makina tornu

3.3.1 Evaluasaun experimental ba metodu kontrolu uza mákina tornu

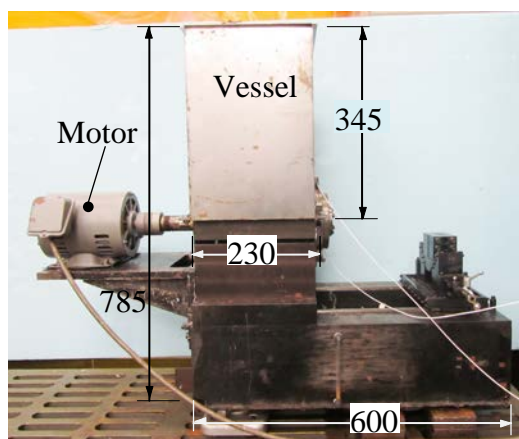
3.3.1.1 Fatór kontrolu I

Evaluasaun experimental nian halao tiha ona hodi aumenta densidade atu hatun frekuensia resonansia. Bazeia ba rezultadu simulasaun nian iha sesaun uluk liu, injesaun bé ba iha mákina nia baze ladun efisiente ba muda mákina tornu nia frekuensia resonansia, tan nee omiti tiha husi evaluasaun experimentu nian. Ho nunee, kontramedida neebe uza iha fatór kontrolu I mak injesaun bé kahur polimer ba iha *vessel* neebe prepara tiha ona iha *headstock* mákina nian.

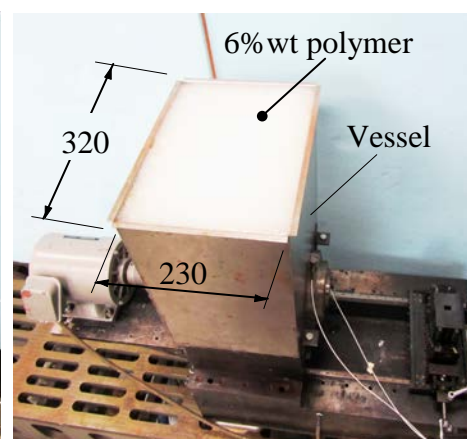
Tabela 3.3 Parametru ba fatór kontrolu I



Parametru ba kontrolu I	
Kuantidade bé nian	Konsentrasaun polimer nian
0	0
10	6wt%
16	6wt%
22	6wt%



Front view

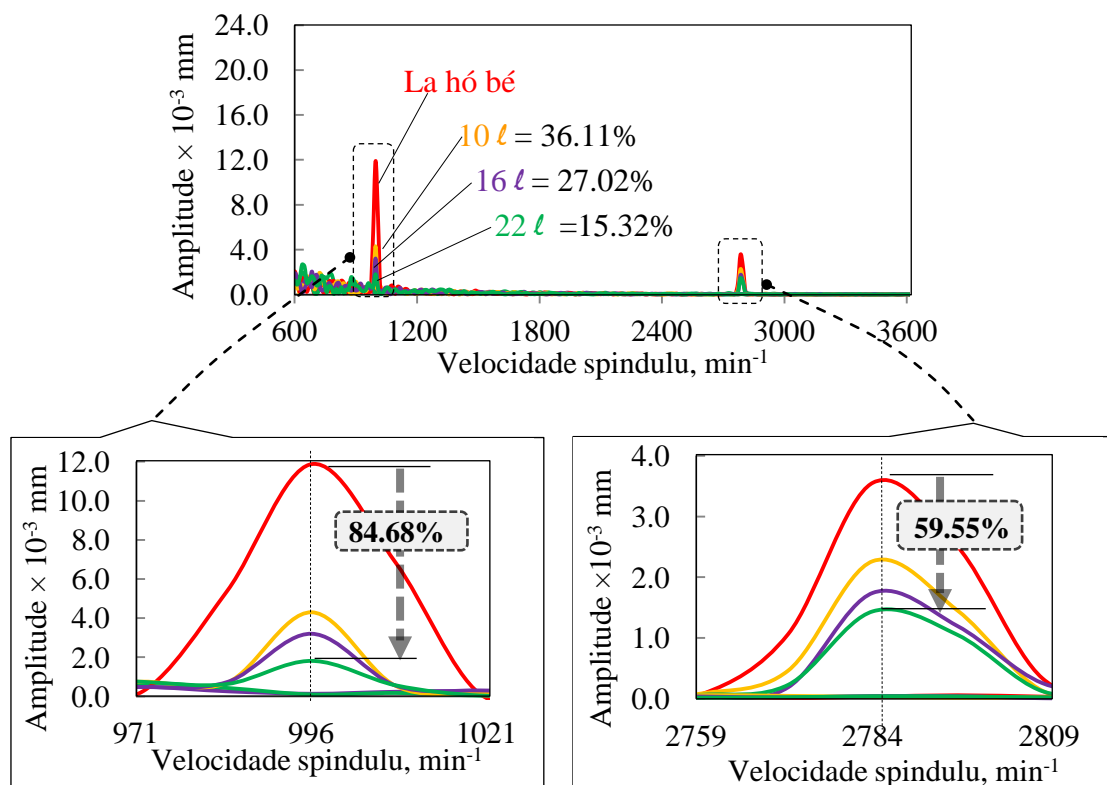


Top view

Fig. 3.13 Modelu no fotografia husi configuraun experimentu nian ba fatór kontrolu I ho modelu makina tornu nian

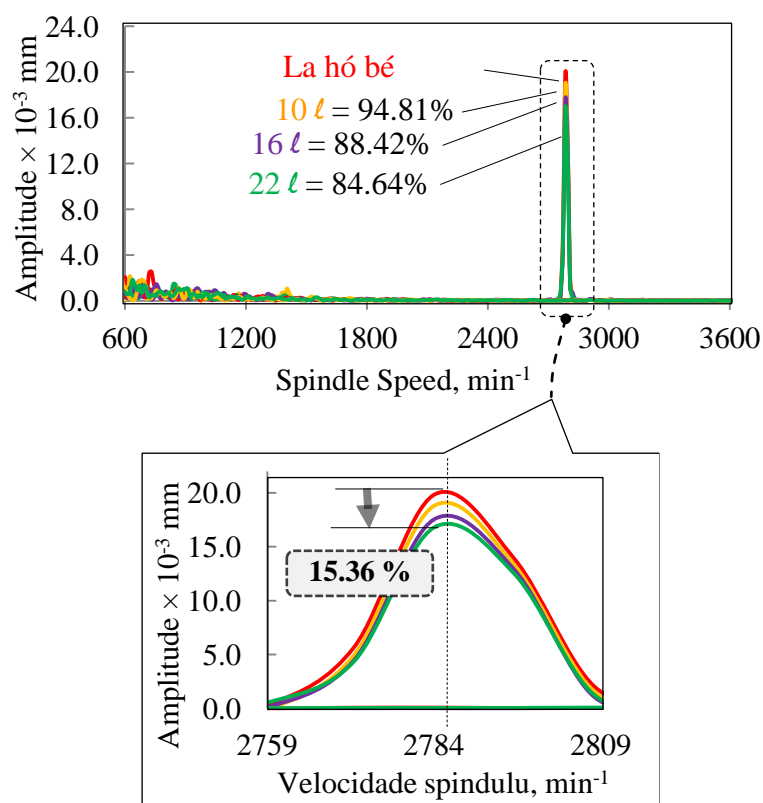
Konfigurasaun experimentu nian ba fatór kontrolu hatudu iha Fig. 3.13. Iha experimentu nee, ami halo dezenyu ba *vessel* bé nian atu preenxe ho bé kahur ho polimer. *Vessel* nee hatur no kaer metin ho parafusu boot iha mákina tornu nia ulun hanesan ho modelu simulasaun nian iha sesaun kotuk. Evaluasaun halao hodi evalua vibrasaun mákina nian uza parametru hanesan; la uza bé, uza bé litru 10, litru 16, no litru 22 depois kahur ho konsentrasaun polimer PEO 6wt%.

Tuir mai, medisaun vibrasaun nian halao hodi halao operaun ba mákina iha rotasaun 996 rpm no 2784 rpm. Velosidade espidulu rua nee representa frekuensia resonansia husi mákina tornu iha diresaun X ho Y tui-tuir malu hodi la aplika kontrolu ruma. Velosidade espidulu nee hili ho razaun tamba ami hakarak evalua metodu kontrolu ba fatór kontrulu I nia efikásia hodi halao operaun ba mákina tornu coincide ho ninia frekuensia resonansia. Uza kondisaun operaun nee,



(a) Vibrasaun iha diresaun X nian

Fig. 3.14 13 Relasaun entre velocidade spindulu (iha resonansia) ho amplitudu vibrasaun nian hodi kontrola densidade (Resultadu husi experimentu)



(b) Vibrasaun iha diresaun Y nian

Fig. 3.14 13 Relasaun entre velocidade spindulu (iha resonansia) ho amplitudu vibrasaun nian hodi kontrola densidade (Resultadu husi experimentu)

relasaun entre amplitudu vibrasaun nian iha *headstock* ho velocidade spindulu nian evalua husi mákina tornu iha diresaun X no Y. Resultdu husi experiment ba kontrola frekuensia resonansia hodi preenxe bé kahur polimer hatudu iha Fig. 3.14. Áxis horizontais representa velocidade spindulu no áxis verticais representa amplitudu vibrasaun mákina tornu nian. Resultadu hatudu katak, la aplika kontramedida ida, amplitudu vibrasaun nian boot los iha diresaun X nian ba 996 rpm no Y nian ba 2784 rpm. Wainhira uza metodu neebe propoin amplitudu vibrasaun nian redús ho eficiente. Iha Fig. 3.14(a), vibrasaun iha diresaun X hatudu katak hodi preenxe bé kahur ho 6wt% polimer, amplitudu vibrasaun nian halo sai kiik liu kedas wainhira uza bé ho litru 22. Amplitude vibrasaun nian iha velocidade espidulu 996 rpm redús quaze 85.68% no quaze 59.55% iha

velocidade 2784 rpm. Iha fali Fig. 3.13(b) vibraun iha diresaun Y nian hatudu katak vibraun kiik liu iha espindulu 996 rpm, neebe konsidera hanesan ruídu (*noise*) deit tan nee mak laiha mudansa ruma amplitudu. Maibe, amplitudu vibraun nian boot liu iha espindulu 2784 rpm. Wainhira aplika uza kontrolu neebe propoin, amplitudu vibraun nian bele hamenus ba too 15.36%.

3.3.1.2 Fatór kontrolu II

Iha nee, evaluaun experimentu nian halao uza fatór kontrolu II atu buka efisiensia ba hamenus vibraun. Iha sessaun experimentu ida nee, ami uza chapa SS40 atu reinforsa elétrico motor nia baze bazeia ba rezultadu simulasaun nian iha sesaun kotuk. Husi rezultadu simulasaun neebe hetan tiha ona, ami desidi atu uza parametru ba komparaun nian hanesan; la uza chapa reinforsa nian, uza chapa ho espessura 12 mm no 36 mm. No mos, rezultadu simulasaun nian hatudu

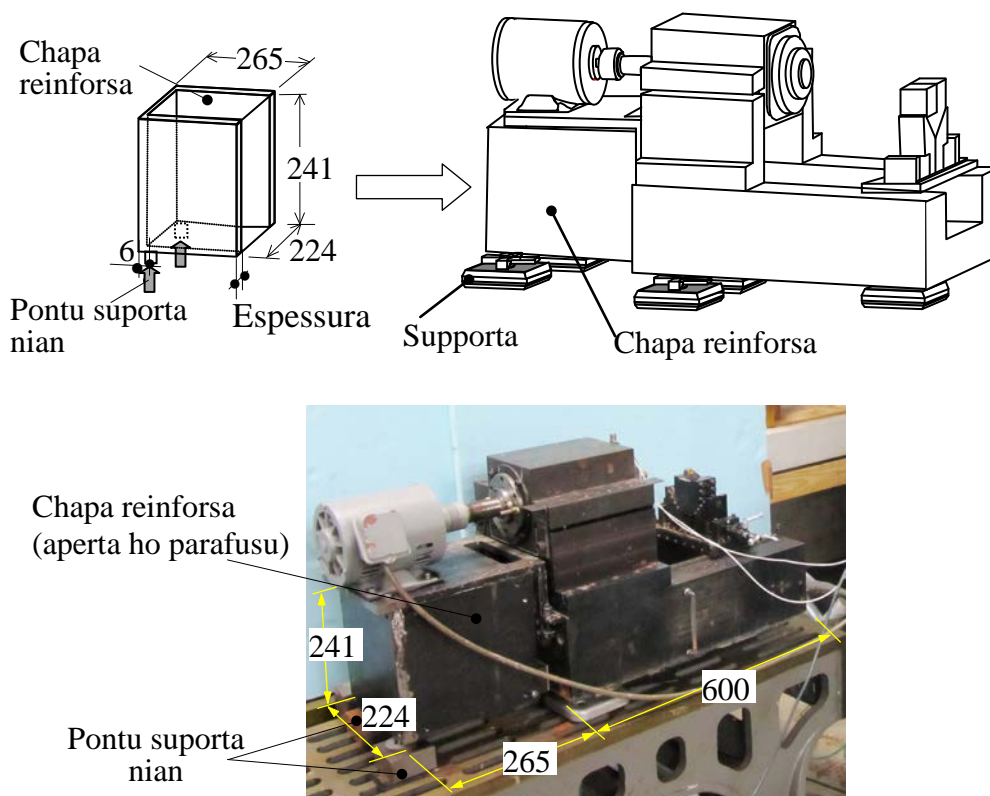
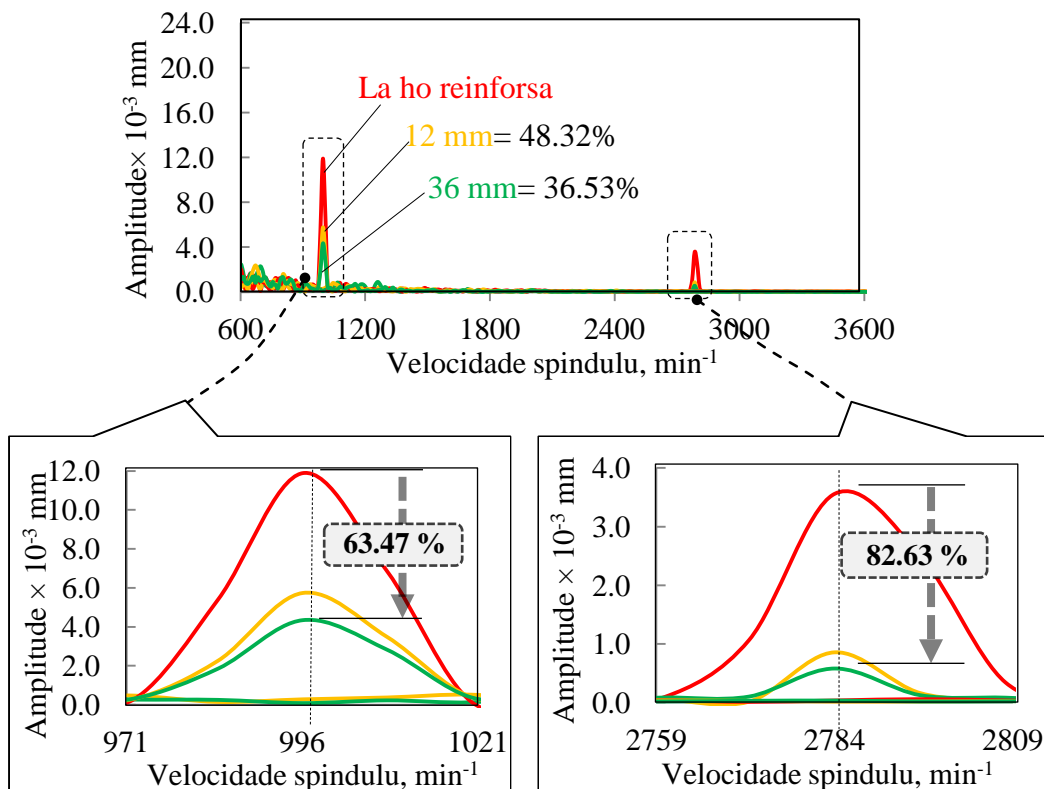


Fig. 3.15 Modelu no fotografia setup experimentu nian ba fatór kontrolu II

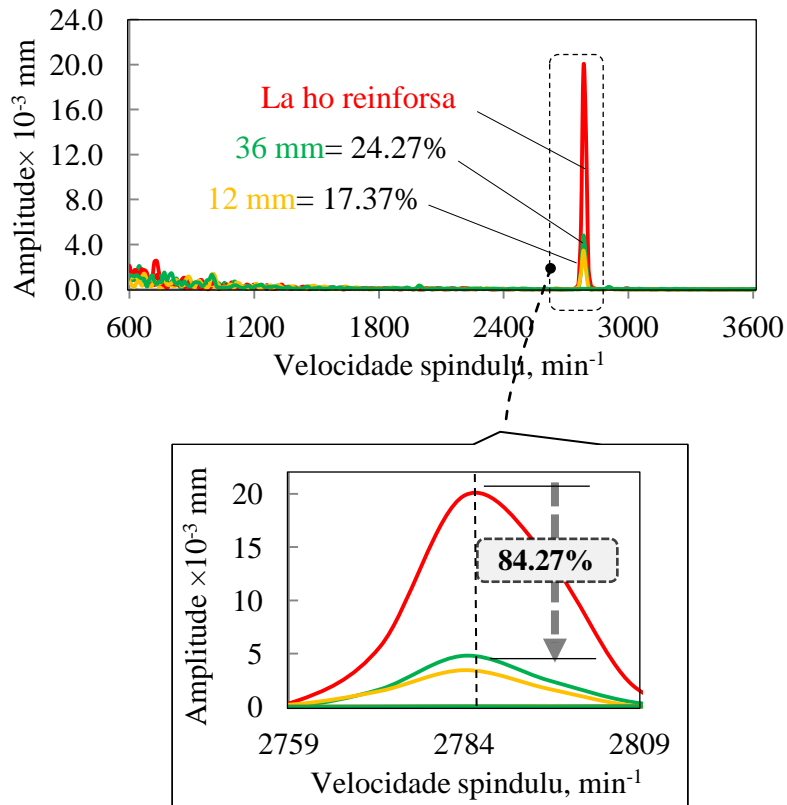
katak halo kuak iha chapa ladun efisiente ba kontrola frekuensia resonansia no hamenus vibraisaun nia amplitudu, tan nee mak hasai tiha husi evaluasaun experimentu nian ba fatór kontrolu I.

Configurasaun experimentu nian ba evaluasaun fatór kontrolu II nian hatudu iha Fig. 3.15. Suporta prinsipiu nebe uza ba configurasaun nee mak kombinasaun suporta A-B-C no mos frame prinsipiu nebe uza mak frame ho espessura 12 mm. Nunee, atu atu aumenta frame nia klean ba rigidez nenbe aas, chapa seluk ho espessura 12 mm monta tan ba iha parte 3 husi frame prinsipiu nia sorin no hametin uza parafusu. Hodi hametin chapa ho frame uza parafusu, ita bele hatun no hasae chapa nia espessura ho fasil hodi aumenta ou hasai frame nee. Ho ida nee, atu aumenta chapa nia espessura ba 36 mm, monta tan deit chapa 12 mm rua iha parte sor-sorin chapa nian. Maibe, kuandu chapa sai klean liu, ninia todan



(a) Vibraisaun iha direisaun X nian

Fig. 3.16 Relasaun entre velocidade spindulu (iha resonansia) ho amplitudu vibraisaun nian hodi kontrola stiffness (Resultadu husi experimentu)



(b) Vibrasaun iha diresaun Y nian

Fig. 3.16 Relasaun entre velocidade spindulu (iha resonansia) ho amplitudu vibrasaun nian hodi kontrola stiffness (Resultadu husi experimentu)

mos sei aumenta no sei halo mákina nia ulun sai todan los no resulta konsidaun neebe la estavel husi mákina nia posisaun wainhira konsirdera uza deit mak suporta prinsipiu. Tamba nee, atu prevene para kondisaun nee, ami uza pontu suporta nian seluk hodi suporta chapa reinforsa. Hodi uza sistema configurasau no parametru nee, evaluasaun ho experimentu halao no performa. Resultadu husi evaluasaun husi experimentu nee fó hatudu iha Fig. 3.16. Iha figura nee, áxis horizontal representa velocidade spindulu no áxis vertikulu representa amplitude husi vibrasaun mákina tornu nian. Iha experimentu nee, velocidade spindulu nian nebe uza mak 996 rpm no 2784 rpm. Husi resultadu nee, ita hare katak wainhira la aplika reinforsa, amplitude vibrasaun nian wainhira halo operasaun ba mákina tornu coincide ho frekuensia resonansia mákina tornu nuan iha diresaun X no diresaun Y boot los. Maibe, wainhira

aplika reinforça hodi uza frame rainforça ho espessura 12 mm no 36 mm, amplitude vibraçaun nian redús quaze 48.32% no 36.53 %, tui-tuir malu iha diresaun X no 24.27 % ho17.3 %, tui-tuir malu iha diresaun Y nian. Nunee mos, ho reinforce frame, amplitudu vibraçaun nian redús quaze 63.47 % ba velocidade espidulu 996 rpm nian no too quaze 84.27% ba 2784 rpm iha diresaun Y. Ho nunee, wainhira uza metodu ida nee, monta no desmonta fasil tebes, fasil atu hasae rigidez, no mos fasil atu kontrola frekuensia resonansia no redús amplitudu vibraçaun nian.

3.3.1.3 Fatór kontrolu III

Evaluasaun experimentu nian ba fatór kontrolu III hodi muda suporta nia posisaun performa no evalua. Bazeia ba rezultadu simulasaun nian iha Fig. 3.10 kotuk ba katak frekuensia resonansia muda efetivu liu wainhira uza fatór kontrolu III,

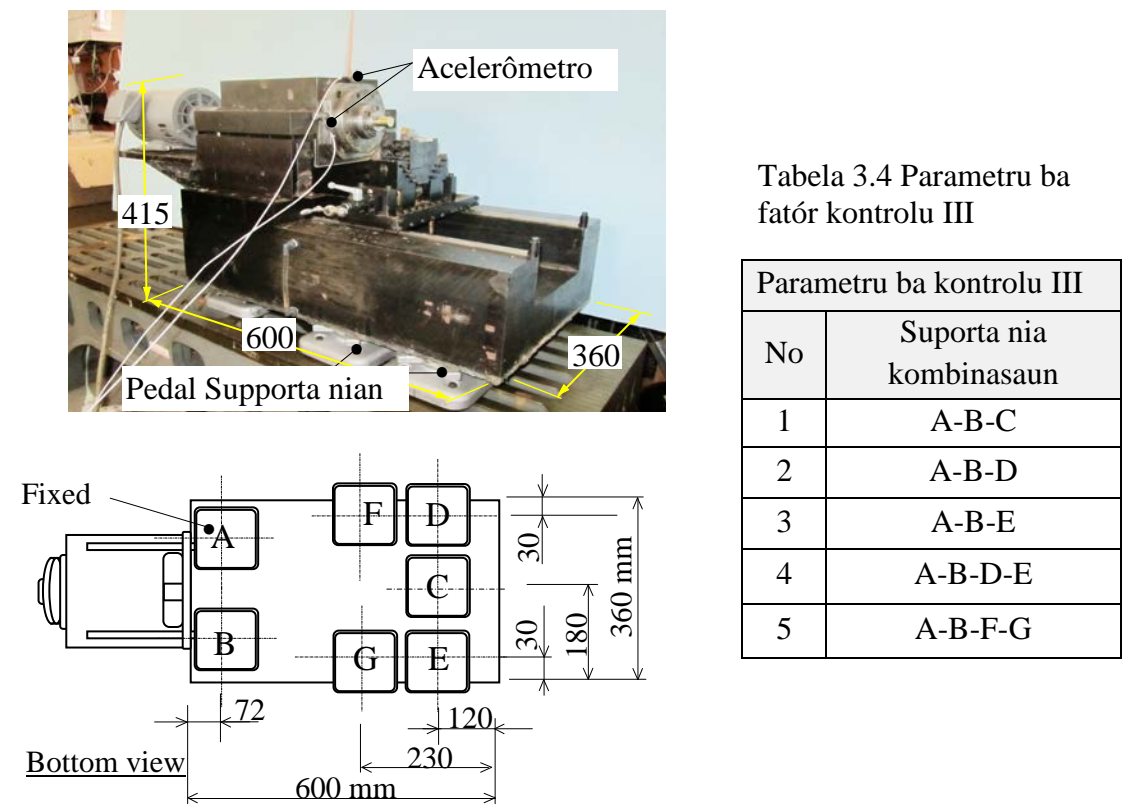
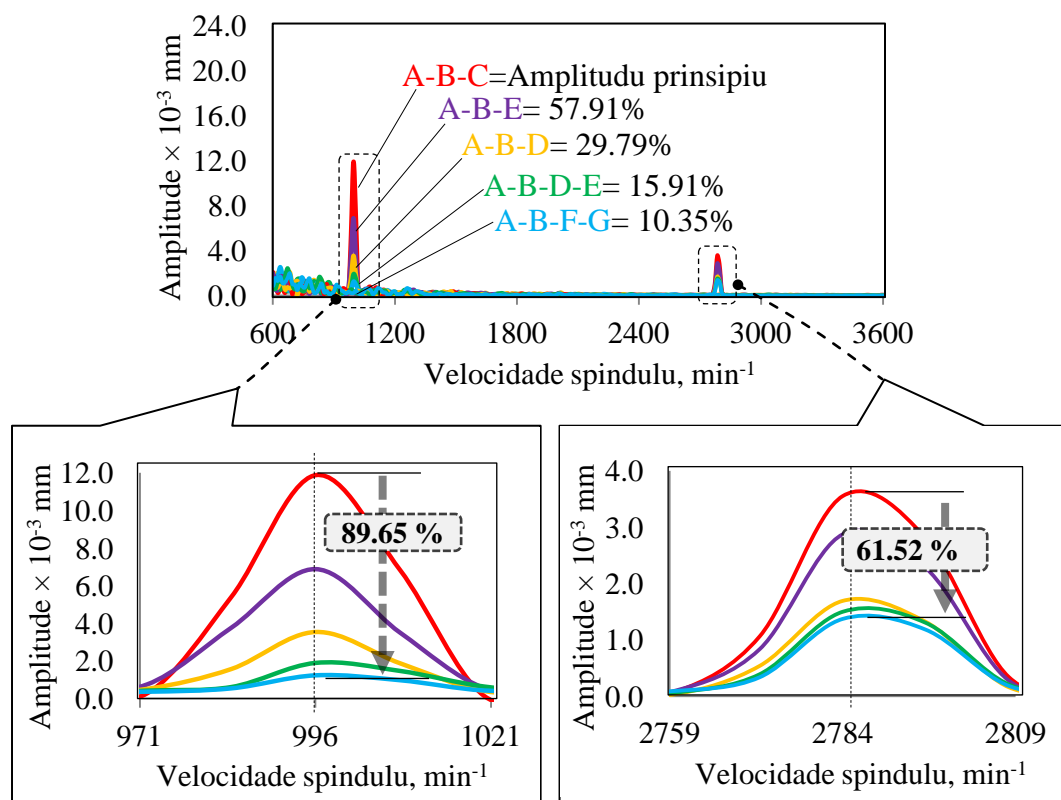


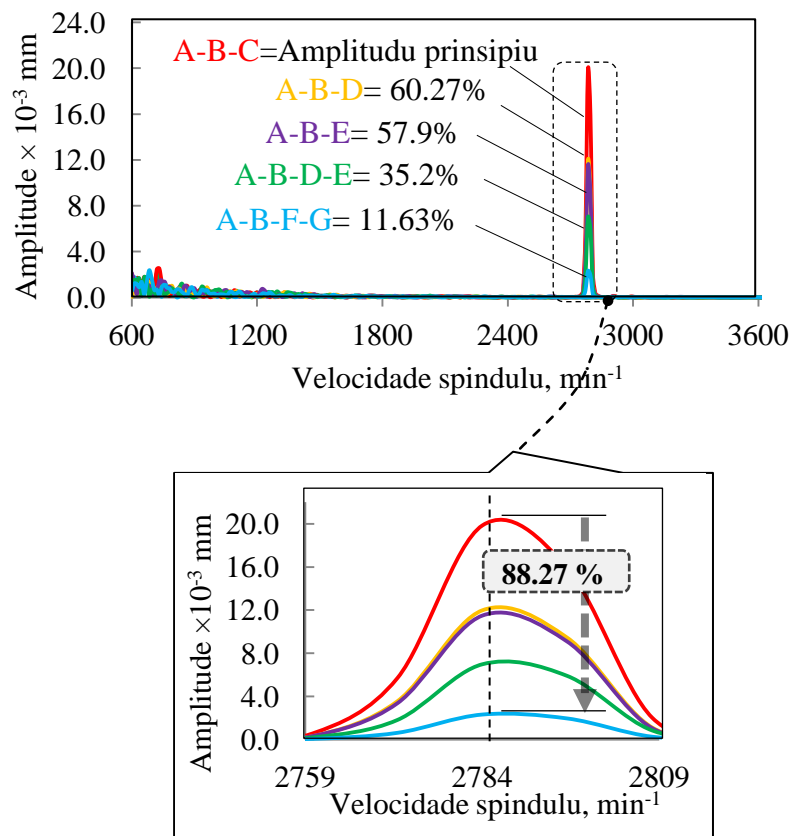
Fig. 3.17 Modelu no fotografia husi configuraçaun experimentu nian ba fatór kontrolu III ho modelu makina tornu

tamba nee, iha experimentu nee, kombinasau husi pontu suporta sira nian ho posisaun neebe vário uza atu evalua efikásia husi metodu nee ba redús vibraisaun nia amplitudu. Konfigurasaun experimentu mákina toru nian ba evaluasaun fatór kontrolu III mak hatudu iha Fig. 3.17. Figura nee hatudu mákina toru neebe hare husi okos. Iha konfigurasaun nee, pontu suporta hitu (A, B, C, D, E, F, no G) ho posisaun nebe diferente mak uza iha nee. Husi pontu suporta sira nee, ami uza kombinasau diferente 5 suporta nian ba evaluasaun vibraisaun mákina nian. Sinco kombinasau suporta sira mak hanesan; A-B-C, A-B-D, A-B-E, A-B-D-E, no A-B-F-G, ho kombinasau suporta A-B-C nudar suporta prinsipiu. Iha nee, pontu suporta sira prepara kedas ho parafusu fatin nunee bele ajusta posisaun suporta nian ho facil.



(a) Vibraisaun iha diresaun X nian

Fig. 3.18 Relasaun entre velocidade spindulu (iha resonansia) ho amplitudu vibraisaun nian hodi kontrola suporta (Resultadu husi experimentu)



(b) Vibrasaun husi diresaun

Fig. 3.18 Relasaun entre velocidade spindulu (iha resonansia) ho amplitudu vibrasaun nian hodi kontrola suporta (Resultadu husi experimentu)

Kuandu uza kombinasau A-B-C, suporta seluk hanesan D, E, F ho G hamamar hotu sira nia parafusu. Prosesu nebe hanesan aplika kuandu uza mak kombinasau suporta A-B-D, suporta seluk (C, E, F ho G) hamamar hotu, nune mos ho kombinasau suporta sira seluk. Ho konfigurasaun nee, amplitudu vibrasaun mákina tornu nian observa no kompara entre kombinasau suporta sira. Resultadu evaluasaun experimentu nian uza fatór kontrolu III hatudu iha Fig. 3.18. Medisaun halao hodi uza espidulu ho velocidade neebe hanesan ho fatór kontrolu I no II mak 996 rpmand 2784 rpm. Resultadu medisaun nian hatudu katak iha Fig. 3.18(a), vibrasaun iha diresaun X nian, vibrasaun nia amplitudu redús tui-tuir malu deit wainhira aplika metodu kontrolu nian uza suporta ho

kombinasaun A-B-E, A-B-D, A-B-D-E, and A-B-F-G. Maibe, rezultadu vibrasaun nian iha Fig.3.18(b) hatudu katak support ho kombinasaun A-B-E redús amplitudu diak liu fali A-B-D. Tamba nee mak amplitudu vibrasaun nian bele redús tui-tuir malu ho sequensia hanesan; A-B-D, A-B-E, A-B-D-E, no A-B-F-G. Husi rezultadu bele hateten katak, wainhira uza metodu neebe propoin hodi muda suporta nia posisaun, amplitudu vibrasaun nian bele redús bainhira operasaun mákina nian koinside ho frekuensia resonansia. Nunee mos, ho metodu kontrolu nee, amplitudu vibrasaun nian bele redús tui-tuir malu quaze 89.65 % no 61.52 % ba rotasaun 996 rpm no 2784 rpm iha diresaun X nian, no mos bele redús amplitudu quaze 88.27 % ba 2784 rpm iha diresaun Y nian.

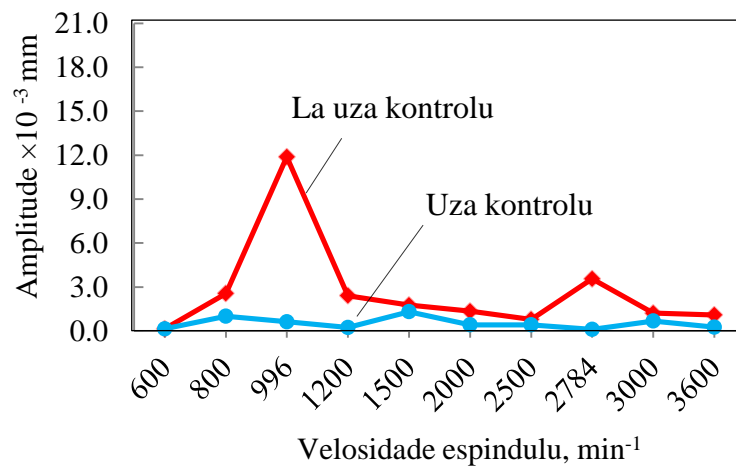
3.3.2 Kombinasaun neebe ótimu ba kontramedida tolu fátor kontrolu nian

Evalua tiha fátor kontrolu ida-idak nia efisiensia ba redús amplitudu vibrasaun nian, kombinasaun neebe ótimu entre kontramedida tolu hanesan: fátor kontrolu I, II, no III condutu no evalua. Kombinasaun entre fátor kontrolu I ho

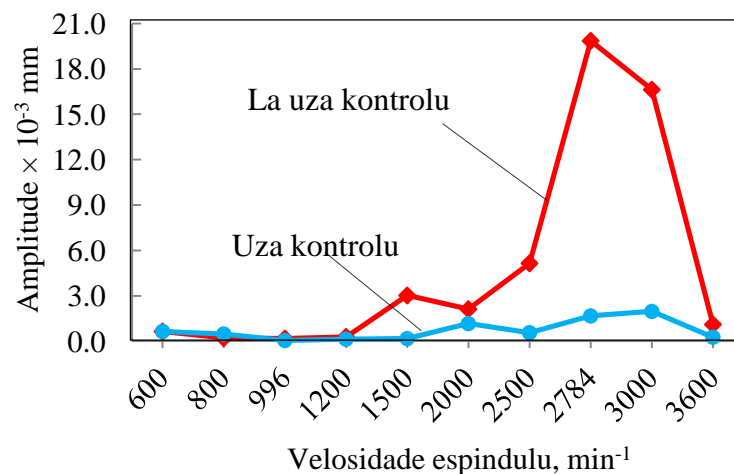
Tabela 3.5 Kombinasaun neebe ótimu ba kontramedida tolu

Velosidade spindulu (rpm)	Fátor kontrolu I (Densidade)	Fátor kontrolu II (Rigidez)	Fátor kontrolu III (Supporta)
600	-	-	A-B-C
800	-	12 mm	A-B-F-G
996	22 liter	-	A-B-C
1200	10 liter	-	A-B-D
1500	-	12 mm	A-B-E
2000	10 liter	-	A-B-E
2500	22 liter	-	A-B-F-G
2784	16 liter	-	A-B-F-G
3000	-	12 mm	A-B-D-E
3600	10 liter	-	A-B-C

fatór kontrolu III uza atu optimiza hodi hamenus mákina torno nia densidade, enquanto kombinasau entre fatór kontrolu II ho fatór kontrolu III uza atu optimiza hodi hasae mákina torno nia rigidez (stiffness). Velosidade oin-oin espindulu nian iha mákina torno nee uza atu evalua kombinasau kontrolu nian nebe ótimu husi velosidade espindulu ida-idak nian. Iha nee, ami hatun no hasae frekuensia iha inversor hodi kontrola velosidade espindulu nian. Rezultadu husi kombinasau entre kontramedida tolu nian neebe ótimu mak apresenta iha Tabela 3.5.



(a) Vibrasaun iha diresaun X nian



(b) Vibrasaun iha diresaun Y nian

Fig. 3.19 Amplitudu vibrasaun nian uza metodu neebe propoin

Espindulu neebe váriu husi 600 rpm too 3600 rpm uza iha experimentu nee no parametru ótimu ba fatór kontrolu ida-idak nebe uza ba kombinasauñ ótimu nian hatudu iha Tabela 3.5. Resposta vibrasauñ nian husi kontrolu nebe uza kombinasauñ sira nee hatudu iha Fig.3.19 ho áxis horizontal nian representa velocidade espindulu, enkuanto áxis vertical representa amplitudu vibrasauñ nian. Resultadu medisaun nian hatudu katak amplitudu vibrasauñ nian boot los wainhira la ho kontrolu, no aumenta boot liu tan kuandu mákina opera coincide ho frekuensia resonansia mákina nian iha espindulu 996 rpm no 2784 rpm. Maibe, amplitude vibrasauñ nian redús too kiik liu kedas wainhira aplika uza kontrolu kombinasauñ nian. No mos, vibrasauñ neebe rezulta tamba opera mákina koincide ho frekuensia resonansia mos redús ba 10% deit, neebe sai kiik 1/10 kompara ho la uza kontrolu kombinasauñ. Tamba nee, atu bele hetan kontrolu nebe ótimu ba kontrola frekuensia resonansia no hamenus vibrasauñ nia amplitudu, ami sugere atu uza metodu kombinasauñ neebe apresenta iha Tabela 3.5.

3.4 Evaluasauñ koa nian

Ikus mai, experimentu koa nian kondúz uza mákina tornu no efikásia husi metodu neebe proposto mos evalua. Bazeia ba resultadu husi kombinasauñ ótimu uza metodu kontrolu tolu, aplikasauñ koa nian performa uza mákina tornu nebe bai-bain ho kondisaun koa nian nebe uza iha experimentu nee fo iha Tabela 3.6. Frekuensia resonansia kontrola bazeia ba resultadu husi kombinasauñ kontrola nebe ótimu (Tabela 3.5). Operasauñ koa nian performa uza bronze ho diámetru Ø18 mm no naruk 40 mm ba peça. Uza peça matrial bronze ho diámetru Ø18mm, velocidade espindulu nian nebe ótimu ba koa nian mak 2784 rpm. Maibe, resultadu medisaun resonansia nian husi mákina tornu hatudu katak vibrasauñ nebe boot mosu iha diresaun Y wainhira uza velocidade espindulu 2784 rpm (Fig. 3.19b la ho kontrolu). Tan nee, uza

velocidade nee sei resulta koa nia rezultadu nebe la ótimu. Nunee, atu bele evita problema nee, ami nia metodu kontrolu ho kombinasauñ ótimu sei uza hodi aplika ba iha evaluasaun nee. Bazeia ba kombinasauñ kontrolu ótimu neebe hatudu iha Tabela 3.5, metodu kontrolu nebe ótimu atu uza ba espindulu 2784 rpm mak kombinasauñ husi bé litru 16 kahur polimer ho konsentrasauñ 6wt% no kombinasauñ suporta A-B-F-G.

Tabela 3.6 Kondisaun kóá nian ba evaluasaun metodu nebe proposto

Cutting speed		158 m/min
Feed speed		0.1 mm/rev
Spindle speed		2784 min ⁻¹
Cutting depth		0.2 mm
Feramenta	Material	Carbide, T725X
	Type	Round
	Nose radius	6 mm
Peça		Bronze 3603, Ø18 ×40 mm
Controlu ba frekuensia resonansia	Densidade	Litru 16
	Rigidez	-
	Suporta	A-B-F-G

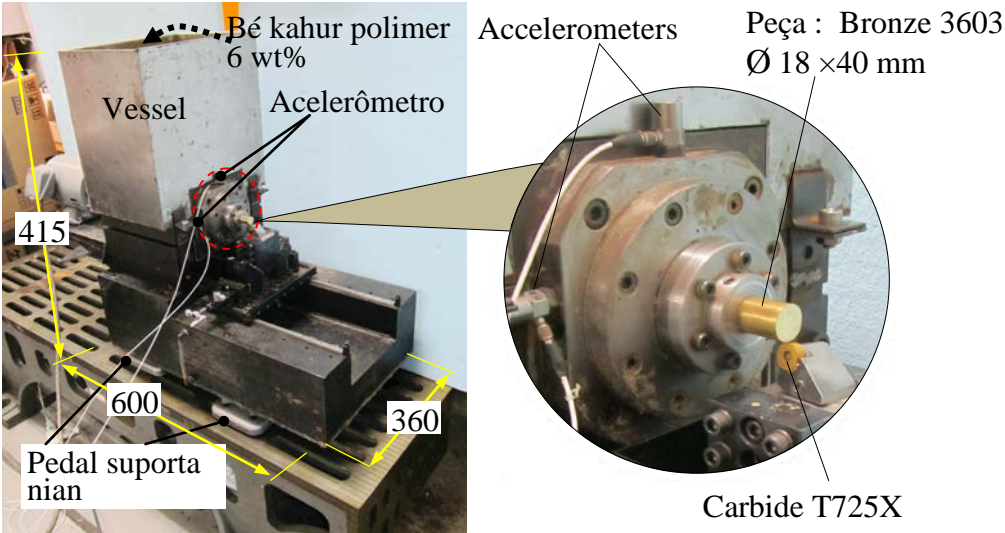


Fig. 3.20 Fotografia husi makina tornu ho kombinasauñ kontrolu nian

Aumenta liu tan, atu uza ba komparasaun, experimentu nebe hanesan mos halao hotu ba konfigurasaun konvensionais nian la ho kontramedida ruma. Rezultadu husi resposta frekuensia mákina tornu nian la ho kontrolu no uza metodu kontrolu neebe propostdado mak hatudu iha Fig. 3.21 no Fig. 3.22. Husi rezultadu nee ita bele haree katak vibrasaun forsadu mákina nian durante

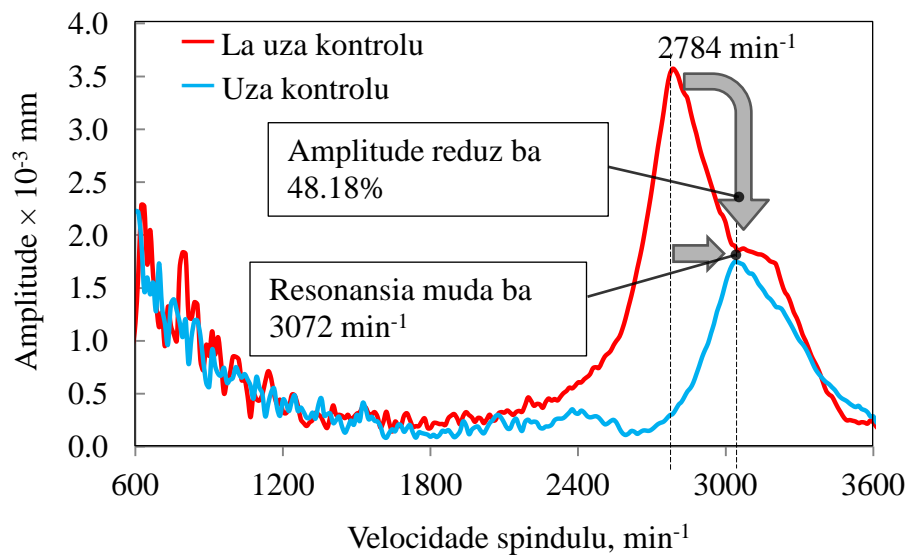


Fig.3.21 Resposta frekuensi nian husi makina tornu hodi kontrola frekuensi resonansia (Resultadu husi experimentu)

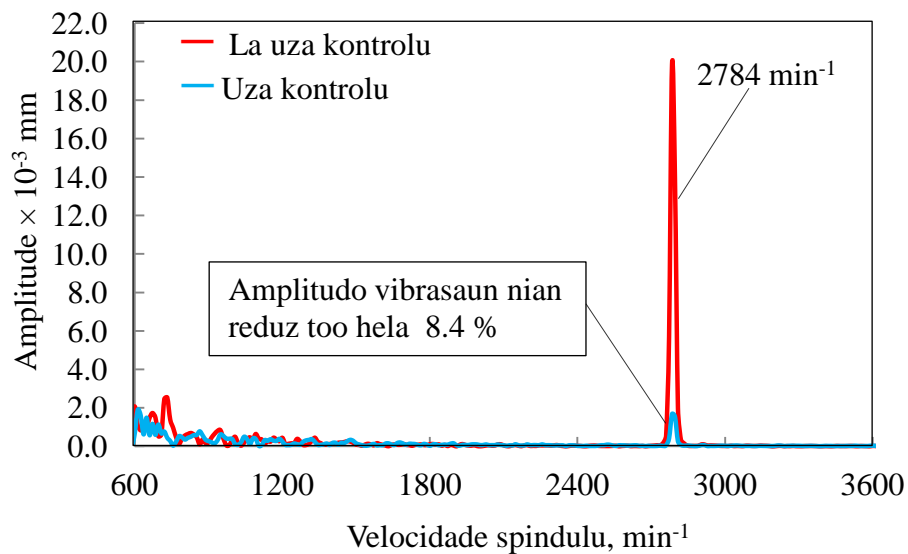


Fig.3.22. Amplitudo vibrasaun nian wainhira opera makina iha 2784 rpm

operaun neebe koinside ho frekuensia resonansia bele prevene hodi kontrola frekuensia resonansia. Rezultadu nee hatudu mos katak, amplitudu vibraun nian sai kiik liu kedas no dinâmiku rigidez mákina nia estrutura mos sai diak wainhira uza metodu pospostado. Fig. 3.23 hatudu osilasaun mákina nian durante prosesu koa nian. Iha figura nee hatudu diferensia boot entre amplitudu osilasaun

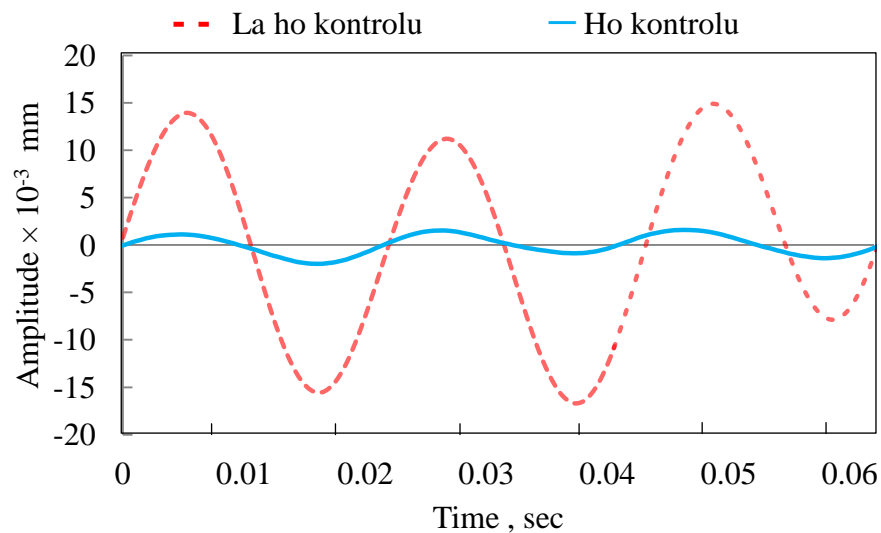


Fig.3.23 Resultadu osilasaun makina tornu nian durante kóá husi diresaun Y nian (Resultadu husi experimentu)

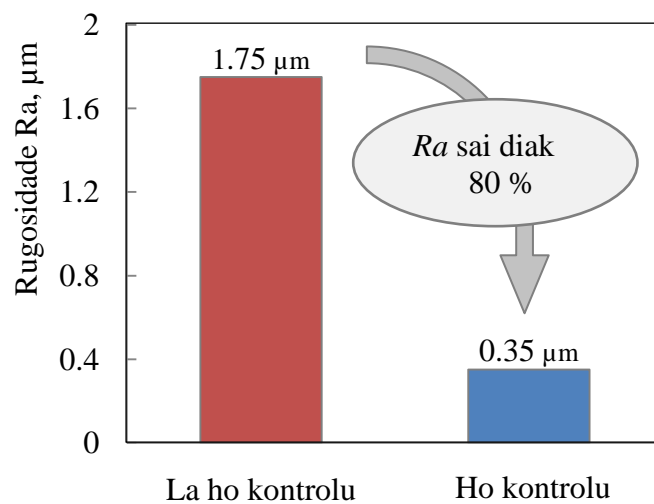


Fig. 3.24 Rugosidade peça nian uza kontrolu frekuensia resonansia (Experimentu nia resultadu)

nian hodi aplika kontrolu frekuensia resonansia no la ho kontrolu. Geralmente, kuandu frekuensia resonansia koincide ho velocidade ótimu espidulu nian, makinazen uza kondisaun koa nian nee sei difisil atu performa. Tamba nee, hodi kontrola frekuensia resonansia, fenómenu resonansia nian bele prevene no osilasaun mákina nian bele hamenus.

Fig. 3.24 fo hatudu rugosidade peça nian *depois de* operasaun koa nian. Wainhira koa uza metodu konvensional, peça nia rugosidade mak $1.75\text{ }\mu\text{m}$, maibe kuandu uza metodu neebe propoin tiha ona, rugosidade peça nian sai kabir liu tan too $0.35\text{ }\mu\text{m}$. Maske uza deit mákina tornu bancada neebe kiik neebe bai-bain, ita bele hetan rugosidade nebe diak no kabir liu hanesan uza prosesu moagem (*grinding*) nian.

3.5 Rezumu

Haree ba rezultadu sira iha leten, bele konfirma katak tékniku propostado nee bele muda mákina ida nia frekuensia resonansia nunee bele mantein kondisaun koa nian neebe ótimu. Rezultadu husi estudu iha kapitulu ida nee bele rezumu hanesan tuir mai nee:

- (1) Metodu ba kontrola frekuensia resonansia iha mákina produsaun estabeleze tiha ona hodi muda densidade estrutura mákina nian, rigidez no posisaun suporta nian.
- (2) Hodi preenxe bé kahur ho polimer ba iha estrutura mákina nian, bele redús frekuensia resonansia no alcanza damping ratio sai boot liu.
- (3) Prosesu evaluasaun koa nian uza mákina tornu hodi aplika metodu propostado halao tiha ona hodi prevene resonansia ho diak, no hadiak peça nia rugosidade sai diak liu tan.

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Kapítulu (4)

DEZENVOLVEMENTU TEKNOLOJIA RESFRIAMENTU FORSADU NIAN HODI BÉ ALKALINA NEEBE FORTE HO MICRO-BOLHAS IHA PERFURASAUN

4.1 Introduction

Geralmente, broca (*drill bit*) sai manas los no fasil atu tohik wainhira halao perfurasaun neebe naruk ba iha peça, nunez konsidera hanesan kondisaun neebe grave se prosesu perfirasaun nee kontinua. Wainhira perfurasaun nee aumenta naruk ba laran, friksaun entre broca ho peça prodús manas no akumula iha broca, ida neebe bele kria failansu, estraga, no hamenus vida broca nian. Ho razaun nee mak, *cermet broca*, *HSS broca*, no *cemented carbide broca* introdúz atu uza ba perfurasaun tanba sira nia tenacidade no rezisténsia ba manas neebe boot. ^[4-1] Sistema resfriamentu no lubrificante oi-oin mak ema uza tiha ona ba halakon manas husi broca nia tutun hodi nunez bele prolunga vida broca nian. ^{[4-2], [4-3]}. Maibe, maske metodu sira nee no mos metodu fornece fluido koa nian ho presaun neebe boot ba iha broca uza tiha ona ^[4-4], efeito resfriamentu seidauk suficiente nafatin. No mos, se haree ba protesaun ba meio ambiente nia *ponto de vista*, seidauk preferível. Aumenta liu tan, atu redús koeficiente friksaun broca nian no manas durante prosesu koa nian, lubrificante sólido husi coating DLC ^[4-5] no TiAlN^[4-6] frequentemente uza iha fábriku no makinazen. Maibe, lubrifikante sólido sira nee seidauk perfeito se haree ba sira nia forsa no durabilidade. Tan nee mak iha estudu ba sesaun ida nee, desenvolvimento ba resfriamentu forsadu hodi fenómeno husi efeito evaporativo bé nian ^[4-7] fornece liu husi koak kiik iha broca, halao atu bele alkansa resfriamentu forsadu. Hafoin, micro-bolhas aumenta ba bé alkalina neebe forte (pH 12.5) atu bele aselera efeito evaporativu

resfriamentu nian. Iha estudu ida nee, espesifikasaun ótimu husi bé alkalina neebe forte klarifika uluk liu husi experimentu. Depois, manas neebe akumulá iha broca sei redús hodi fornese bé alkalina neebe forte kahur ho micro-bolhas liu husi kuak kiik iha broca nia klaran. Efikásia husi metodu resfriamentu forsadu nee sei klarifika mos liu husi experimentu. Aumenta liu tan, efikásia husi metodu nee ba aplikasaun iha industia mos sei evalua liu husi experiment perfurasaun nian.

4.2 Espesifikasaun husi bé alkalina neebe forte ho micro-bolha

4.2.1Espesifikasaun husi bé alkalina

Bé nudar konduktor manas nian neebe excelente, maibe la konviniente nudar fluido ba koa nian. Desde inísio sékulo 20 nian, wainhira F.W. Taylor uza bé ba dala uluk atu halo malirin prosesu makinazen no nia konklui katak bele prolunga vida *feramenta* nian, fluido ba koa nian barak mak ema uza no sugeste tiha ona ^{[1-7],[4-8]}. Maske efikásia husi evaporative resfriamentu bé nian boot liu kompara ba fluido koa nian, utilizaun bé ba makinazen iha industria sei uituan ho razaun katak bé halo feruzu ba iha materiais sira. Nunee, mistura husi bé ho solvente sai nudar fluido bé-miscível ba resfriamentu utiliza dala barak ona iha produsaun no fábriku sira. ^[4-9] Maibe iha sékulo ikus nee, estudu barak mak halo tiha ona ho objetivo atu hamenus utilizaun ba fluido koa nian iha produsaun no fábriku tamba kestaun kustu nian, ekológiku, saude ema nian, no kestaun sira seluk neebe iha relasaun ba ambiente. Ho razaun ida nee, utilizaun bé alkalina neebe forsa hanesan fluido koa nian apresenta iha kapítulu ida nee.

Hanesan mentiona tiha ona katak bé eleva korosaun, maibe kuandu uza bé alkalina neebe forte, sei la halo feruzu ba metal sira nunee suficiente ba uza hanesan fluido koa nian. Korosaun neebe kria husi bé bele evita se bé nia pH hasae ba pH 12.5 (bé alkalina), nunee bele uza durante makinazen. Tamba nee

mak, iha peskiza nee, prova korosaun nian husi materiais sira neebe uza frekuentamente iha makinazen wainhira iha bé alkalina nia laran sei klarifika liu husi experimentu. Espesifikasaun husi gerador ba bé alkalina neebe forte ho pH 12.5 neebe uza iha experimetu nee mak hatudu iha Tabela 4.1. Investigasaun ba mudansa iha bé alkalina nia pH durante fulan rua halao uluk hodi tau bé alkalina nebe forte iha ambiente ho kondisaun $20^{\circ}\text{C}\pm 1$, $40^{\circ}\text{C}\pm 1$ no $12^{\circ}\text{C}\pm 1$, hanesan hatudu iha Tabela 4.2. Rezultadu husi investigasaun nee hatudu iha Fig. 4.1. Rezultadu nee konfirma katak pH tun deit 0.2 iha 12°C , 0.3 iha 12°C no 0.5 iha 45°C , nunee bele konsidera katak bé alkalina bele uza durante period neebe naruk nia laran.

Tabela 4.1 Espesifikasaun husi gerador ba produsaun bé alkalina neebe forte


	Metodu gerasaun	Tipo gerasaun fechado
	POCA (K_2CO_3)	2.18g/l
	Valor pH nian	pH 12.5
	Quantidade husi generation	10 l/h
	Voltagem & Potência	100 V & 300W
	Medida	495W×430D×1100H

Tabela 4.2 Condisaun experimentu nian ba mudansa bé alkalina nia pH

Fluido	Bé alkalina neebe forte
Ambiente nia condisaun	$20\pm 1^{\circ}\text{C}$, 40°C and 12°C Umidade: 60%
Quantidade bé nian	10 l
Medida	Ø 250×230 mm

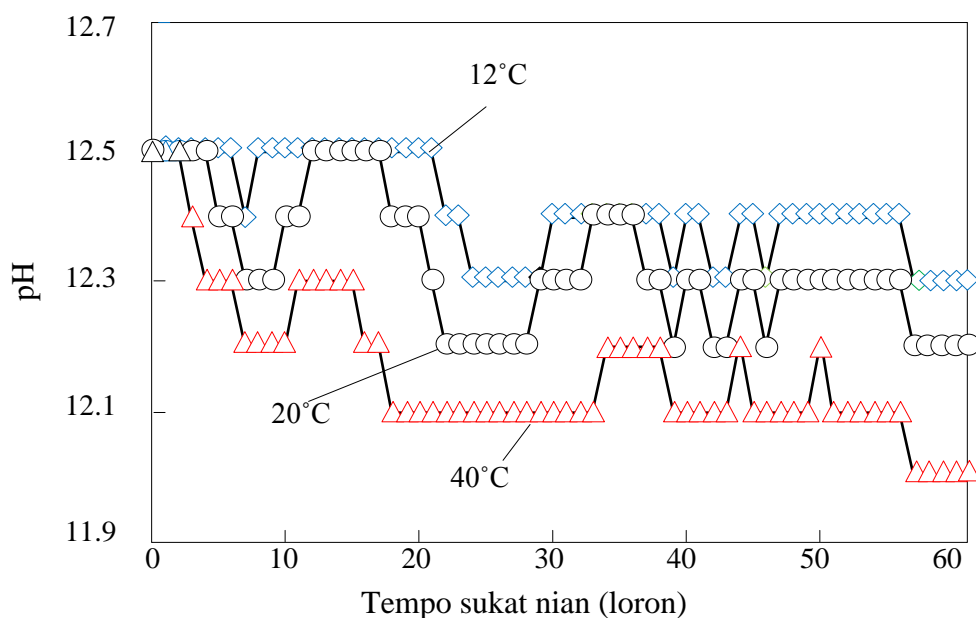


Fig. 4.1 Variaisaun pH nia valor iha temperatura neebe oi-oin





Hanesan esplika tiha ona iha Kapítulu 2, bazeia ba propriedade korosaun husi bé alkalina neebe forte ^[2-29], korosaun sei la mosu iha aço materiais kuandu pH bé alkalina boot liu 10.0, no entre pH 8.5 ~ pH 13.0 ba *titânio* no *níquel alloy* sira. Hodi fakto ida nee mak konsidera katak makinazen ba materiais sira nee wainhira uza resfriamento forsadu hodi hatama sira ba iha bé alkalina nia laran, bele redús efeitua manas nian iha fermento. Tamba nee, pH husi bé alkalina neebe forte ho ninia valór entre pH 10.0 ~ pH 13.0 konsidera adekua ba aplikasaun iha makinazen. Prova ba korosaun husi materias sira neebe kóko iha bé alkalina forte nia laran apresenta iha Tabela 4.3. Evaluasun nee performa iha temperatura $20 \pm 1^\circ\text{C}$ ambiente nian ho ninia umidade 60 % durante fulan rua nia laran. Bé alkalina troka semana ida dala ida atu bele preserva ninia pH. Rezultadu experimentasaun ba rezisténsia korosaun materiais sira nian iha bé alkalina nia laran mak hatudu iha Tabela 4.4. Materiais sira neebe koko iha experiment nee mak: Materiais peça nian (titânio puro, titânio alloy, pure titanium, níquel alloy,

nickel-based alloys), materiais industria nian neebe comum (aço, alumínio, bronze, cobre), materiais feramenta ba koa nian (HSS, carbide, cerment, cerâmico, CNB, diamante), no materiais revestimento sira (TiN, TiC, DLC, TiAlN, TiAlCr).

Tabela 4.3 Kondisaun testo nian ba korosaun

Médio iha balde	Bé alkalina neebe forte (pH 12.5)
Kondisaun ambiente nian	Temperatura ambiente nian: 20±1 °C, Umidade: 60%
Durasaun	Fulan rua

Tabela 4.4 Rezultadu husi materiais sira neebe kóko iha bé alkalina forte,pH 12.5, nian laran (ba fulan rua nia laran)

Materiais peça nian	Kondisaun iha bé alkalina nia laran			Materiais feramenta nian	Kondisaun iha bé alkalina nia laran
Inconel 718	○			Carbide (S30T, T725X)	○
				HSS	○
Ti6Al4V	○			Cerâmico (LX11)	○
				Cermet (NS530)	○
Ti (pure)	○			CBN (KBN525)	○
				Diamante (DA2200)	○
Aço (S45C)	○			Materiais revestimento nian	
Alumínio	×			TiC	○
Cobre		Muda ba dark brown		TiN	○
				DLC	○
Bronze		Muda ba dark green		TiAlCr	×
				TiAlN	×

Símbolu: ○ = La feruzu, × = Feruzu

Rezultadu nee hetan husi experimento hodi hatama materiais sira mentiona tiha ona iha leten nee ba iha bé alkalina nia laran ho pH 12.5 ho kondisaun iha Tabela 4.3. Rezultadu nee hatudu katak kuaze materiais barak mak la feruzu iha bé alkalina nia laran exclui alumínio ho alumínio alloy sira. Nunee konsidera katak makinazen uza bé alkalina forte nee possível. Maibe, tamba alumínio feruzu, nunee presiza tau atensaun wainhira halao makinazen ba nia. No mos, ba bronze no cobre, tenke uza ho kuidadu tamba sira nia kór muda wainhira uza ho bé alkalina.

4.2 Espesifikasaun husi micro-bolha

Iha peskiza nee, ami konsidera katak efisiensia resfreamentu neebe boot bele hetan husi fornese bé alkalina ho micro-bolha liu husi kuak iha broca nia laran ba pontu koa nian. Fotografia no espesifikasaun husi gerador micro-bolhas nian neebe uza iha experiment nee mak hatudu tui-tuir malu iha Fig. 4.2 no Tabela 4.5. Instrumentu nee prodús bolha ar nian rihun ba rihun ho distribusaun bolha sira ho dimensaun neebe diferente hatudu iha Fig. 4.3. Ita bele haree katak bolha ho dimensaun 10 µm mak prodús barak liu. Tan bolha sira nee dezaparese lais deit,



Fig. 4.2. Fotografia gerador micro-bolhas nian

Tabela 4.5 Espesifikasaun gerador micro-bolhas nian

Gerador ba micro-bolhas	
Modelu	A-01
Power consumption kW	0.56
Bé nia quantidade ℓ/min	8~11
Pressaun MPa	0.35~0.45

tan nee, atu bele hatene se micro-bolha sira nee bele fornese too iha pontu koa nia, entaun ita presiza hatene vida micro-bolha sira nian iha bé alkalina nia laran. Fig.4.4 ilustra konfigurasaun experimetu nian atu sukat vida bolha sira nian iha bé alkalina nia laran. Iha experimentu nee, bé alkalina ho litru 30 prepara tiha iha balde laran, depois micro-bolhas fornece ba bé laran durante minutu 10 nia laran ho vazaun (flow rate) 8 ℓ/min . Oras neebe presiza desde hapara forneseментu micro-bolhas ba bé alkalina laran too bé alkalina nee sai transparente fali mak konsidera hanesan vida micro-bolha nian. Experimentu nebe hanesan performa hotu ba bolhas ho dimensaun 1~2 mm no 3~5 mm (fornese ho vazaun 32 ℓ/min).

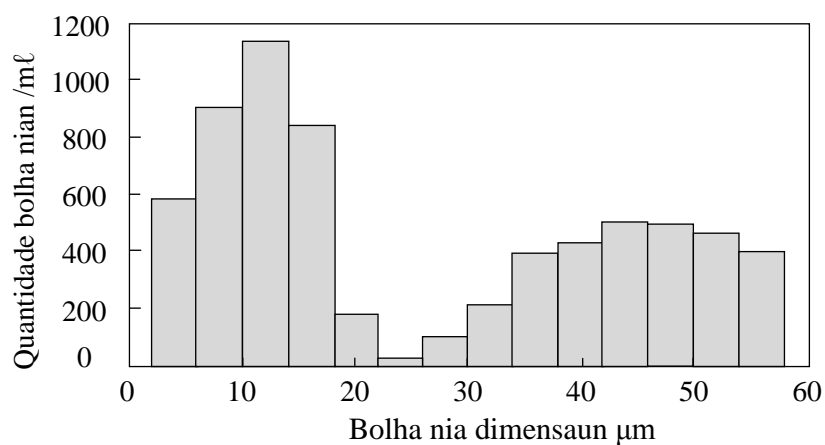


Fig. 4.3 Distribusaun bolha sira ho dimensaun neebe diferente ^[4-10]

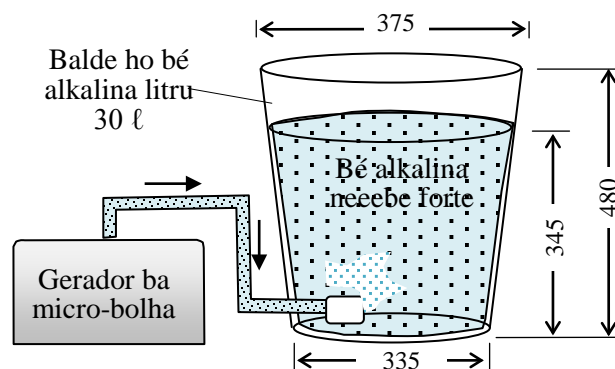


Fig. 4.4 Configurasaun experimetu nian atu sukat vida bolha nian iha bé alkalina nia laran

Aparência husi dimensaun bolha nian neebe diferente bele observa iha Fig.4.5. Bé ninia kór sai hanesan susu-ben wainhira micro-bolha fornese ba bé laran. Rezultadu médiasaun ba vida micro-bolha nian mak hatudu iha Fig. 4.6. Husi rezultadu nee ita bele observa katak micro-bolhas preserva ba 5 minutus iha

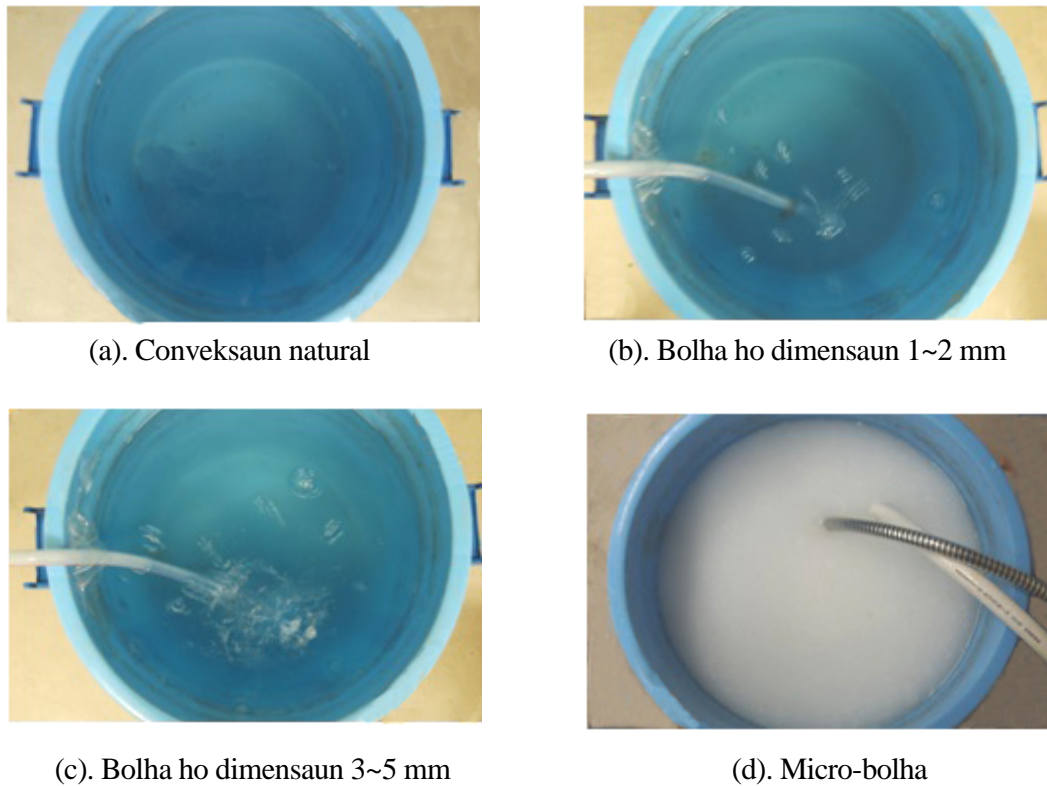


Fig. 4.5 Aparência husi dimensaun bolha nian neebe diferente

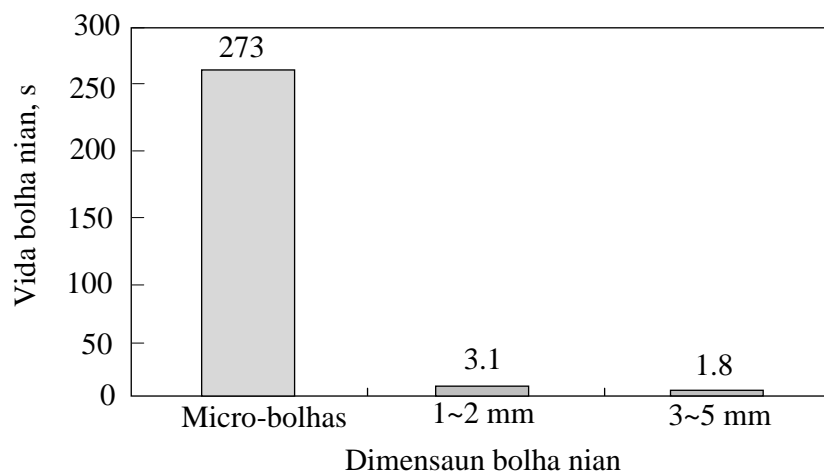


Fig. 4.6 Relasaun entre dumensaun bolha nian ho ninia vida iha bé alkalina nia laran

bé alkalina forte nian laran, nunee bele tranporte micro-bolha liu husi tubo ba too pontu koa. Ho possibilidade ida nee, resfriamentu forsadu uza metodu nee konsidera possível. Maibe, bolha sira iha bé alkalina laran ho dimensaun 1~2 mm no 3~5 mm prevene deit ba sec 1 ou 2 depois desaparece. Nunee mos, wainhira fornese bolha sira ho dimensaun neebe boot, sira lakon tiha antes too iha ponto koa nian. *Conseqüentemente*, fornese bé alkalina forte kahur bolha ho dimensaun nee konsidera difícil. Tamba nee mak iha estudu nee ba oin, ami desidi atu uza deit mak micro-bolha hodi fornese ba bé alkalina nia laran.

Atu hadiak kapasidade resfriamentu nian, experimentu simples ida halao atu buka hatene vazaun (flow rate) micro-bolha nian iha bé alkalina neebe ótimu. Konfigurasaun experimentu nian atu avalia ar nia quantidade ilustra iha Fig.4.7. Iha experimentu nee, bé alkalina bomba sai husi balde no micro-bolha iha gerador micro-bolha nian laran. Bé ho micro-bolha liu husi kontador vazaun nian 'A' no enxe ba iha *Messzylinder* atu bele sukat bé nia kuantidade. Wainhira bé alkalina iha *Messzylinder* sai transparente tiha, bé nia kuantidade sukat dala ida tan. Quantidade bé nian wainhira lori micro-bola iha bé alkalina litru ida nia laran evalua husi diferensia entre bé iha *Messzylinder*. Rezultadu ba quantidade ar nian neebe iha bolhas sira laran mak hatudu iha Fig.4.8. Husi rezultadu nee ita bele haree katak gerador nee prodús micro-bolha neebe barak wainhira

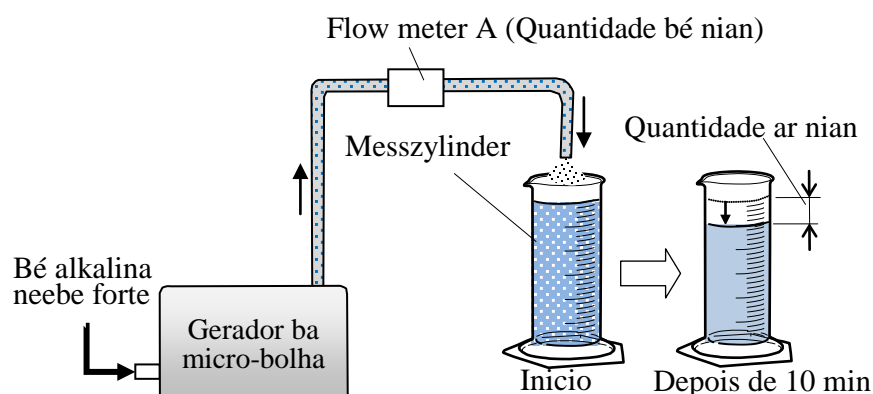


Fig.4.7 Configurasau experimentu nian ba sukat ar nia quantidade iha bé alkalina laran

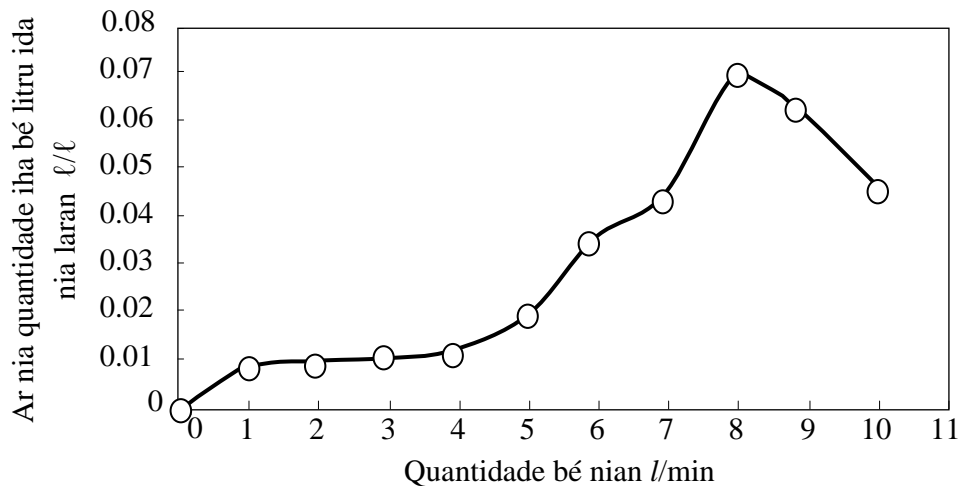


Fig.4.8 Resultadu experimenu nian ba quantidade ar nian iha bé alkalina laran

gerador uza vazaun (flow rate) 8l/min. Nunee, vazaun ida nee sei uza durante experimentu nee ba oin. Vazaun ida nee bele mos hetan waininhira muda pressaun gerador micro-bolha nian ba 0.4 Pa. Wainhira uza presaun menus ou boot liu 0.4 Pa, quantidade micro-bolha nian sai menus tiha fali. Atu hatene efikásia husi kapasidade resfriamentu forsadu bé alkalina ho micro-bola nian, experimentu seluk halao atu evalua *coeficiente de transferência de calor* (heat transfer coefficient). Ilustra iha Fig. 4.9, *borracha aquecedor* (rubber heater) ho ninia espesifikasaun hatudu iha Fig. 4.10, taka entre *chapa de aço* rua (SPCC, 100×100×1 mm) no tara iha balde nian laran neebe enxe ho bé alkalina. Chapa rua nee sukat iha pontu 10 (chapa ida pontu 5 ×2) uza termopar (thermocouple) too kondisaun neebe estável. *Coeficiente de transferência de calor* kalkula husi médio entre temperatura husi *chapa de aço* ho bé alkalina neebe forte uza ekuasaun (4-1).

$$h = \frac{Q}{A(T_a - T_w)} \quad (4-1)$$

Neebe: h = Convective heat transfer coefficient of the process (W/(m²K))

Q = heat transferred per unit time (W)

A= Heat transfer area of the surface (m²)

T_w= Temperatura of strong alkalina water (°K)

T_a= Temperatura of the metal surface (°K)

- Termopar (thermocouples)

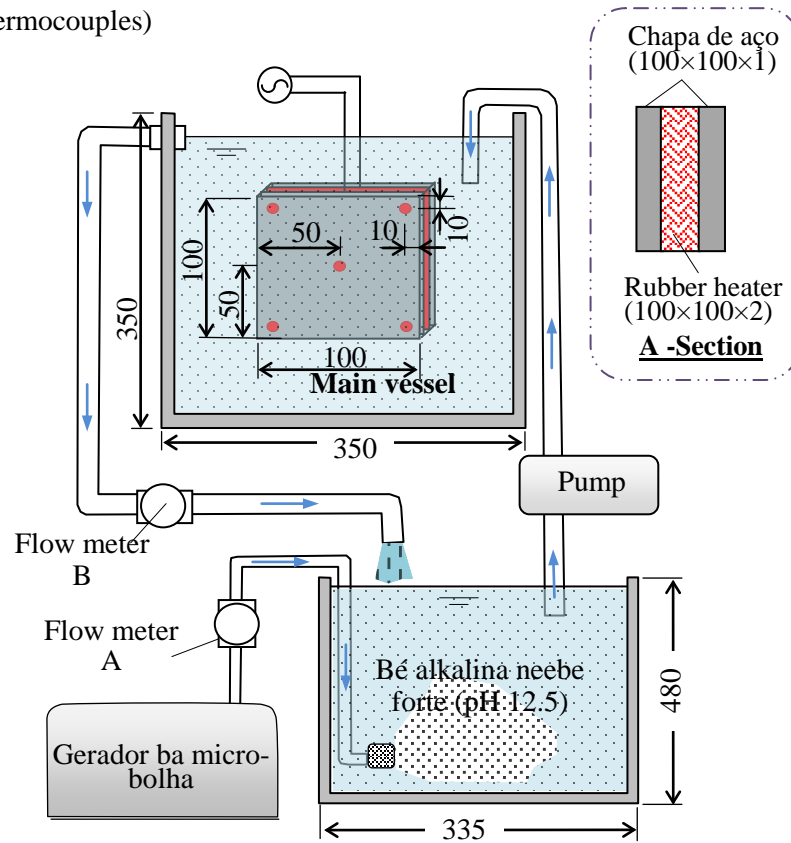
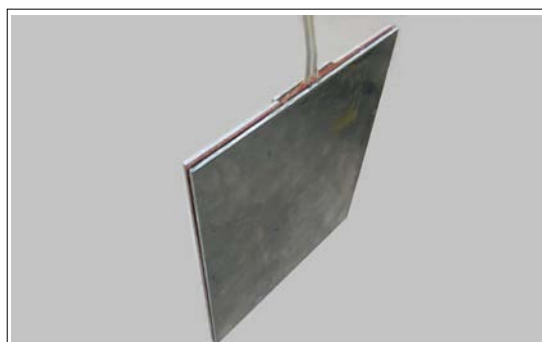


Fig. 4.9 Konfigurasaun experimentu nian ba sukat *heat transfer coefficient* husi bé alkalina ho micro-bolha



Especifikasaun <i>rubber heater</i> nian	
Input voltage (V)	96.7 V
Input power (W)	50
Operasaun temp. (°C)	600
Medida (mm)	100×100×2

Fig. 4.10 Fotografia *rubber heater* nian



Especifikasaun bomba bé nian	
Output power (kW)	0.4
Bé nia qualidade (ℓ/min)	8~11
Pressaun (MPa)	2.1
Medida (mm)	580×440×740

Fig. 4.11 Fotografia bomba ne nian

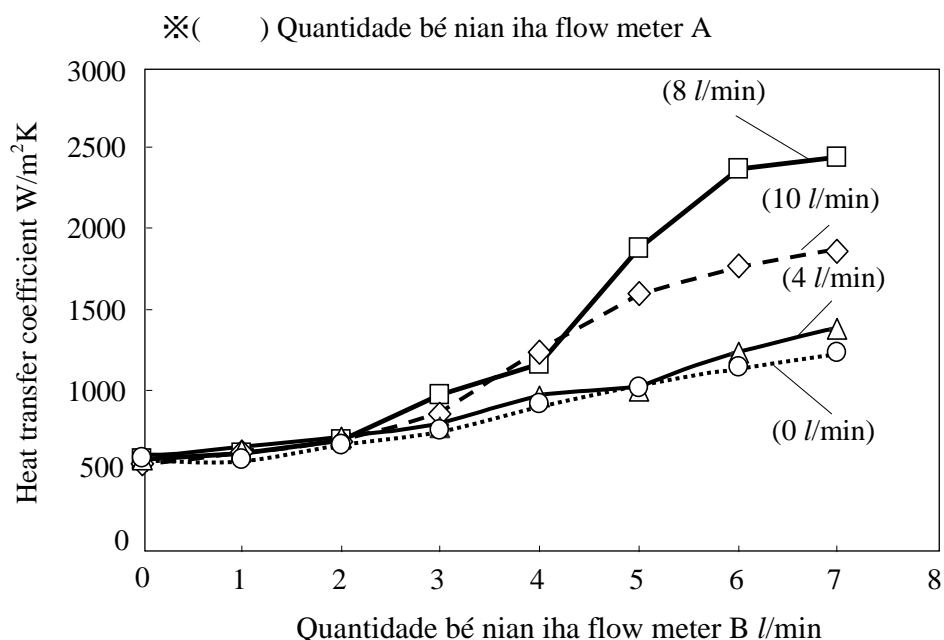


Fig. 4.12 Relasaun entre bé nia kualidade ho *heat transfer coefficient*

Bé alkalina kahur micro-bolhas fornese ba *vessel* principal hodi bomba bé nian ho presaun 2.1MPa no vazaun 10 l/min. Evaluasaun halao hodi sukat diferensia iha ninia konvektaun husi *transferência de calor*. Atu bele hatene vazaun ótimu bé nian neebe bomba sai husi bomba bé nian, avaliasaun halao hodi sukat diferensia vazaun neebe suli liu husu flow meter 'B' neebe uza ba kalkulasaun koeficiente *transferência de calor* nian. Fotografia bomba ne nian neebe uza iha experimento nee mak hatudu iha Fig.4.11. Tamba quantidade micro-bolha neebe prodús depende ba vazaun, nune iha kondisaun nee, parametru ba experimentu defini hodi fornese micro-bolha ho quantidade neebe vário ba bé alkalina laran. Ho parametru nee, *vessel* principal no broca ho iha laran selesiona ba uza iha experimentu nee. Hafoin, *avaliação relativa* aplika ba iha efeito husi resfriamentu forsadu wainhira fornese bé alkalina kahur micro-bolha. Fig.4.12 apresenta rezultadu husi dados ba avaliasaun koeficiente *transferência de calor* nian. Wainhira la uza bomba, koeficiente *transferência de calor* 500 W/m^2K . Bainhira fornese bé alkalina uza bomba ho vazaun 7 l/min, kapasidade resfriamento nia aumenta ba 1200 W/m^2K , no aumenta boot liu tan ba 2500

W/m^2K bainhira fornese bé alkalina ho vazaun 7ℓ/min kahur micro-bolha ho vazaun 8 ℓ/min. Tan micro-bolha ho quantidade neebe barak mak iha bé alkalina laran, coeficiente *transferência de calor* sai boot no efikásia resfriamento husi evaporasaun bé nian aumenta makaas wainhira fornese ho ar. Husi rezultadu ida nee, bele confirma katak efeitu resfriamentu neebe boot bele prodús liu husi circulasau bé alkalina kahur ho micro-bolha.

4.3. Prosesu perfurasaun ho bé alkalina neebe forte kahur micro-bolha uza *through-hole* broca

4.3.1 Broca nia temperatura

Temperatura iha broca nia tutun durante fornese bé alkalina kahur micro-bolha investiga iha experiment nee. Konfigurasaun experimentu nian ba sukat temperatura iha broca nia tutun ilustra iha Fig.4.13. Iha experimentu ida nee,

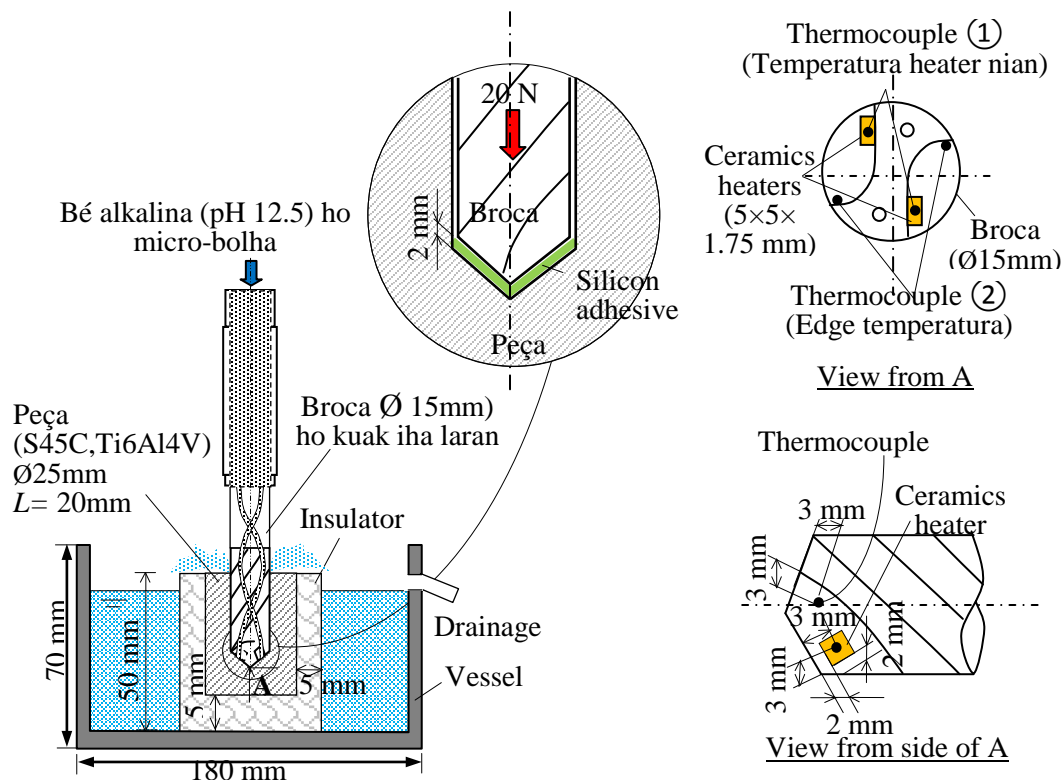


Fig. 4.13 Konfigurasaun experimentu nian no posisaun thermocouple atu sukat temperatura iha broca nia ninin iha parte kôa nian

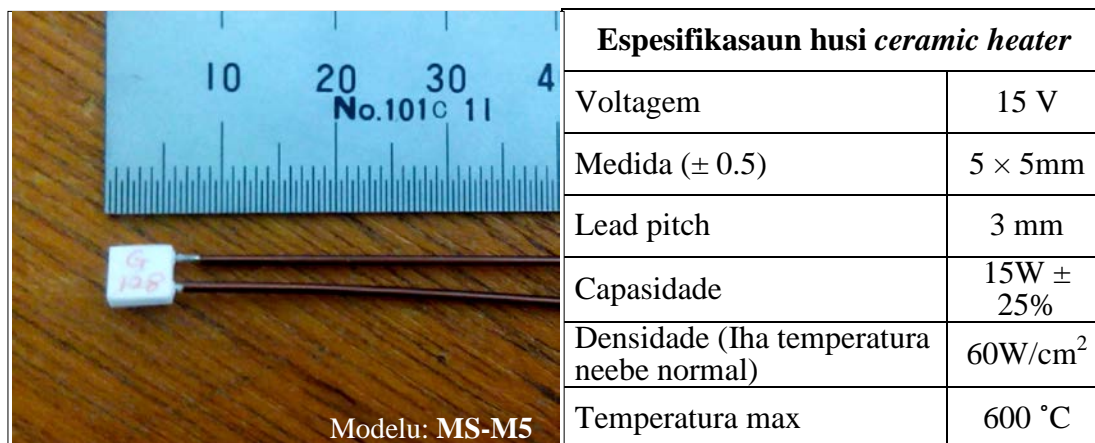
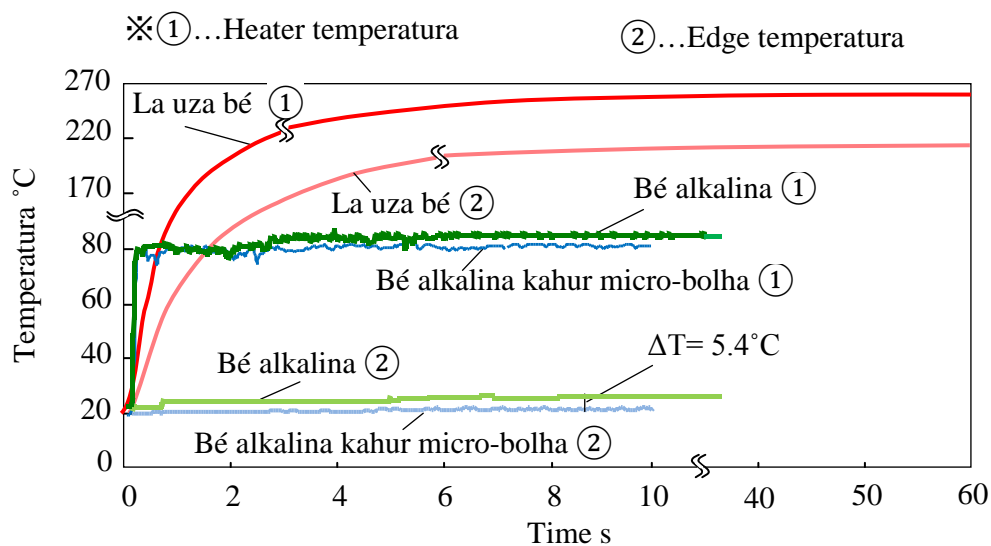


Fig. 4.14 Fotografia no especificação do aquecedor de cerâmica

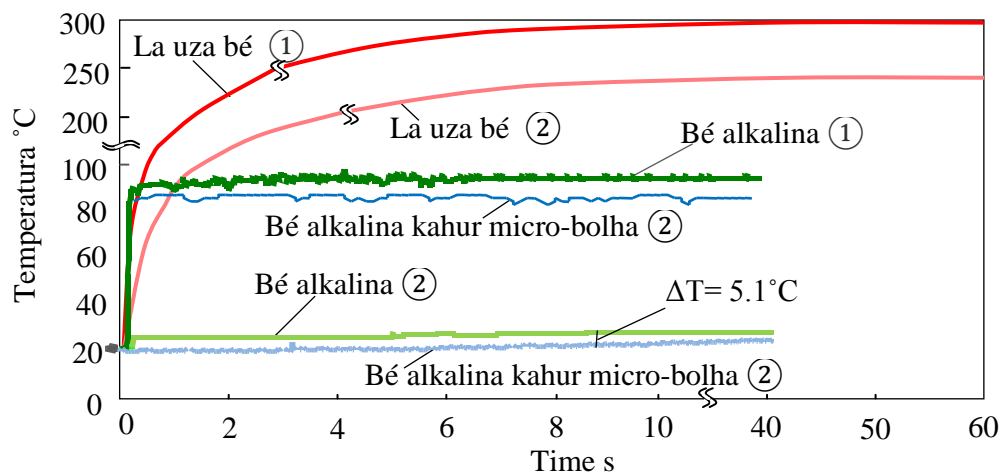
em vez de halao koa ba peça, ami uza metodu simple ida hodi fornese manas ba iha broca nia tutun, nunez fasil atu sukat ninia temperatura. Iha konfigurasaun nee, *aquecedor de ceramic* (ceramic heater) rua neeba kiik kola metin ba iha broca nia ninin ($\varnothing 15 \text{ mm}$, ho *through-hole*), no mos termopar (*thermocouple*) tipo-T cola metin ba iha broca nia le'et (5 mm husi parte hodi koa nian) iha fatin rua besik parte koa nian hodi *silicon bond* ho *espessura* 2 mm too nia solidifika. Depois, forsa 20N aplika ba broca nia leten atu broca nia tutun ho peça bele kontaktu ba malu. Peça ho tipo rua (S45C, Ti6Al4V) mak uza iha experimentu nee. Manas ho máximo temperatura 260°C mak fornese ba *ceramic heater* ho razaun ba konsiderasaun limitasaun ba medisaun husi termopar tipo-T, no limitasaun husi *silicon bond* ba resisti manas. Wainhira la uza resfriamentu, temperatura iha parte koa nian husi broca too 260°C bainhira fornese 0.12 kW ho voltagem 29.8 V ba ceramic heater ida-idak, nunez kondisaun nee mak sei uza iha experimentu ida nee. Parte liur husi peça nian isola ou taka metin ho *polystyrene foam* (Condutividade térmica 0.04 W/mK) ho *espessura* 5 mm atu previne resfriamentu husi ambiente ba peça. Experimentu nee kondúz ho kondisaun 3: Kondisaun maran nian, kondisaun hodi fornese bé alkalina ho vazaun ($7 \ell/\text{min}$) liu husi *through-hole*, no kondisaun fornese bé alkalina (7

ℓ/min) kahur ho mistura micro-bolha (8 ℓ/min) ba iha kontainer ho kuantidade 20ℓ liu husi broca ho *through-hole*. Rezultadu husi temperatura iha broca nia ninin ba peça S45C no Ti6Al4V apresenta iha Fig.4.15. Ba peça S45C, efeito resfriamentu husi bé alkalina boot liu dala 3.5 compara ho la uza bé alkalina. Wainhira fornese bé alkalina kahur ho micro-bolha, efeito resfriamentun boot liu uituan dala 3.5 kompara ho la uza bé alkalina. Maske resfriamentu forsadu ida nee boot liu uituan wainhira uza bé alkalina deit, laiha diferensi boot mak observa husi experimentu ida nee. Tamba, konsidera ba iha limitasaun termopar ho tipo-T atu bele sukat temperatura neebe aas liu, no mos limitasaun aplikasaun husi *silicon bond* no *ceramic heater* nee rasik, la bele aplika temperatura neebe boot, nune mak efeito evaporasaun nian neebe boot la aparese. Maibe ita bele konsidera katak efeito resfriamentu husi bé alkalina nian suficiente ba mantein resisténsia no dureza broca nian. Particularmente, ba peça Ti6Al4V, material ida neebe ho konduktividade térmica neebe kiik, forsa térmica iha broca sai makaas wainhira fura kuak neebe naruk. Nune, ita bele konsidera katak metodu resfriamentu ida nee efetivo tebes ba hamenus manas iha broca nia tutun.



(a) S45C

Fig. 4.15 Temperatura iha broca nia ninin ba kondisaun ho resfriamentu neebe vário



(b) Ti6Al4V

Fig. 4.15 Temperatura iha broca nia ninin ba kondisaun ho resfriamentu neebe vário

4.3.2 Rugosidade da superfície (Surface roughness)

Iha sessaun nee, experimentu koa nian halao no efikásia husi metodu resfriamentu forsadu husi bé alkalina kahur micro-bulha evalua hodi sukat *rugosidade da superfície* peça nian. Máquina NC frais ho spesifikasaun hatudu iha Tabela 4.6 no ninia fotografia hatudu iha Fig. 4.16 mak uza ba evaluasaun koa nian. Kondisaun konvensional perfurasaun no spesifikasaun broca nian neebe uza atu fura materiais aço carbono S45C no Ti6Al4V hatudu iha Tabela 4.7. Perfurasaun nee halao uza broca ho diamentru Ø15 mm. Iha experimentu ida nee, *rugosidade da superfície* peça nian sukat *depois de* koa primeiro nian no mos antes atinzi too iha vida broca nian. Prosesu medisaun halao hodi foti media valor nian husi pontu 9 iha fatin tolu kuak nia naruk 5 mm, 15 mm no 25 mm. Fig.4.17 ilustra konfigurasau experimentu nian ba evaluasaun perfurasaun nian. Kondisaun 4 experimentu nian hanesan: Koa la uza bé, uza resfriamentu konvensional, koa iha bé alkalina 40ℓ laran (ho vazaun 7 ℓ/min), no mos koa iha bé alkalina 40ℓ laran (7 ℓ/min) kahur ho micro-bolha (ho vazaun 8 ℓ/min), mak uza iha experimentu ida nee.

Tabela 4.6 Espesifikasaun makina NC frais nian

Tabela working surface	mm	610×381
Tabela loading weight	kg	250
Tabela movement stroke X-axis	mm	510
" Y-axis	mm	381
" Z-axis	mm	460
Distance from the Tabela top face to the surface of the spindle nose	mm	100~560
Spindle speed	min ⁻¹	130~5000
Feed speed	mm/min	0~5000
Power of motor for spindle	kW	5
Machine weight	kg	2600

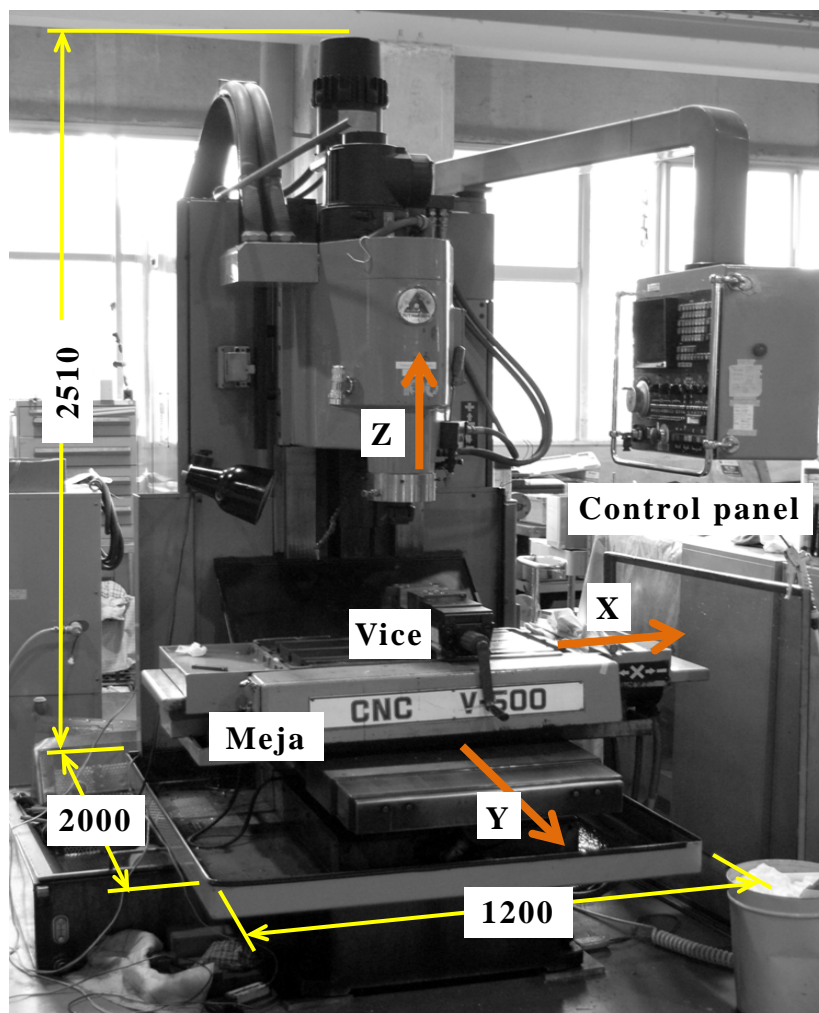


Fig. 4.16 Fotografia husi makina NC frais neebe uza iha experimetu (Unit: mm)

Tabela 4.7 Kondisaun perfurasaun nian ba evaluasaun resfriamento forçado husi bé alkalina neebe forte kahur micro-bolha

Especifikasaun broca nian	
Diâmetro	Ø 15 mm
Naruk	150 mm
Material	Carbide ho TiN
Through hole	Ø 5mm × kuak 2
Especifikasaun médio resfriamento nian	
Médio	Bé alkalina neebe forte (pH12.5)
Micro-bolha	8 l/min iha 40 l bé alkalina
Kondisaun ba perfurasaun	
Spindle speed	500 min ⁻¹
Cutting speed	24 m/min
Feed speed	40 mm/min
Depth of drilling	Husi 0 to'o 25 mm
Peça	S45C and Ti6Al4V

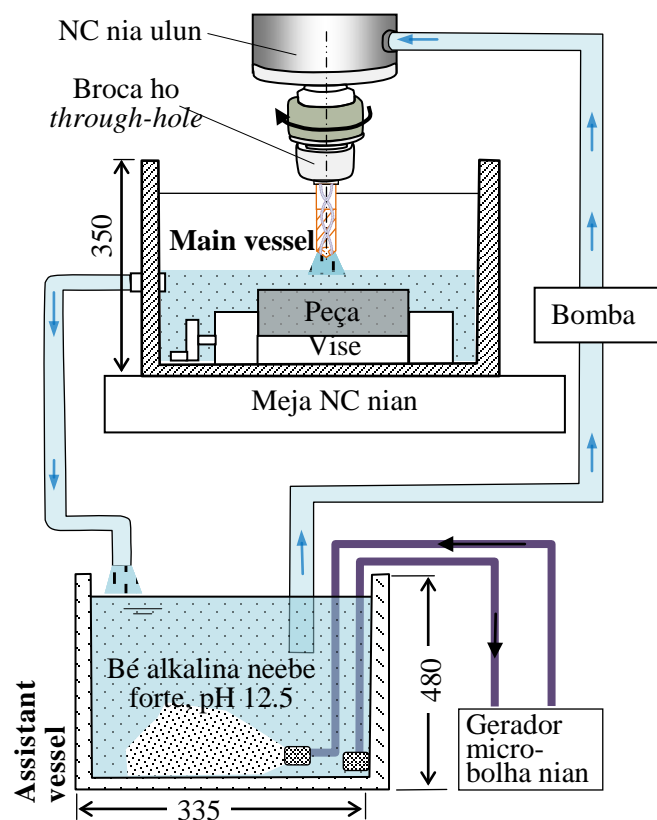
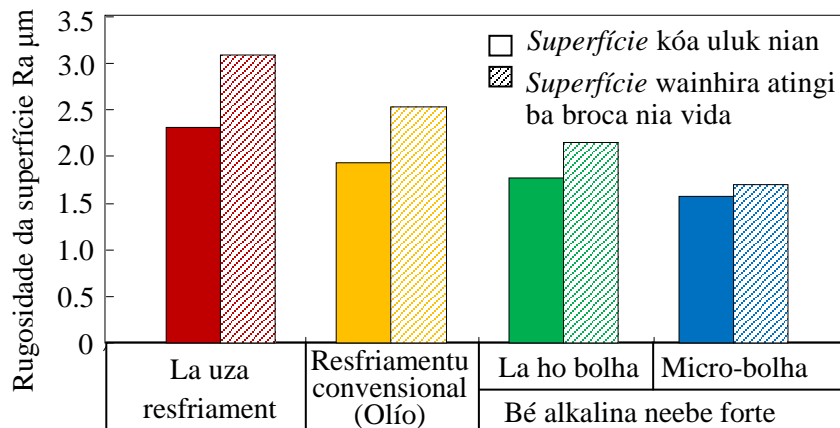


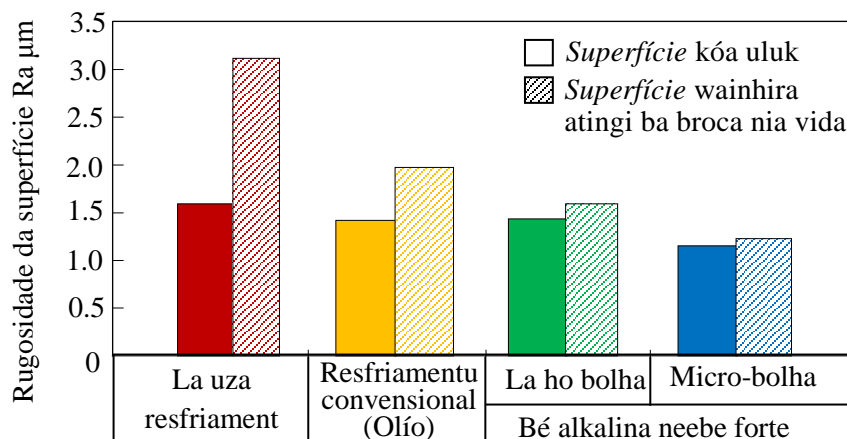
Fig. 4.17 Configurasaun experimentu nian ba evaluasaun perfurasaun nian

Dala ruma iha obstrusaun iha koak kiik broca nian laran tamba peça kiik koa nian belit metin tiha iha koak laran nunez difisil ba bé atu liu. Atu resolve ou evita problema nee, uza bomba bé ho presaun 2.1 MPa ba leten bele dudu sai peça oan ho fasil.

Rezultadu medisaun ba *rugosidade da superfície* (média aritmética Ra) ba S45C no Ti6Al4V apresenta iha Fig.4.18. Rezultadu nee fó hatudu katak uza refriamentu forsadu husi bé alkalina neebe forte kahur micro-bolha durante furamentu ba S45C (Fig.4.18a), peça nia *rugosidade* sai diak 30.5% kompara ho



(a) S45C



(b) Ti6Al4V

Fig. 18 *Rugosidade da superfície* husi koak perfurasaun nian uza kondisaun resfriamentu neebe vário

la uza bé alkalina, no mos sai diak 17.2% kompara ho perfurasaun konvensional. Wainhira halao perfurasaun ba Ti6Al4V (Fig.4.18b), peça nia *rugosidade* sai diak 27.2% kompara ho la uza bé alkalina, no 18% kompara ho perfurasaun konvensional. Tamba efeito resfriamentu evaporasaun nian husi bé alkalina kahur micro-bolha boot uituan atu bele suprimi deformasaun térmico iha broca, nune bele mantein nafatin dureza no resistensia broca nian, mantein broca nia kroat, no mos redusaun iha broca nia rigidez bele hamenus neebe resulta ba iha vibraun neebe kiik ho *rugosidade* neebe kabeer.

4.3.3 Vida broca nian

Iha estudu ida nee, evaluasaun ba vida broca nian uza metodu forneseменту bé alkalina kahur micro-bolha halao no sukat. Kondisaun perfurasaun hatudu tiha ona iha Tabela 4.7 uza iha experimentu ida nee. Hanesan mos iha evaluasaun ba broca nia temperatura, kondisaun 4 experimentu nian hanesan: Koa la uza bé, uza resfriamentu konvensional, koa iha bé alkalina 40ℓ laran (ho vazaun 7 ℓ/min), no mos koa iha bé alkalina 40ℓ laran (7 ℓ/min) kahur ho micro-bolha (ho vazaun 8 ℓ/min), mos uza iha experimentu ida nee. Atu defini vida broca nian hanesan hatudu iha Fig.4.19, broca nia vida konsidera too ona rohan wainhira *flank wear* broca nian (broca nia tohik) atinzi ba too 0.15 mm.

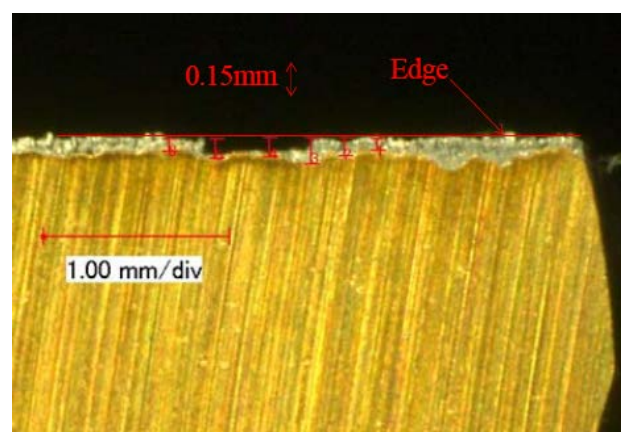


Fig. 4.19. Fotografia husi broca nia ninin neebe tohik (defini nudar vida broca nian)

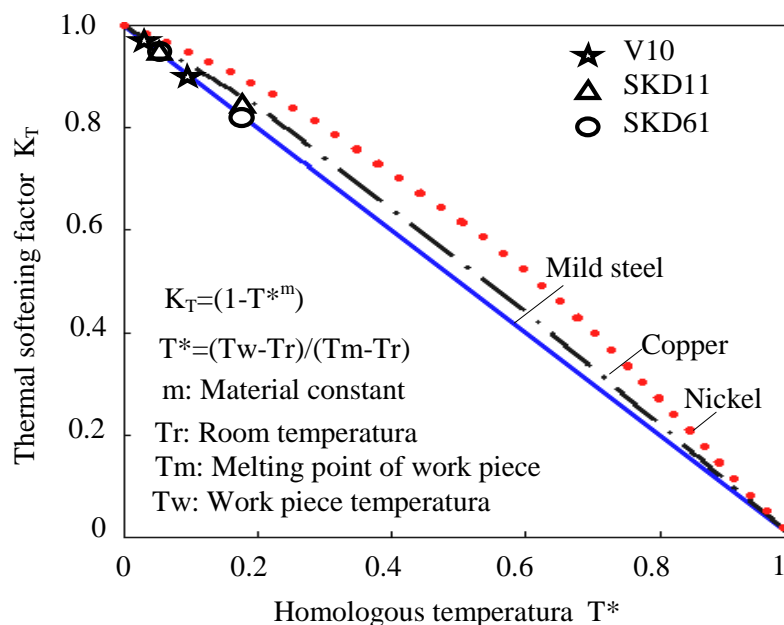
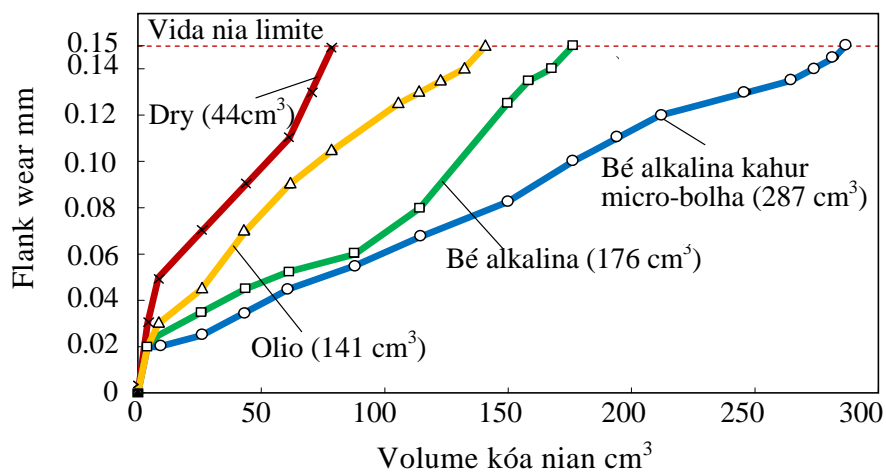


Fig. 4.20. Relasaun entre *softening factor* ho temperatura ^[4-11]

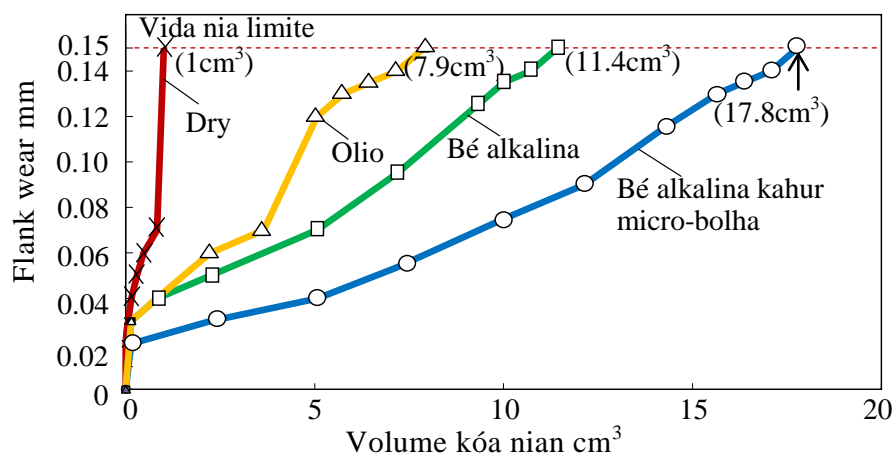
Metal hotu-hotu iha temperatura normal, sira nia *thermal softening factor* mak 1.0. Maibe, iha sira nia *ponto de fusão* (ou *melting point*), sira nia *thermal softening* zero no dureza (ou *hardness*) mos zero, hanesan hatudu iha grafiku iha Fig.4.20. Relasaun entre *thermal softening factor* ho temperatura quase linear. ^{[4-}

^{11]} Por ezemplu, materiais karboneto (ou carbide) ho *ponto de fusão* 2500°C, ninia dureza HRC 92 temperatura ambiente nian, HRC 62.5 iha 800°C ($92 \times (1.0 - 800 \div 2500)$), no HRC 46 iha 1250°C, ($92 \times (1.0 - 1250 \div 2500)$). HRC mak abreviatura husi *Rockwell Hardness*. Dureza HRC 62.5 iha 800°C bele uza nudar ferramento koa nian, mas HRC 46 at 1250°C la bele tamba konsidera mamar liu atu hodi koa aço materiais. Tamba nee, temperatura husi feramenta bele afeita sira nia dureza. No mos, koa uza ferramento neebe mamar iha influencia boot ba ninia vida. Ho razaun ida nee mak ami propoin metodu resfriamentu forsadu iha estudu nee, atu nunnee bele prevene broca sai mamar kuando manas no mos bele prolonga broca nia vida. Rezultadu mediasaun ba vida broca nian husi experimentu mak apresenta iha Fig. 4.21. Ba perfurasaun peça S45C (Rezultadu hatudu iha Fig .4.21(a)), vida broca nian wainhira uza bé alkalina kahur micro-

bolha prolonga dala 6.5 kompara ba perfurasaun la uza resfriamentu ruma, dala 2 kompara ba uza resfriamentu husi olio, no dala 1.6 kompara ba uza bé alkalina deit. Uza efeitu resfriamentu forsadu husi bé alkalina neebe forte kahur micro-bolha, broca bele sai malirin no mos redusaun iha ninia dureza bele hamenus. Ba peça Ti6Al4V (materiais neebe ninia konduktividade térmico kiik los), rezultadu vida broca nian wainhira fura material ida nee hatudu iha Fig.4.21(b). Rezultadu perfurasaun nian hatudu katak efeitu resfriamentu forsadu husi bé alkalina neebe forte kahur micro-bolha boot los kompara ba perfurasaun la uza resfriamentu,



(a) S45C



(b) Ti6Al4V

Fig. 4.21 Resultadu husi vida broca nian durante halao perfurasaun ba S45C no Ti6Al4V uza resfriamentu oin-oin kompara ba método proposto

olio, no bé alkalina deit. Vida broca nian wainhira uza efeito resfriamentu forsadu husi bé alkalina neebe forte kahur micro-bolha prolunga dala 17.8 kompara ba la uza resfriamentu, dala 2.2 kompara ba uza olio, no dala 1.6 kompara ba uza bé alkalina deit. Tamba konduktividade térmico husi peça Ti6Al4V no ninia chip kiik los, manas neebe resulta durante perfurasaun kondúz tama fali ba broca nia laran nune halo broca nia temperatura sai boot ho konsekuensia redusaun iha broca nia dureza. Husi rezultadu experimeto nian iha leten, ita bele hateten katak prosesu perfurasaun ba materiais ho konduktividade térmico kiik (difícil atu koa) bele realiza uza metodu resfriamentu forsadu husi bé alkalina neebe forte kahur micro-bolha neebe ami propoin ona iha estudu ida nee.

4.4. Rezumu

Husi rezultadu sira neebe esplika tiha ona iha leten, bele konfirma katak teknilojia ba fresfriamentu forsadu ba perfurasaun uza bé alkalina neebe forte kahur micro-bolha bele hadiak no aumenta efeito resfriamentu evaporasaun nian. Rezultadu husi estudu ba kapitulu ida nee ninia rezumu mak hanesan tuir mai nee:

- (1) Wainhira aumenta micro-bolha ba iha bé alkalina nia laran, bele prodús efeito resfriamentu forsadu neebe boot los ho ninia *coeficiente de transferência de calor* neebe aas tebes ho valor too $2500\text{W/m}^2\text{K}$.
- (2) Uza metodu neebe ami propoin, temperatura broca nian bele hamenus too 70%, peça nia *rugosidade* bele sai diak too 30%, no vida broca nian bele prolunga dala 6.5 times kompara ba la uza resfriamentu.
- (3) Metodu resfriamentu forsadu uza bé alkalina neebe forte kahur micro-bolha konsidera efetivo ba konserva meio ambiente.

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Kapítulu (5)

DESENVOLVEMENTU BA TEKNOLOJIA IMERSAUN MÁKINA PRODUSAUN IHA BÉ ALKALINA NEBE FORTE ATU REDÚS CO₂

5.1 Introdusaun

5.1.1 Fundo estudu nian

Desde sékulo ikus liu ba, matenek nain sira enfrenta problema iha fundo energia nian no destruisaun ambiente naturais iha eskala global. Hamenus utilizaun ba iha eletricidade, olio mákina no koa nian, no fluido ba resfriamentu sira neebe bele fo perigu ba ambiented no saude ema nian sai ona hanesan fátor ida neebe importante tebes neebe presiza konsidera iha area fabrikasaun no produsaun. Partikularmente, hamenus emisaun CO₂ importante tebes ba prevene rai husi aquecimento global (*global warming*). Desde olio lubrifikasaun ho quantidade neebe barak mak uza ona atu lubrifica mákina sira, olio koa nian uza barak hanesan resfriamentu iha makinazen, sira prodús poluisaun hodi emiti CO₂. Kondisaun ida nee konside nudar problema boot ida ba conserva ita nia ambiente. Nunee, fluido koa seluk presiza tebes atu bele hamenus impacto ba iha ambiente. Tamba nee, fabrikasaun neebe eco-amigáveis (*eco-friendly*) ^[5-1] sai ona nudar pedido jerál iha prosesaun teknolojia nian neebe fó konsiderasaun ba konservasaun energia nian. Sistema resfriamentu oin-oin mak aplika tiha ona iha makinazen atu hamenus manas iha feramenta, nunee bele prolonga feramenta nia vida no mos alkansa *rugosidade da superfície* neebe diak ba rezultadu final koa nian. Maibe, feramenta, resfriamentu no kondisaun koa nian neebe ótimu mesak seidaunk

bele garantia rezultadu final koa nian neebe ótimu. Por ezemplu, manas husi rolamentu neebe suporta espidulu iha mákina tornu (*lathe machine*) mos iha influensa ba rezultadu ikus koa nian. Manas ida nee mai husi friksaun iha rolamentu laran wainhira nia dulas, neebe sai kauza ba deformaun térmika atu mosu. Kuando konsidaun ida nee mosu, peça sei muda-aan husi ninia posisaun original, nunee halo rezultadu ikus koa nian sai ladun diak. Ba resolve problema ida nee, metodu barak mak ema apresenta tiha ona ba hatun deformaun térmika iha mákina produsaun sira nunee bele hasae presisaun fabrikasaun nian ^{[5-2], [5-3]}. No mos, teknolojia ba resfriamentu forsadu barak mak estabeleze tiha ona atu bele hasae akurasaun no produtividade ^{[5-4], [5-5]}. Metodu sira nee barak mak uza refrigerasaun ho kapasidade neebe aas ba resfriamentu forsada atu hakalon manas no suprimi impaktu térmika iha mákina no feramenta. Maibe, se konsidera atu bele conserva ambiente, presiza metodu seluk neebe adekuaudu ba problema iha leten.

5.1.2 Proposta pesquisa nian

Iha estudu ida nee, ami propoin tékniku foun neebe bele minimize deformaun térmika rezulta husi manas neebe excessivo no mos bele redús CO₂ neebe emiti durante makinazen. Estudu ida nee halao hodi performa experimentu koa nian uza mákina *torno de bancada*, neebe submerge iha bé alkalina nia laran. Efeito evaporasaun resfriamentu husi bé alkalina bele hamenus deformaun térmika iha mákina produsaun, no mos hamenus gerasuan calor iha pontu koa nian iha feramenta liu husi kondisaun imersaun. Tan nee mak estudu ba sistema imersaun ba prosesu makinazen halao no desenvolve uza efeito evaporasaun husi resfriamentu forsadu. Konkretamente, mákina kiik *torno de bancada* sei hatama iha bé alkalina neebe forte nia laran, depois deformaun térmika husi mákina nia estrutura, prosesu akurasaun no vida feramenta nian sei evalua liu husi experimentu. No mos, atu bele prova efikásia husi metodu ida nee, rezisténsia ba

korosaun elementus sira mákina nian iha bé alkalina neebe forte halao no investiga. Atu hadiak kapasidade resfriamentu nian, investigasaun ba aumenta micro-bolha iha bé alkalina laran mos halao hotu.

5.2 Resistansia elementus sira mákina nian husi korosaun iha bé alkalina neebe forte

Maske bé nia efeito evaporasaun ba resfriamentu nee boot tebes kompara ba fluidu koa nian sira seluk ^[5-6], ninia aplikasaun ba resfriamentu durante makinazen iha industria sei uituan ho razaun katak bé sai kauza ba korosaun iha mákina produsaun sira, peça sira no elementu seluk mákina nian. Maibe, hanesan deskreve iha engênaria korosaun nian katak wainhira valor logarítmica husi konsentrasaun íon (mol/ℓ) metal ida nian menus husi -6, metal nee sei la feruzu. Hanesan esplika ona iha kapítulu 2 no mos kapítulu 4, bazeia ba propriedades korosaun iha bé alkalina laran ^[2-29], materiais aço sei la feruzu wainhira pH bé nian boot liu 10.0. Nunee mos ba níquel no níquel *alloy* sira, pH ho eskala entre of pH 8.5 ~ pH 13.0 konsidera hanesan pasividade kímiku níquel nian, nunee sei la feruzu. Hanesan mos ba titânio no titânio alloy sira, pH 13.0 ba kraik sei la provoka korosaun ba titânio. Ho faktu sira nee mak pH ho eskala entre pH 10.0 ~ pH 13.0 konsidera suficiente hodi uza ba metodu mákina nian sem kria feruzu ba iha mákina nee rasik. Ho metodu ida nee, prosesu makinazen ho resfriamentu evaporativu neebe efetivu husi bé alkalina bele halao no fó beneficio ba redusaun calor iha mákina produsaun. Nunee mos, bé alkalina neebe forte mos iha benefisiu barak tamba nia iha kapasidade permeabilidade neebe aas, detergensia neebe diak, hamoos dekompozisaun neebe excelente, emulsifikasaun no eradikasaun neebe diak. Aumenta liu tan, wainhira bé alkalina neebe forte nee husik kleur iha ambiente, nia sei lakon ninia alkalinidad no sai bé bai-bain (laos ona alkalina) ho pH entre 7.0 to'o 8.0.

Iha kapítulu 4 liu ba, investigasaun resistansia ba korosaun iha bé alkalina neebe forte nian laran halao tiha ona ba materiais balun. Maibe, tan iha estudu ida nee, materiais barak mak sei submerge wainhira mákina ida hatama tomak iha bé alkalina nia laran, materiais sira hotu neebe uza ba produsaun mákina ida nian sei identifika hotu no investiga sira nia rezisténsia ba korosaun. Metodu experimentu ba investigasaun korosaun no espesifikasaun husi gerador ba bé alkalina neebe presente tiha ona iha Tabela 4.1, Kapítulu 4 mak hatudu fali iha Tabela 5.1. Uza gerador *movél* ida nee, ita bele prodús bé alkalina ho pH 12.5 ho facil.

Tabela 5. 1 Espesifikasaun husi gerador ba bé alkalina neebe forte

Metode produsaun nian	Tipo gerasaun fechado
POCA	K ₂ CO ₃
pH nia valor	pH 12.5
Quantidade produsaun nian	10 ℓ/h
Voltagem & Power	100 V & 300W
Dimensaun	495W×430D×1100H

Tabela 5.2 Kondisaun testu nian ba evaluasaun rezisténsia ba korosaun

Médio iha balde laran	Bé alkalina neebe forte (pH 12.5)
Kondisaun ambiente	Temperatura ambiente nian.: 20±1°C, Umidade: 60%
Durasaun	Fulan rua

Hanesan espliha tiha ona iha leten katak materiais sira balun ninia resistansi ba korosaun investiga tiha ona iha Kapítulu 4 kotuk ba, característica korosaun nian iha bé alkalina neebe forte husi materiais oi-oin hanesan: materiais husi mákina produsaun nia estrutura, peça, feramenta, elementus mákina nian, feramenta neebe revestimento tiha ona no materiais neebe pinta tiha ona ho cor sei investiga iha estudu ida nee. Kondisaun testu nian ba evaluasaun rezisténsia matriais sira neebe mentiona iha leten husi korosaun mak hatudu iha Tabela 5.2. Ezemplu husi materiais balun uza iha experimentu nee mak hatudu liu husi fotografia iha Fig. 5.1. Materiais sira nee hatama iha bé alkalina ho pH 12.5 nian laran no hatur iha temperatura ambiente nian $20 \pm 1^{\circ}\text{C}$ no umidade 60%. Evaluasaun halao hodi husik materiais sira nee iha bé alkalina laran durante fulan rua nian laran. The materials were left for two months inside strong alkalina water for observation of corrosion phenomenon on the test materials. Maske bé alkalina nia pH la menus barak durante fulan rua nia laran, iha testo ida nee, bé alkalina troka semana ida dala ida atu nunee bele mantein ninia pH. Rezultadu husi testo ida nee mak hatudu iha Tabela 5.3.



Fig 5.1 Fotografia husi materiais balun neebe immerse iha bé alkalina laran

Kuaze materiais mákina produsaun nian barak mak la feruzu *alem de* alumínio no alumínio alloy. Fotografia husi materiais balun antes no depois hatama ba bé alkalina durante dulan rua nia laran hatudu iha Fig.5.2 tuir mai nee.



Fig. 5.2 Fotografia husi materiais balun depois no antes hatama iha bé alkalina laran

Iha testo ida nee, ami observa katak materiais barak mak la feruzu. Roska parafuzu nian neebe kiik sai feruzu maibe roska boot lae. *Cobre* no *cobre alloy* la feruzu maibe sira muda deit sira nia kór. Rolamentu no *parafuzu da esfera* (*ball screw*) la feruzu. Nune bele konsidera katak halao makinazen hodi iha bé alkalina nia laran nee *posível*. Maibe, iha tinan ikus-ikus nee nia laran, materiais ba revestimento (*coating materials*) hanesan TiAlN no TiAlCr mak uza barak ona iha feramenta ba koa nian tamba sira nia dureza neebe aas no mos coeficiente friksaun neebe kiik, ami observa katak materiais neebe inklui ho komponente alumínio (Al) sei feruzu lalais. Maibe TiAlN and TiAlCr la hatudu feruzu tamba sira iha kuantidade alumínio (Al) neebe uituan. Observasaun seluk hatudu katak mola tanki olio nia matan no mos rede iha soe foer fatin nian neebe halo husi alumínio sai feruzu. Komponente mekâniku no elêtriku balun neebe uza ba montaze no arrumasaun nian hanesan parafusu no mola oan neebe halo husi alumínio ou *cobre* bele sai feruzu ou muda sira nia kor, nune presiza fó atensaun neebe diak. Kona ba graxa (*grease*) neebe iha rolamentu no guia linear nia laran, ami observa katak laiha erupsaun mak akontese. No mos, lai mudansa ba rolamentu no guia linear sira nia karakterístika. Rolamentu nia karakterístika evalua liu husi testo ida hodi hadulas parte liur rolamentu nian ho tali ida neebe ninia rohan kesi ba objeto todan ruma, hafoin husik objeto nee no sura ninia velocidade rotasaun nian. Ba guia linear, ninia karakterístika evalua hodi monta nia ba posisaun inklina, hafoin mak sukat ninia movimentu wainhira halai tun. Servo motor nia karakterístika evalua depois de nia maran kompletu tiha kedas, hafoin mak confirma ninia konfigurasaun no funsaun iha mákina NC tornu. Materiál revestidu sira hanesan karbon diamante (DLC) and nitreto titânio (TiN) mos la feruzu, nune sira bele uza nudar lubrifikante sólidu ba *deslizamento* iha *superfícies* wainhira mákina nia estrutura tomak submerge iha bé alkalina laran.

Tabela 5.3 Rezultadu husi materiais oi-oin neebe mak hatama iha bé alkalina laran

Makina produsaun nia estrutura	S45C	○	Kondisaun la muda
	SUS304	○	Kondisaun la muda
	Cast iron	○	Kondisaun la muda
Peça	Ti	○	Kondisaun la muda
	Ti6Al4V	○	Kondisaun la muda
	Inconel 718	○	Kondisaun la muda
	S45C	○	Kondisaun la muda
	Copper	△	Descolorizasaun deit
	Brass	△	Descolorizasaun deit
	Aluminum	×	Feruzu
Feramenta	HSS	○	Kondisaun la muda
	Carbide	○	Kondisaun la muda
	Cermet	○	Kondisaun la muda
	Diamond	○	Kondisaun la muda
	CBN	○	Kondisaun la muda
	Ceramic	○	Kondisaun la muda
Material revestido	DLC	○	Kondisaun la muda
	Ti AlN	×	Descolorizasaun deit
	TiAlCr	×	Descolorizasaun deit
Elemento elétrico	Push-button switch	△	Terminal feruzu, Parafuzu feruzu
	Command switch	△	Terminal feruzu, Parafuzu feruzu
	Optoelectronic switch amplifier	△	Terminal feruzu, Parafuzu feruzu
	Servomotor	△	Parafuzu deit mak feruzu
	Box terminal	○	Kondisaun la muda
	Electromagnetic contactor	×	Electromagnet feruzu
	Solenoid valve	△	Descolorizasaun deit
	Solenoid valve base	△	Descolorizasaun deit
	Flat cable	○	Kondisaun la muda
	Cable connector	○	Kondisaun la muda
	Direct acting two port solenoid valve	△	Parafuzu deit mak feruzu

○ : La feruzu △ : Descolorasaun no parafuzu deit mak feruzu × : Feruzu

Tabela 5.3 Rezultadu husi materiais oi-oin neebe mak hatama iha bé alkalina laran (continua)

Elemento makina nian	V-belt	×	Nakfera uituan
	Drive belt	○	Kondisaun la muda
	Timing belt	○	Kondisaun la muda
	O-ring	○	Kondisaun la muda
	Bearing	○	Kondisaun la muda
	Linear guide	○	Kondisaun la muda
	Ball screw	○	Kondisaun la muda
	Oil seal	△	Mola mak feruzu
	Oil pump	×	Terminal feruzu (Falha)
	Wire hose	○	Kondisaun la muda
	Excel hose	○	Kondisaun la muda
	Cap connector	△	Parafuzu deit mak feruzu
	Tube fitting	○	Kondisaun la muda
	Oil level gauge	○	Kondisaun la muda
	Rubber bushing	○	Kondisaun la muda
	Exhaust cleaner	×	Korosaun no discolorizaun
	Check valve	△	Parafuzu deit mak feruzu
	Lubricator	○	Kondisaun la muda
	Regulator	△	Parafuzu deit mak feruzu
Materiais báziku	Acrylic acid resin	○	Kondisaun la muda
	Vinyl chloride	○	Kondisaun la muda
	Nylon	○	Kondisaun la muda
	Polyurethane	○	Kondisaun la muda
	Polycarbonate	○	Kondisaun la muda
	Nitrile rubber	○	Kondisaun la muda
	Polyurethane rubber	○	Kondisaun la muda
	Fluoro rubber	○	Kondisaun la muda
	Chloroprene rubber	○	Kondisaun la muda
	Chlorosulfonated Polyethylene rubber	○	Kondisaun la muda
	Oilproof vinyl mixture	○	Kondisaun la muda
	Urethane elastomer	○	Kondisaun la muda
Pinta	Lacquer paint	○	Kondisaun la muda
	Urethane resin paint	○	Kondisaun la muda
	Epoxy resin paint	○	Kondisaun la muda

○ : La feruzu △ : Descolorasaun no parafuzu deit mak feruzu × : Feruzu

5.3 Hasae koefisiente transferência calor nian husi bé alkalina neebe forte kahur ho micro-bolha

Iha sessaun ida nee, coeficiente transferência calor nian husi bé alkalina neebe forte hasae hodi kahur ho micro-bolha, hafoin ninia efikásia klarifika liu husi experimentu. Uluk liu, vida micro-bolha nian iha bé alkalina nia laran investiga hanesan halao tiha ona iha Kapítulu 4, Fig.4.4. Atu relembra, experiment ida nee halao hodi fornese micro-bolha ba bé alkalina litru 30 ho vazaun (flow rate) 8 ℓ/min durante 10 minutos, hafoin sukat tempo neebe presiza atu bé alkalina sai transparente fila fali. Distribuisaun kuantidade micro-bolha sira iha bé alkalina laran mak hatudu iha Fig.5.2. Prosesu neebe hanesan aplika mos ba bolha sira ho medida 1~2 mm no 3~5 mm, neebe fornese uza vazaun 10 ℓ/min. Rezultadu medisaun experimentu nian mak hatudu iha Fig.5.3. Husi rezultadu nee, ita bele observa katak micro-bolha bele mantein iha bé alkalina latan too kuaze 5 minutos nia laran, nunee bele tranporte liu husi tubo ba too pontu koa. Ho possibilidade ida nee, resfreamentu forsadu uza metodu nee konsidera possível. Maibe, bolha sira iha bé alkalina laran ho dimensaun 1~2 mm no 3~5 mm prevene deit ba sec 1 ou 2 depois desaparece. Nunee mos, wainhira fornese bolha sira ho dimensaun neebe boot, sira dezaparese lalai deit too iha pontu koa nian. Tan nee mak fornese bé alkalina forte kahur bolha ho dimensaun nee konsidera difisil.

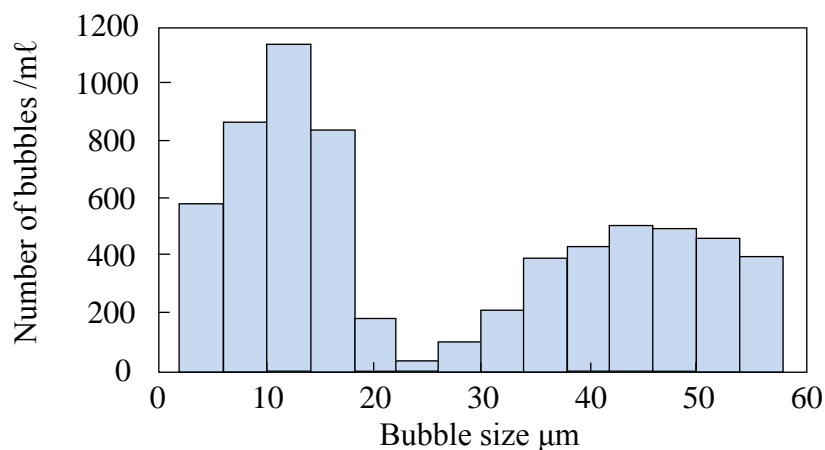


Fig. 5.2 Distribusaun bolha sira ho dimensaun neebe diferente ^[4-10]

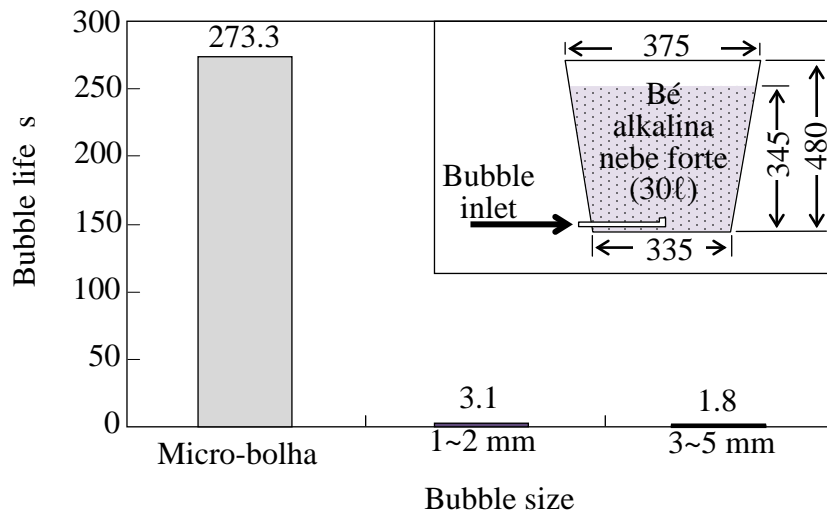


Fig. 5.3 Relasaun entre dimensaun bolha nian ho ninia vida iha bé alkalina nia laran

Micro-bolha uza barak tiha ona iha area oi-oín nudar refrigerante no tratamentu ba fore residuo sira ^{[5-7], [5-8], [5-9]}. Bolha kiik neebe lori ar no haleu ho bé bele aumenta efeito resfriamento nian. No mos, prosesu separasaun hanesan flutuasaun ba foer ou oliu sai fasil wainhira uza micro-bolha. Tan nee mak, atu verifika kapasidade resfriamentu wainhira uza micro-bolha, koefisiente transferência calor nian evalua liu husi experimentu uza *borracha aquecedor* (*rubber heater*). Ilustra iha Fig. 5.4 katak, borracha aquecedor (100 × 100 × 2mm) cola entre chapa aço rua (SPCC, 100 × 100 × 1mm), hatama ba iha bé alkalina iha container laran (L1190 × W980 × H790 mm) hamutuk ho mákina *torno de bancada*. Temperatura husi chapa aço ruan nee sukat hodi tara borracha aquecedor iha container nia klaran no fornese ho eletricidade 50 Watt. Bainhira temperatura husi chapa rua nee alcanca ba kondisaun neebe estável (*steady state condition*), mediasaun halao hodi komesa halao gravasaun ba temperatura no mos kalkula ninia koefisiente ba transferência calor nian. Experimentu ida nee halo ho kondisaun hanesan: uza resfriamentu naturais husi bé alkalina, aumenta ho micro-bolha (8 ℓ/min), no mos aumenta micro-bolha no opera mákina iha rotasaun 3600 rpm. Fotografia ba konfigurasaun experimentu ida nee nian hatudu iha Fig.5.5.

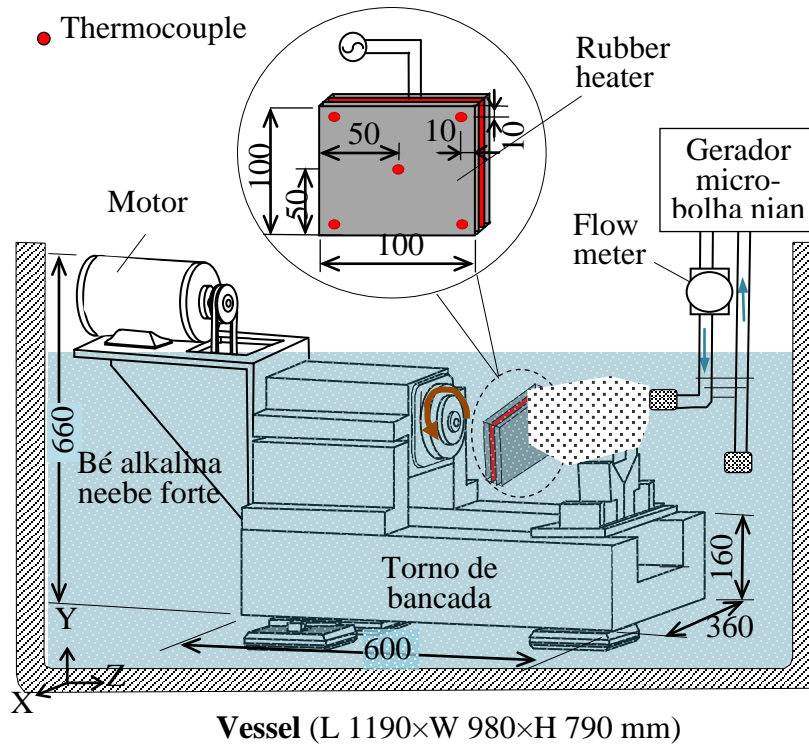


Fig.5.4 Configurasun experimentu nian atu sukat coeficiente transferêcia calor nian

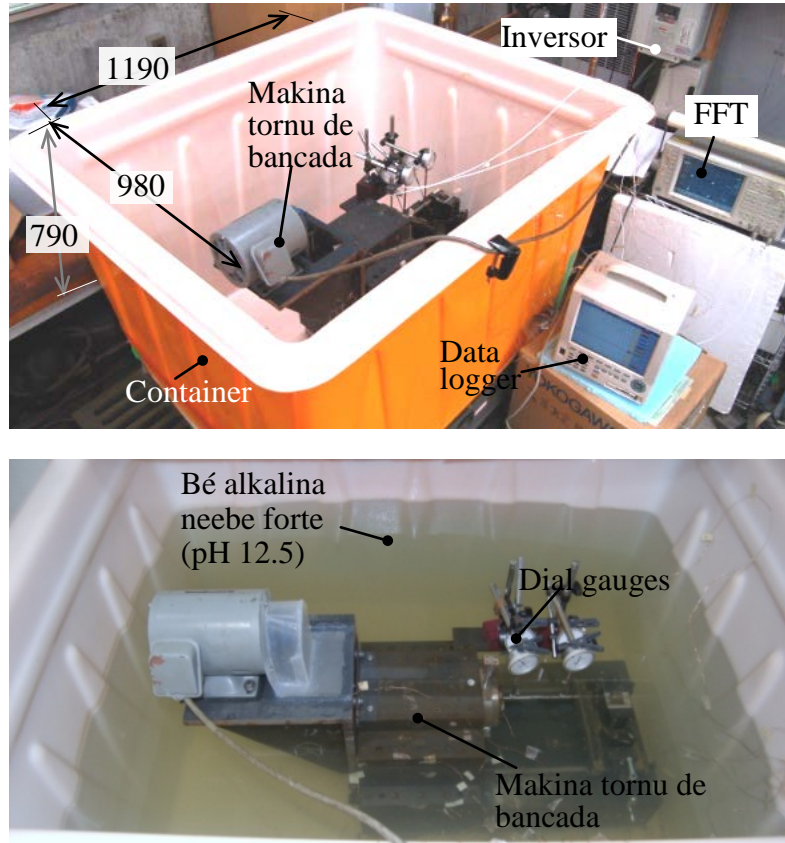


Fig.5.5 Fotografia ba configurasaun experimento nian

Fig.5.6 hatudu média temperatura nian sukat husi experimentu iha Fig. 5.4 uza metodu resfriamentu neebe oi-oin kada 5 minutos durante 50 minutos. Rezultadu nee hatudu katak wainhira uza resfriamentu bé alkalina kahur micro-bolha no halao operasaun ba mákina iha rotasaun 3600 rpm bele mantein temperatura iha 22°C.

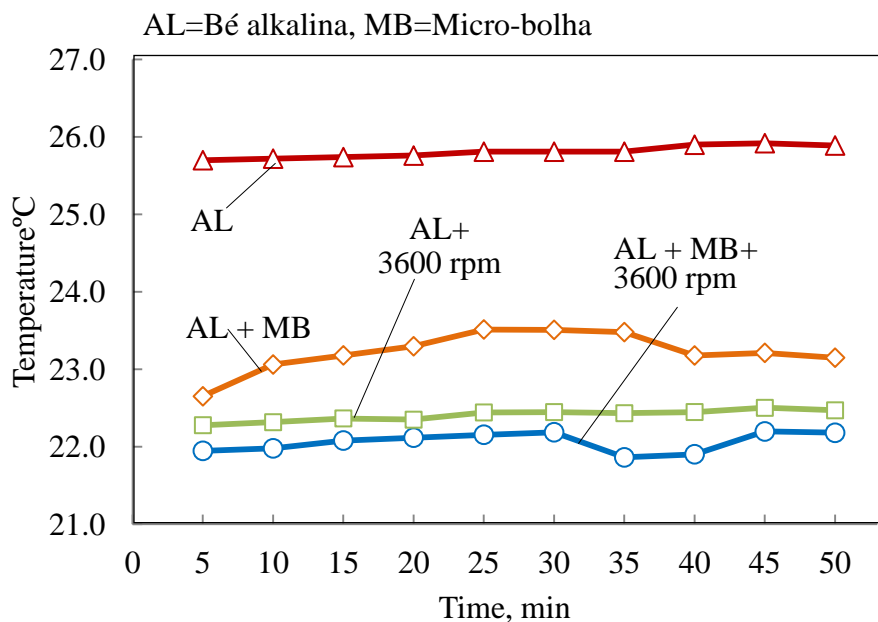


Fig. 5.6 Média temperatura husi resfriamentu neebe oi-oin

Koefisiente husi transferênciá calor nian kalkula husi médio entre temperatura husi *chapa de aço* ho bé alkalina neebe forte uza equasaun equation 5.1.

$$h = \frac{Q}{A(T_a - T_w)} \quad (5.1)$$

Neebe: h = Convective heat transfer coefficient of the process (W/(m²K))

Q = heat transferred per unit time (W)

A= Heat transfer area of the surface (m²)

T_w= Temperatura of strong alkalina water (°K)

T_a= Temperatura of the metal surface (°K)

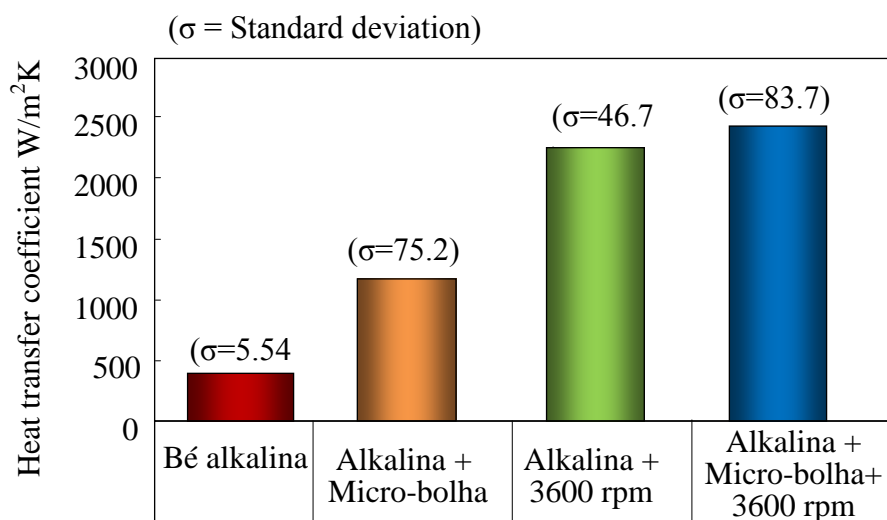


Fig. 5.7 Relasaun entre bé alkalina, micro-bolha, no rotasaun 3600 min⁻¹ ho corficiente husi transferencia calor nian.

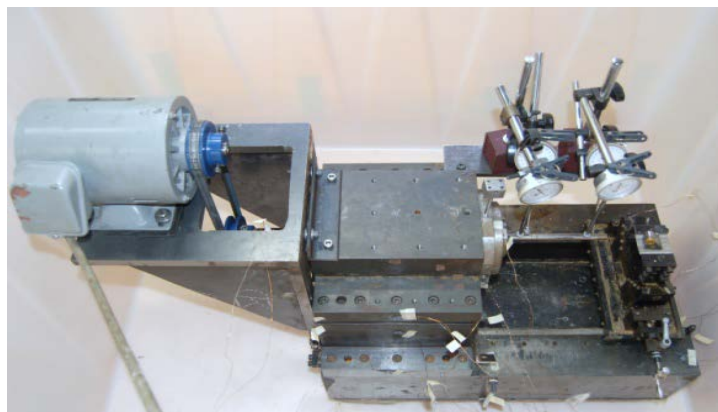
Rezultadu husi kalkulasaun koefisiente husi transferensia calor nian hatudu iha Fig.5.7 iha leten. Rezultadu nee apresenta katak kompara ba resfriamentu uza natural conveksaun bé alkalina nian, koefisiente husi transferencia calor nian aumenta dala 5.5 wainhira uza halao operaun mákina iha bé laran no aumenta dala 6 times wainhira aumenta ho micro-bolha. Nunee, bele klarifika katak fornese micro-bolha iha bé alkalina laran bele hasae efeitu resfriamentu nian.

5.4. Investigasaun ba vibrasaun no deformasaun térmika mákina torno nian no qualidade prosesaun uza metodu immersaun nian

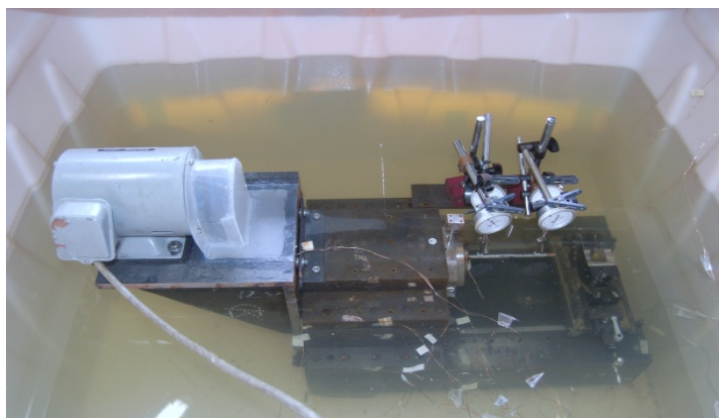
Esplika tiha ona iha Kapítulu 3 katak bé bele hatun mákina nia frekuensia resonansia maibe hasae vibrasaun nia amplitudu. Nunee, iha sesaun ida nee, investigasaun ba vibrasaun mákina tornu iha bé laran halao no sukat. Deformasaun térmika kauza husi friksaun entre rolamentu bele afeita rugosidade peça nian, nunee influencia husi kondisaun submerge nian ba deformasaun térmika mákina tornu nian mos investiga hotu. No mos, qualidade prosesaun uza metodu immersaun nian investiga atu bele hatene efikásia metodu nee nian.

Tabela 5.4 Especificasaun makina tornu de bancada uza iha experimentu nee

Head stock	Height of center from bed	177 mm
	Height of center from floor	337 mm
	Spindle speed	Max. 3600 min ⁻¹
Bed	Size (W×L×H)	600×360×660
Tool post	Stroke of Y axis	30 mm
Tabela	Stroke of Z axis	200 mm
Motor	Power	0.75 kW
	Speed control	Inverter
Mass		200 kg



(a) La hó bé alkalina



(b) Hó bé alkalina

Fig. 5.8 Fotografia husi kondisaun imersaun nian

Espesifikasaun mákina tornu bankada neebe uza iha experimentu ida nee mak apresenta iha Tabela 5.4. Estutura mákina nee nian modifika tiha hodi halo a'as motor nia tur fatin hodi nunee prevene motor husi bé. Konsidera ba possibilidade xoke husi elétriku no perigu husi ahi lakan neebe bele mosu, presiza tau atensaun wainhira halao instalasaun fiu mákina nian. Ho konfigurasan ba experimentu neebe mak hatudu iha Fig. 5.8, mákina nia vibrasaun, deformasaun térmika no kualidade prosesaun ho kondisaun imersaun nian investiga no kondúz. No mos, kondisaun experimentu la uza bé alkalina (Fig.5.8a) ho uza bé alkalina (Fig.5.8b) uza ba komparaun.

5.4.1 Investigasaun ba vibrasaun

Iha sesaun ida nee, influencia husi kondisaun imersaun iha bé alkalina neebe forte ba mákina tornu investiga. Konfigurasan experimentu nian neebe hatudu iha Fig.5.9 mak uza ba experimentu ida nee. Iha experimentu nee, mákina tornu hatama tomak iha bé alkalina laran. Mákina nia vibrasaun sukat iha fatin rua hodi acelerômetru iha mákina nia ulun husi diresaun X no Y. Medisaun halao hodi sukat

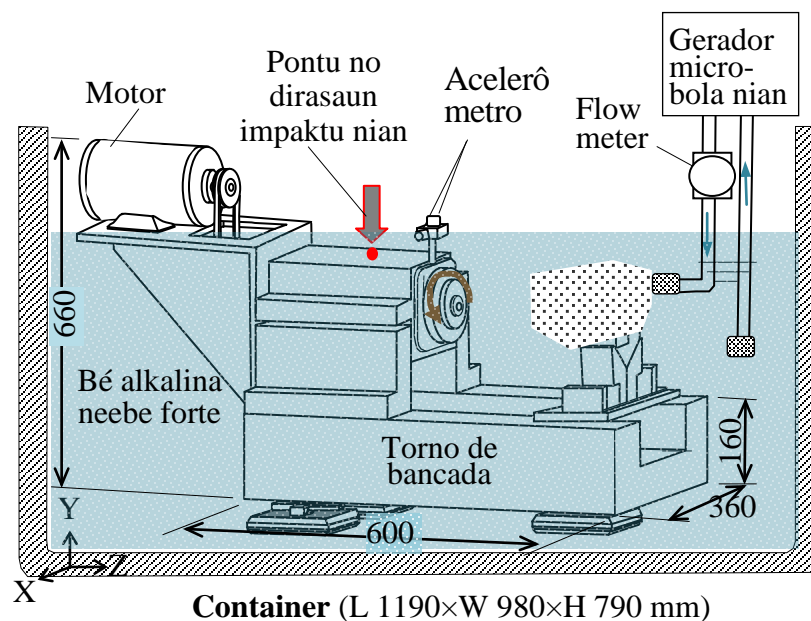
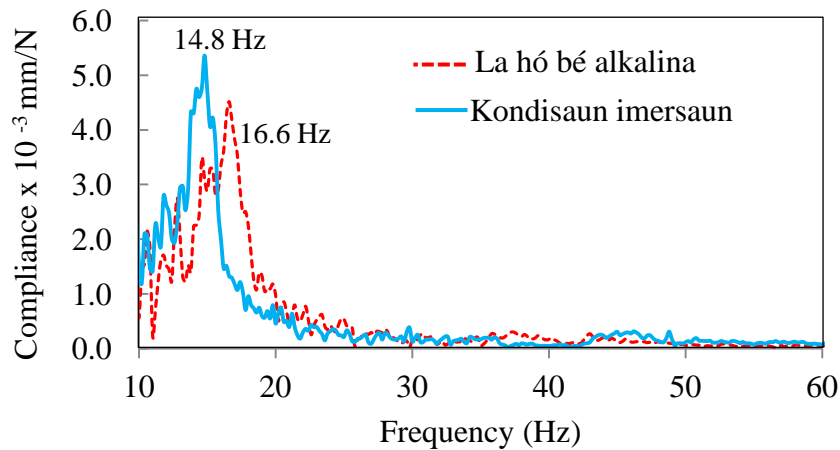
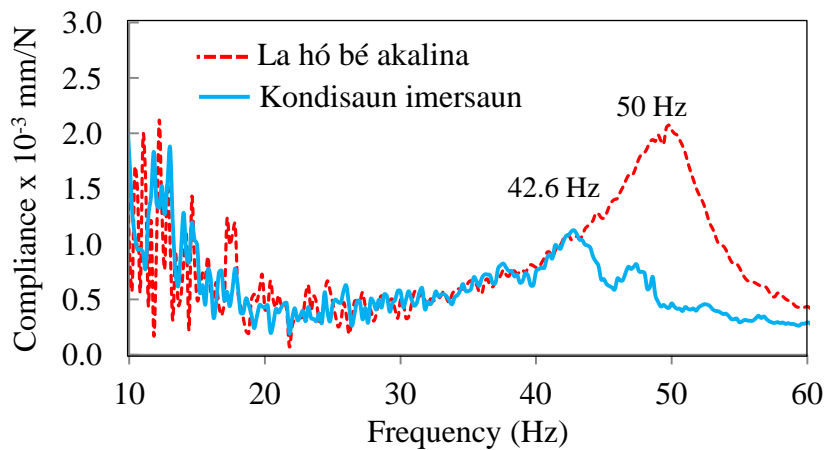


Fig.5.9 Configurasan experimentu nian ba sukat vibrasaun iha makina tornu



(a). Torno bancada nia resonansia iha X-áxis



(b). Torno bancada nia resonansia iha Y-áxis

Fig. 5.10 Makina torno bancada nia frekuensia resonansia uza impact test

frekuensia resonansia mákina nian la hó bé alkalina no hó bé alkalina iha kondisaun imersaun. Depois rotasaun ba mákina nee sei halao koresponde ho mákina ninia resonansia atu nunee bele evalua efikásia husi imersaun nian. Mákina tornu bancada nia resonansia mak hatudu iha Fig. 5.10. Wainhira fó forsa ho impaktu ba iha mákina niaulun husi diresaun vertical, rezultadu hatudu katak la hó imersaun, vibrasaun neebe boot mosu iha frekuensia 16.6 Hz no 50 Hz tuituir malu iha diresaun X no Y. Wainhira enxe bé ba iha kontainer laran, frekuensia resonansia tun ba 14.8 Hz iha diresaun X nian no 42.6 iha diresaun Y nian. Wainhira frekuensia resonansia muda a'an, operasaun mákina nia sai diak.

Tuir mai, mákina tornu nee opera iha rotasaun 996 rpm no 3000 rpm, espindulu neebe mak corresponde ho mákina tornu nia resonansia iha 16.6 Hz and 50 Hz, no analiza sira nia amplitude. Amplitudu vibraisaun nia ba rotasaun 996 rpm hatudu iha Fig. 5.11 no ba rotasaun 3000 rpm hatudu iha Fig. 5.12. Rezultadu medisaun nian hatudu katak vibraisaun nia amplitude redús quaze 57% iha rotasaun 996 rpm espindulu nian no kuaze 68% iha rotasaun ba espindulu 3000 rpm wainhira uza mákina iha bé alkalina laran. Tamba nee mak bele konsidera katak operasaun mákina ho kondisaun imersaun bele hatun mákina nia vibraisaun, ida neebe efetivu tebes atu bele hetan rezultadu ikus koa nian neebe ótimo.

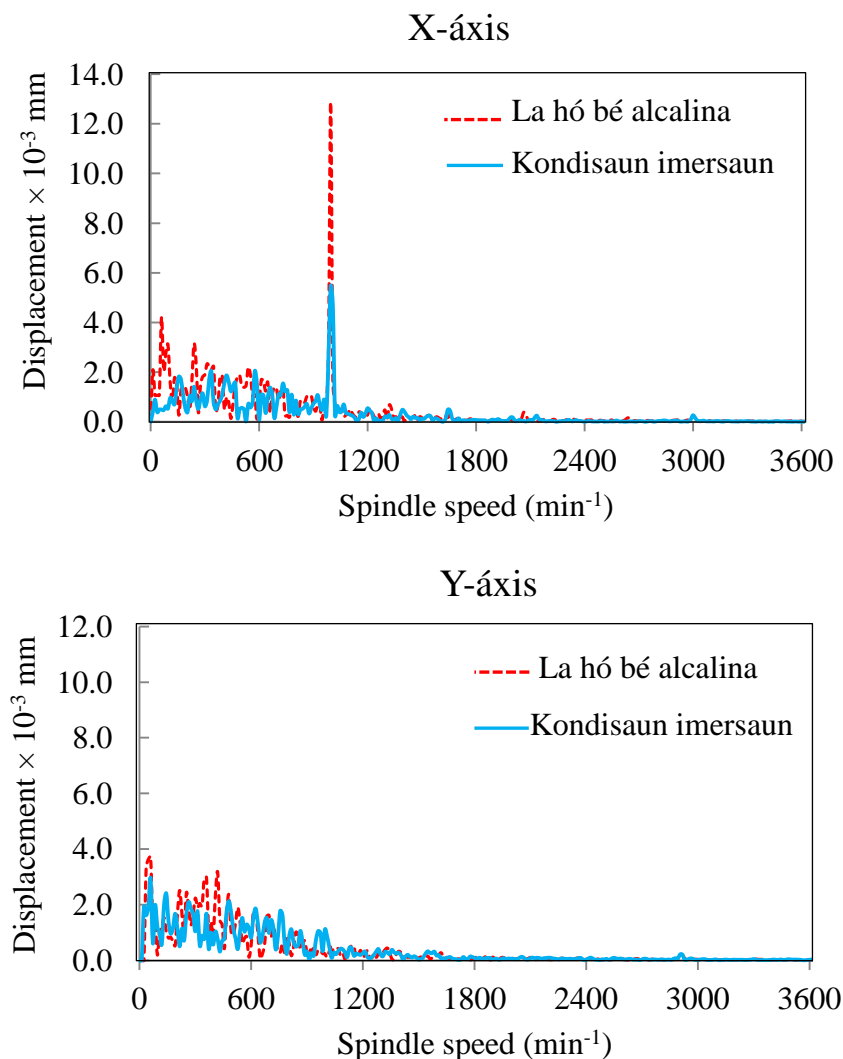


Fig. 5.11. Amplitudo makina torno bancada nian opera coincide resonansia iha 996 rpm

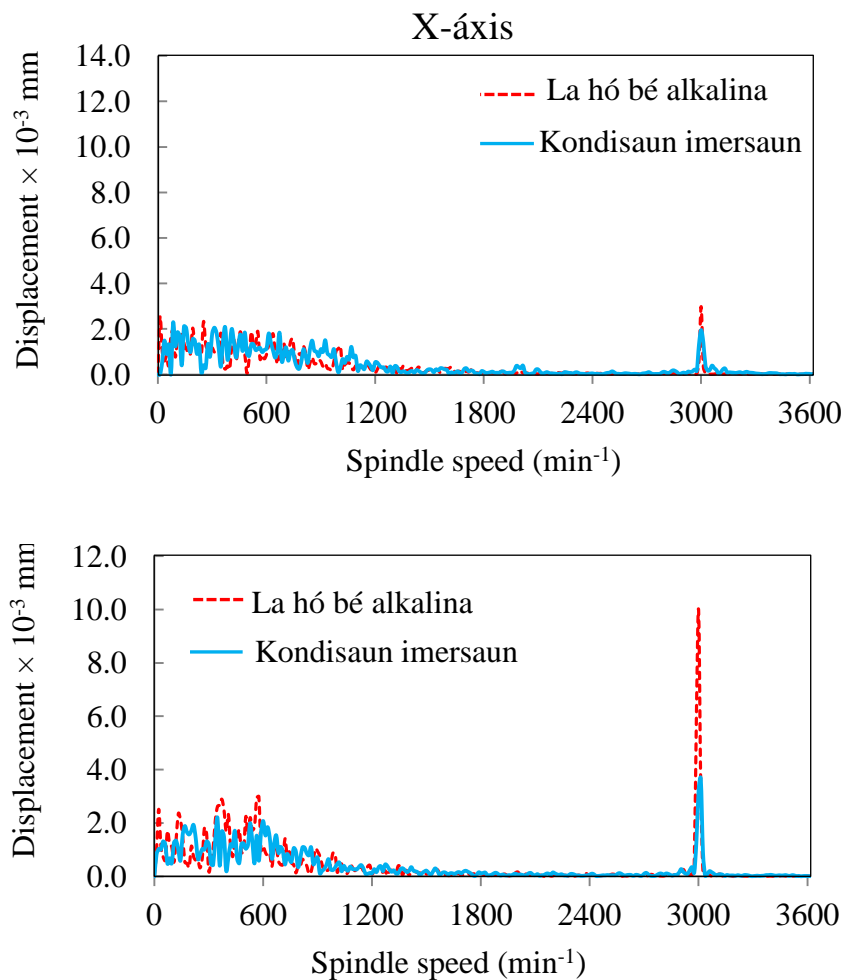


Fig. 5.12. Amplitudo makina torno bancada nian opera coincide resonancia iha 3000 rpm

5.4.2 Investigasaun ba mudansa iha temperatura no deformasaun térmika

Deformasaun térmika rezulta husi calor neebe mai husi friksaun rolamentu nian bele afeita peça nia rugosidade iha rezultadu ikus koa nian. Iha experimentu ida nee, influence husi kondisaun imersaun nian ba temperatura no deformasaun térmika husi mákina tornu bancada sukat hodi hatama mákina ba bé laran. Espesifikasaun husi mákina tornu bancada apresenta iha Tabela 5.4 liu ba mak uza ba experimentu. Konfigurasaun experimentu nian ba investigasaun temperatura no deformasaun térmika mak hatudu iha Fig. 5.13. Iha experimentu ida nee, mákina tornu bancada exclui ninia motor hatama tomak ba bé alkalina

laran no kontinua fornese ho micro-bolha, depois mak halao medisaun ba karakterístika husi deformasaun térmika. Atu investiga temperatura mákina tornu nian, mákina nee sei opera iha espidulu ho rotasaun 960 rpm, 3000 rpm no 3600 rpm ba oras rua nia laran. Mákina nia temperatura grava liu husi termopar ho tipo-T (hatudu iha marka ho circulu mean ● iha Fig. 5.13) neebe kola ba mákina nia isin lolon. Kada 20 minutes, mákina sei hapara no mákina nia espidulu dulas manualmente ho liman atu sukat deformasaun térmika husi *test bar* (iha diresaun X no Y) uza *dial gauges*.

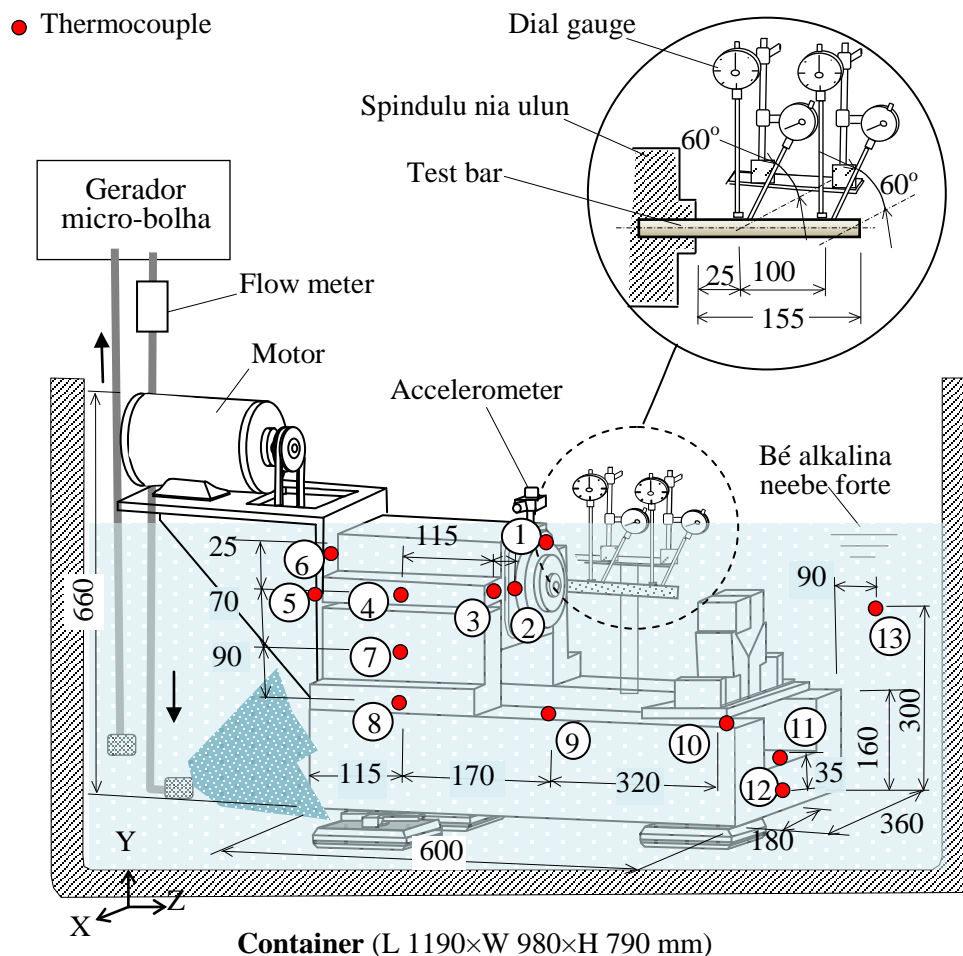
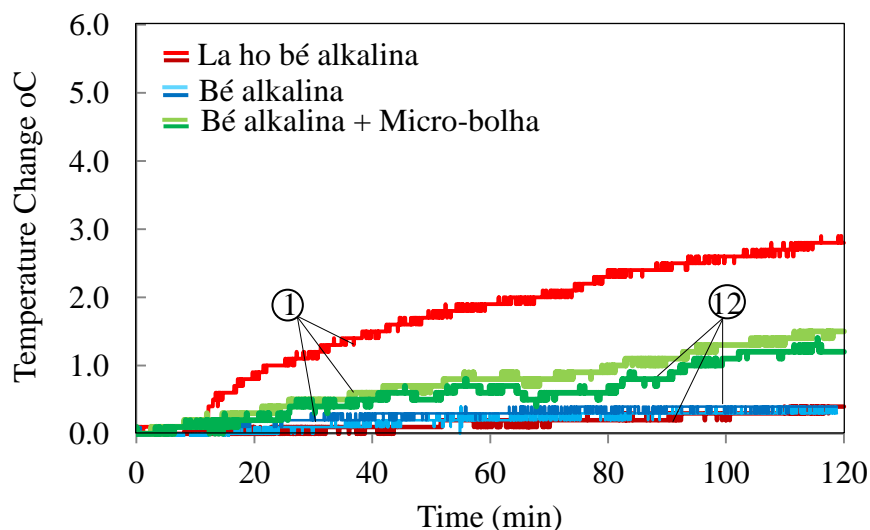
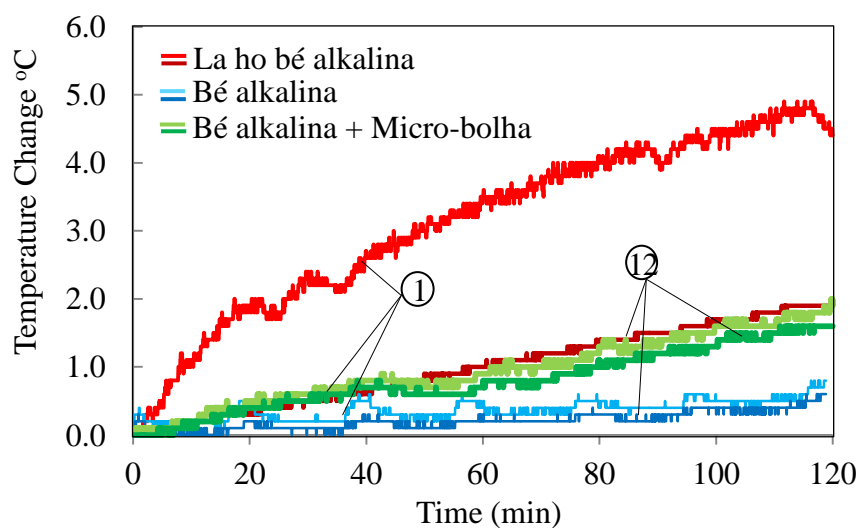


Fig. 5.13 Vizaun esquemática no configuraun experiementu nian atu sukat makina tornu nia temperatura

Fig.5.14(a) apresenta rezultadu temperatura mákina tornu nian sukat besik mákina nia uluk iha pontu ① no iha pontu ⑫. Wainhira opera mákina iha espidulu 996 rpm, temperatura diferensia iha mákina nia ulun iha pontu ① (Ida neebe iha influensa boot ba akurasaun koa nian) mak 2.9°C ba kondisaun la uza imersaun, 0.4°C kuandu immerse iha bé alkalina laran, no wainhira aumenta ho micro-bolha, ninia temperatura diferensia mak 1.5°C . Nunee mos, wainhira opera iha espidulu 3000 rpm, temperatura aumenta 4.8°C wainhira la uza imersaun, aumenta 0.8°C

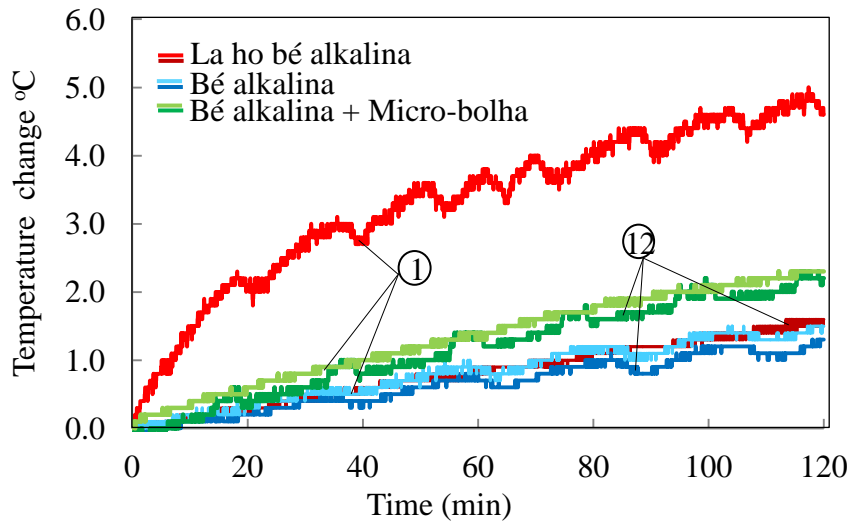


(a). Mudansa temperatura makina torno nian opera iha 996 min^{-1}



(b). Mudansa temperatura makina torno nian opera iha 3000 min^{-1}

Fig.5.14. Mudansa temperatura makina tornu nian opera iha spindulu oi-oin

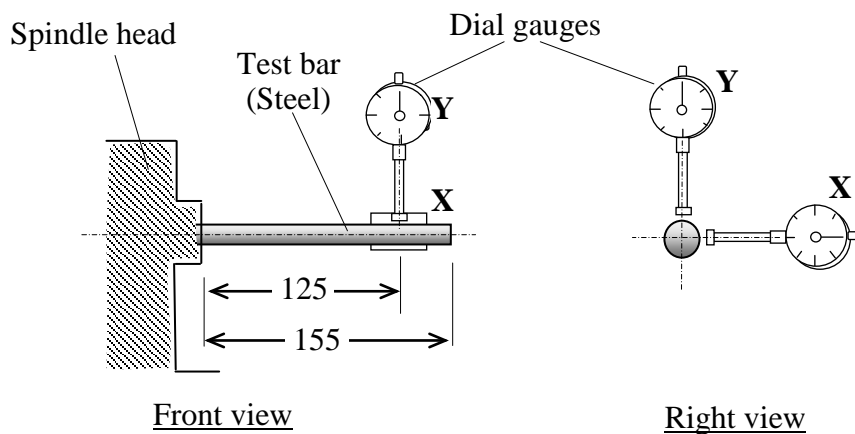


(c). Mudansa temperatura makina torno nian opera iha 3600 min⁻¹

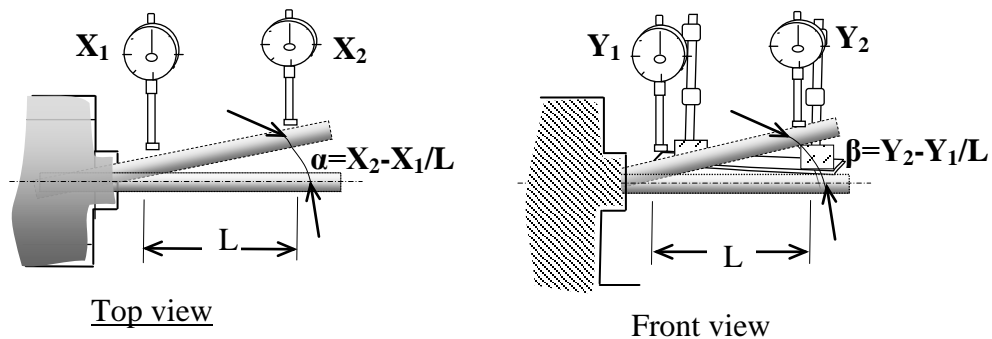
Fig.5.14. Mudansa temperatura makina torno nian opera iha spindulu oi-oim

Wainhira immerse iha bé alkalina laran, no aumenta 1.8°C wainhira fornese ho micro-bolha. Nunee mos, wainhira opera iha espindulu 3600 rpm, temperatura aumenta 5.0°C wainhira la uza imersaun, aumenta 1.4°C wainhira uza bé alkalina no aumenta 2.2°C wainhira kahur ho micro-bolha. Ho efeito resfriamentu forsadu ida nee, bele konsidera katak deformasaun térmika mákina nian bele suprimi. Husi rezultadu nee ita bele observa katak wainhira uza micro-bolha, temperatura aumenta boot liu fali kompara ba uza bé alkalina mesak. Kondisaun ida nee akontese tamba calor neebe prodús husi gerador micro-bolha nian halo bé sai manas lais durante contínuo operasaun ba periodu neebe naruk. Wainhira temperatura sae durante operasaun mákina nian, nee tamba rezultadu husi friksaun iha rolamentu. Maibe, temperatura neebe sae wainhira aumenta micro-bolha, nee tamba gerasaun manas husi gerador micro-bolha nian neebe opera durante oras rua nia laran. Tamba gerador nee manas, nia halo bé alkalina sai manas lalais nunee halo mákina nia temperatura mos aumenta. Maske temperatura aumenta, iha kazu rua nee, distribusaun temperatura iha mákina nia estrutura konsidera kiik liu, nunee operasaun gerador micro-bolha nian ba tempu neebe badak bele hasae efeito resfriamentu wainhira aumenta ho micro-bolha.

Fig. 5.15 apresenta vizaun eskemátika husi konfigurasan *dial gauge* ba medisaun deformasaun térmika. Iha experimentu ida nee, evaluasaun halao hodi sukat dezlokamentu relativu (*relative displacement*) ho dezlokamentu angular (*angular displacement*). Dezlokamentu relativu sukat hodi monta *dial gauge* 25 mm husi *test bar* ninia tutun iha diresaun horizontal no vertical atu sukat dezlokamentu iha áxis X no áxis Y. Dezlokamentu angular sukat liu husi kalkulasaun ba diferensia entre *dial gauge* rua. Nia kalkula hodi ekuasaun $\alpha = X_2 - X_1/L$, $\beta = Y_2 - Y_1/L$. Tamba posisaun inisio husi test bar la konsentrik ho



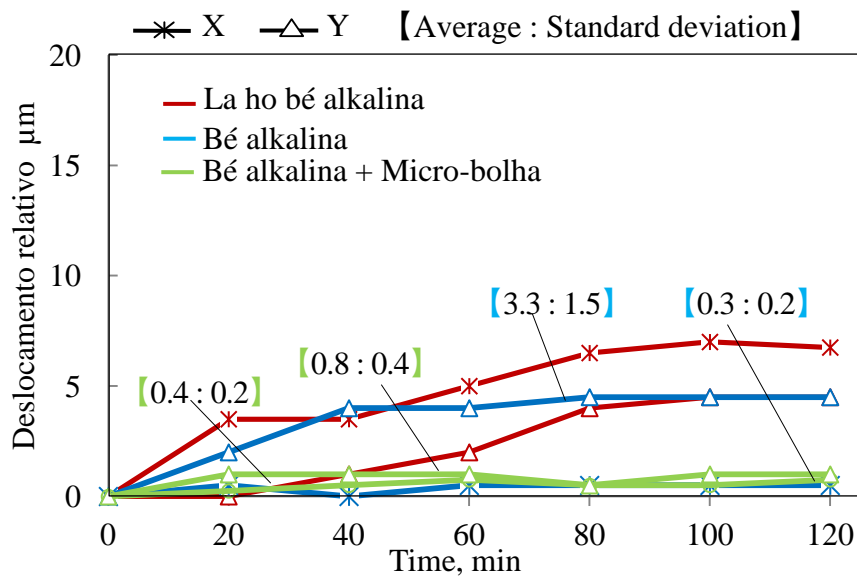
(a). Dezlokamentu relativu



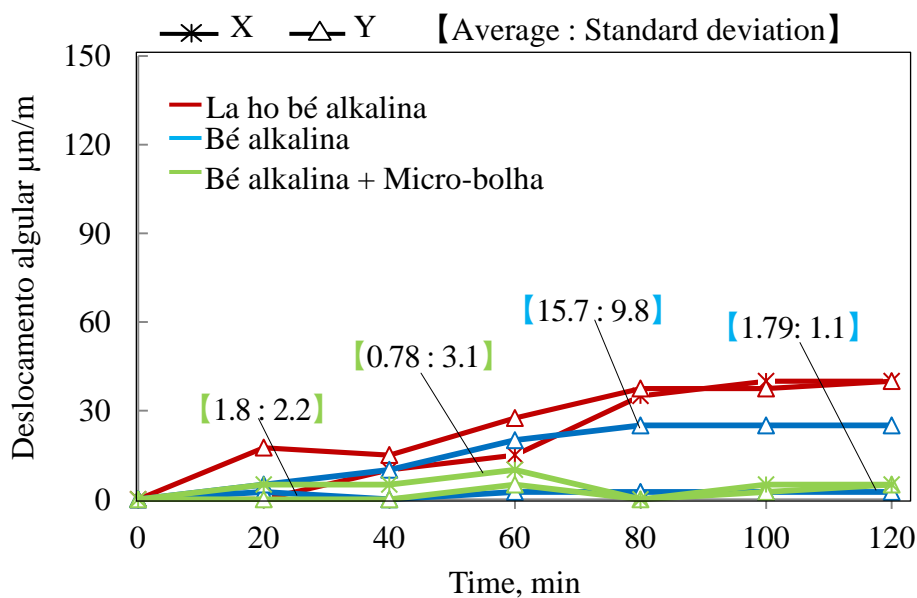
(b). Dezlokamentu angular

Fig. 5.15 Vizaun eskuemátika husi konfigurasan *dial gauge* ba medisaun deformasaun térmika

espidulu mákina tornu nian, data primeiro husi dezlokamentu test bar nian uza hanesan referensia ba data neebe tuir mai. Fig.5.16 no Fig. 5.17 tui-tuir malu apresenta dezlokamentu relativu no dezlokamentu angular husi test bar wainhira mákina opera iha rotasaun 996 rpmno 3000 min⁻¹.

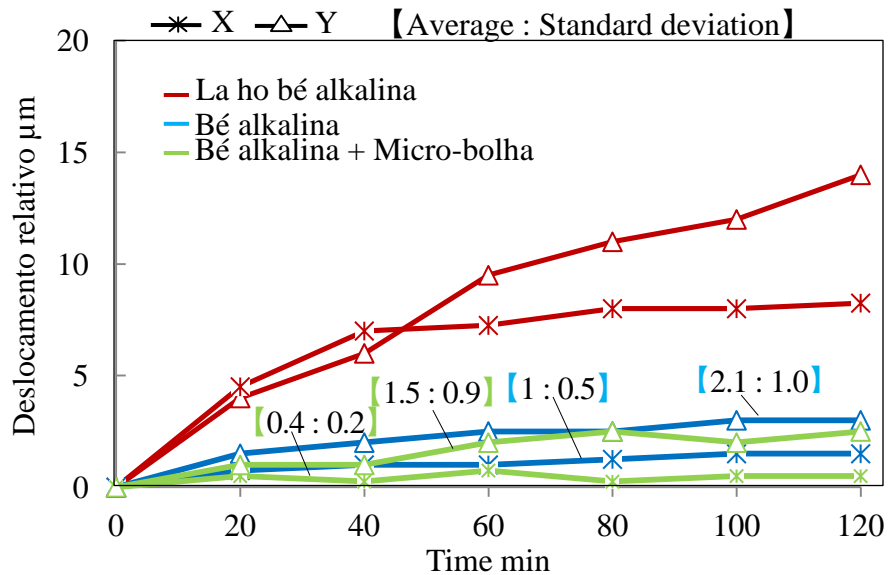


(a) Dezlokamentu relativu

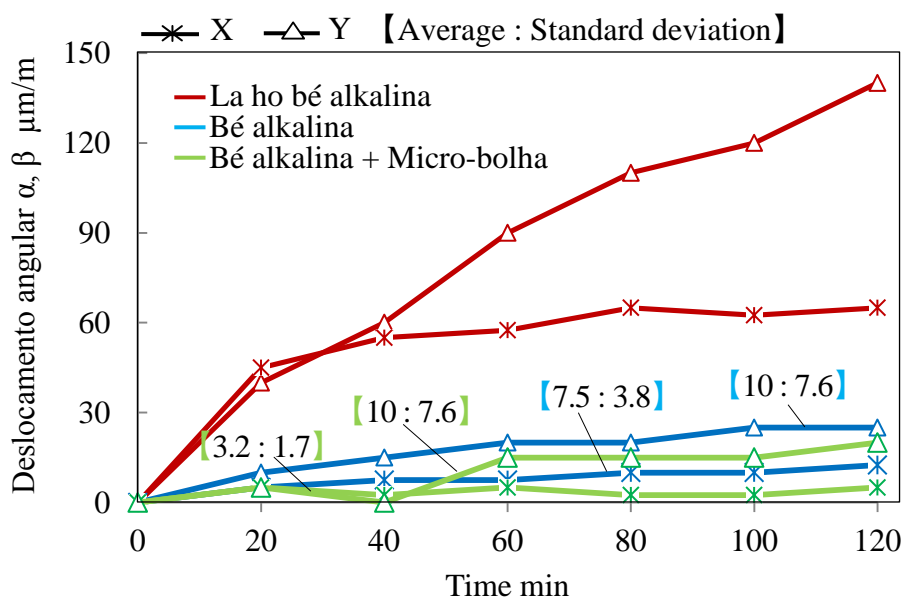


(b) Dezlokamentu angular

Fig. 5.16 Deformasaun térmica husi test bar wainhira opera makina tornu bancada ho rotasaun 996 rpm



(a) Dezlokamentu relativu



(b) Dezlokamentu angular

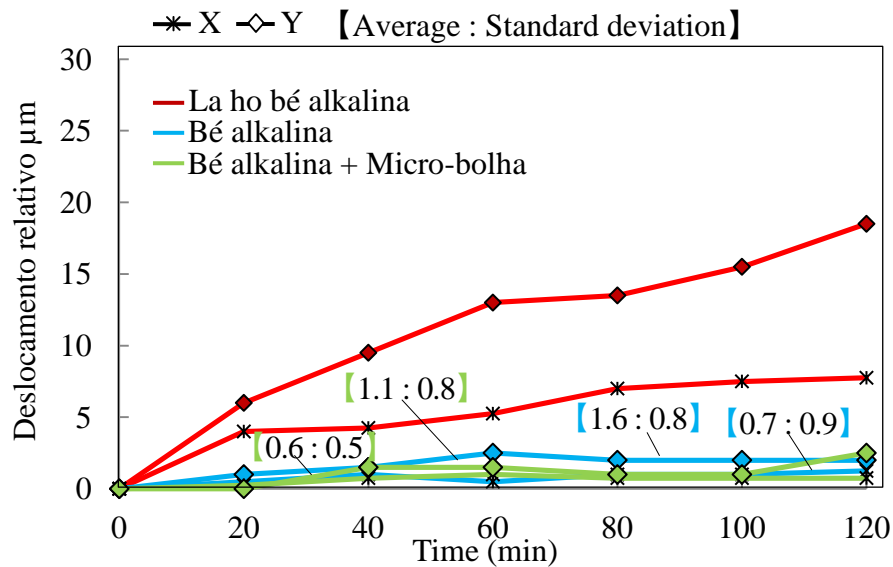
Fig. 5.17 Deformasaun térmica husi test bar wainhira opera makina tornu bancada ho rotasaun 3000 rpm

Data entre 20~120 min fahe ba interval 6 no sira nia médio (*average*) ho *standard deviation* kalkula no analiza. Rezultadu hatudu katak, ba kondisaun la uza bé, dezlokamentu relativu boot los iha $\Delta X=4.5\mu\text{m}$ no $\Delta Y=4.8 \mu\text{m}$, enkuanto dezlokamentu angular $\alpha=40 \mu\text{m/m}$ no $\beta=42 \mu\text{m/m}$, wainhira opera mákina iha

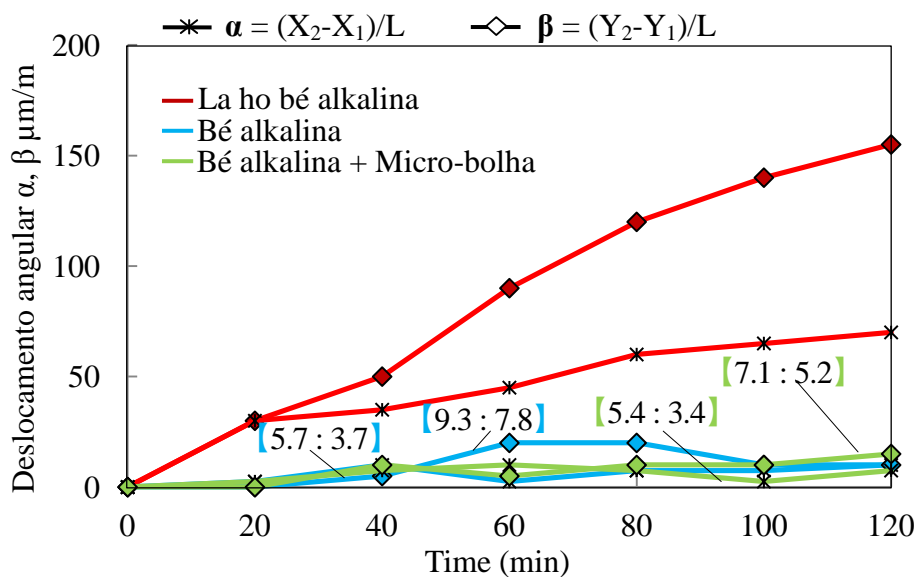
996 rpm. Ba operasaun iha rotasaun 3000 rpm, dezlokamentu relativu iha $\Delta X=8.3 \mu\text{m}$ no $\Delta Y=14.0 \mu\text{m}$, enkuanto dezlokamentu angular $\alpha=65 \mu\text{m/m}$ no $\beta=140\mu\text{m/m}$. Wainhira halao operasaun iha bé alkalina neebe forte nia laran, deforsaun térmika iha rotasaun rua nee redús significamente. No mos, deformasaun térmika sai kiik wainhira micro-bolha aumenta ba bé laran. Ba kondisaun aumenta micro-bolha ba bé laran, dezlokamentu relativu menus husi $0.5\mu\text{m}$ iha X-áxis no $2.5\mu\text{m}$ iha Y-áxis, enkuanto dezlokamentu angular menus husi $20\mu\text{m}$ in X-áxis no $5\mu\text{m}$ in Y-áxis ba rotasaun rua, respetivamente. Tan nee, deformasaun térmika redús notavelmente. Husi rezultadu nee ita bele obseva katak supresaun iha dezlokamentu relativu no dezlokamentu angular wainhira immerse mákina iha bé alkalina laran kahur micro-bolha efetivu tebes.

Ba rotasaun 3600 rpm, ita bele espera katak ninia deformasaun térmika sei boot liu fali wainhira uza rotasaun 996 rpm no 3000 rpm. Nee tamba espidulu ho rotasaun neebe aas kria friksaun entre rolamentu dala barak liu kompara ba rotasaun neebe kiik, nune kondúz ba inkrementu manas neebe rápidu. Rezultadu medisaun ba deformasaun térmika uza rotasaun 3600 rpm hatudu iha Fig.5.18. Ita bele hare husi rezultadu nee katak dezlokamentu relativo iha $\Delta X=7.8 \mu\text{m}$, $\Delta Y=18.5 \mu\text{m}$, enkuanto dezlokamentu angular $\alpha=70 \mu\text{m/m}$ no $\beta=155 \mu\text{m/m}$ wainhira la uza bé alkalina. Wainhira uza bé alkalina kahur micro-bolha (iha kondisaun imersaun nian), dezlokamentu relativu menus husi $2.5 \mu\text{m}$, enkuanto dezlokamentu angular $20\mu\text{m/m}$ deit, nune mak deformasaun térmika konsidera suprimi ho makaas. Hanesan mos halao ba rotasaun rua neebe esplika tiha ona, iha nee data entre 20~120 minutus mos fahe ba interval 6 no sira nia médio (*average*) ho *standar deviation* kalkula no analiza. Rezultadu hatudu momos katak, supressaun iha dezlokamentu relativo no dezlokamentu angular husi kondisaun la uza bé alkalina ba uza bé alkalina kahur micro-bolha boot tebes (Husi $\Delta X: 0.75\mu\text{m} \Rightarrow 0.61 \mu\text{m}$, $\Delta Y: 1.57\mu\text{m} \Rightarrow 1.07 \mu\text{m}$, $\alpha: 5.71 \mu\text{m/m} \Rightarrow 5.36 \mu\text{m/m}$,

β : $9.29 \mu\text{m}/\text{m} \Rightarrow 7.14 \mu\text{m}/\text{m}$). Tan nee mak bele konklui katak immerse mákina produsaun iha bé alkalina laran bele redús mákina nia vibraasaun no mos suprimi deformaasaun térmika ho efetivu, neebe mak rezulta iha prosesaun ho akurasaun neebe boot.



(a). Dezlokamentu relativu



(b). Dezlokamentu angular

Fig. 5.18 Deformaasaun térmika husi test bar wainhira opera mákina tornu bancada ho rotasaun 3600 rpm

5.4.3 Qualidade makinazen uza metodu imersaun nian

Iha sesaun ida nee, presesu makinazen atu evalua metodu imersaun nia kondúz no performa. Iha experimentu ida nee, *alem de* uza mákina tornu bancada ba halao evaluasaun, mákina NC frais sei uza ba evaluasaun ida nee. Razaun la uza mákina tornu bankada mak tamba mákina nee ninia prosesu laós automatiku, tan nee difisil atu evalua rezultadu prosesaun nian wainhira perfoma makinazen manualmente. No mos, tamba *feed speed* mákina torno bancada diriji manualmente husi diresaun Z, nunee ami konsidera katak rezultadu medisaun nian husi *rugosidade supperfície* bele inklui erro humanu. Tamba nee mak uza fali mákina NC frais neebe hatudu iha Fig.5.19. Experimentu halao hodi sukat temperatura husi chip koa nian, vida chip nian, no rugosidade peça nia ba evaluasaun efisiensia husi metodu imersaun nian.

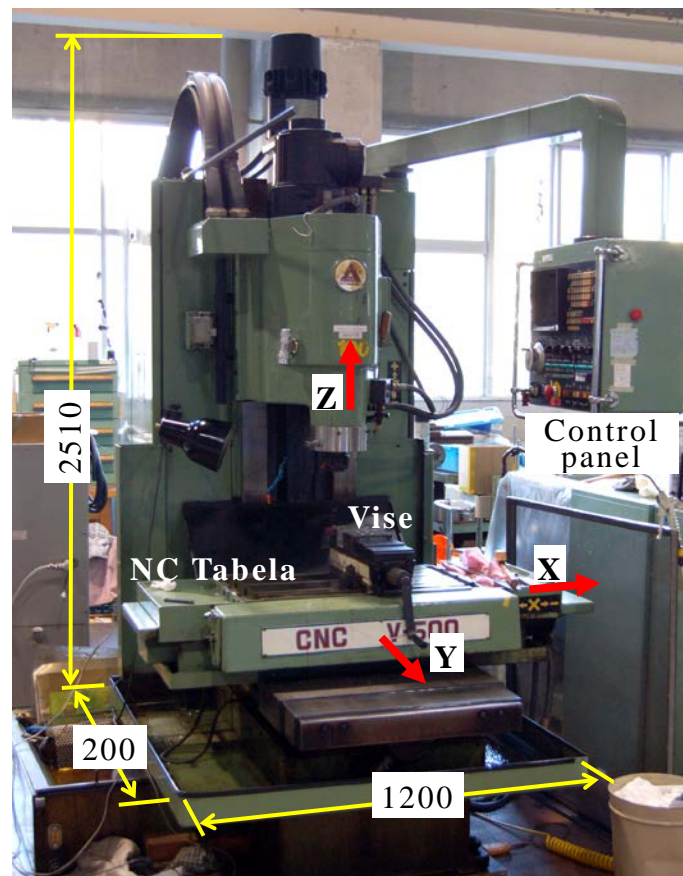


Fig.5.19 Fotografia husi makina NC frais (Unit: mm)

5.4.3.1 Evaluasaun ba temperatura iha feramenta nia tutun

Hamenus temperatura iha feramenta nia tutun bele prolunga vida feramenta nian no hadiak rugosidade peça nian. Sukat temperatura iha feramenta nia tutun durante makinazen difisil tebes tamba feramenta iha kondisaun dulas nia laran, tan nee mak konfigurasaun neebe reversu ba metodu koa nian halao atu bele sukat temperatura iha feramenta nia tutun. Konfigurasaun reversu nee halao hodi monta peça ba mákina frais nia espidulu no feramenta mota fali iha *vise*. Tamba difisil atu sukat temperatura exatamente iha pontu koa nian, temperatura sukat deit iha 3 mm husi pontu koa nian iha fatin rua hanesan ilustra iha Fig.5.20. Kondisaun ba prosesu koa nian neebe uza iha experimetu ida nee mak hatudu iha Tabela 5.5 Bainhira dados temperatura nian husi pontu rua nee sukat no halibur hotu ona, temperatura feramenta nian iha pontu koa nian kalkula no análise uza CAE. Rezultadu husi experimentu nian sei kompara ho CAE nian atu bele hatene temperatura husi feramenta nia tutun.

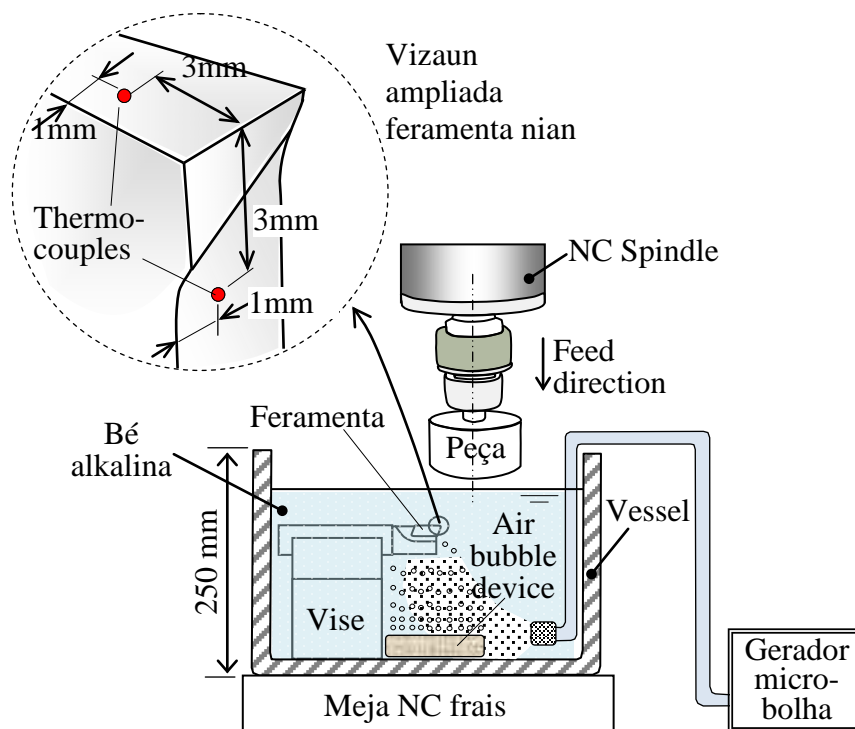


Fig. 5.20 Kofigurasaun experimentu nian atu sukat temperatura feramenta nian

Tabela 5.5 Kondisaun koa nian atu sukat feramenta nia temperatura

Kondisaun kóá nian		
Cutting speed 80 m/min	Feed speed 0.25 mm/rev	Depth of cut 0.4 mm
Peça		
Material : Ti6Al4V	Cutting force : 3178 N/mm ²	
Feramenta		
Rake angle: 5°	Coated carbide	

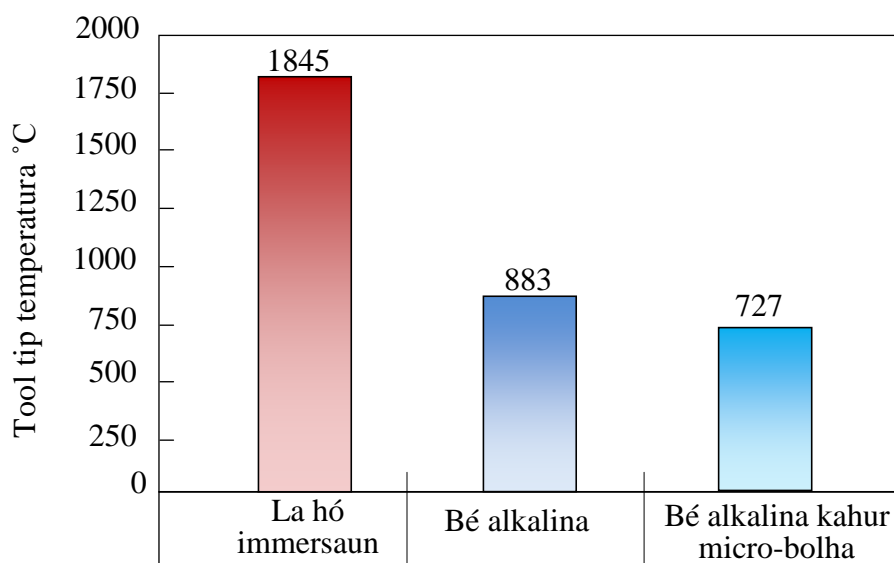


Fig. 5.21 Rezultadu husi feramenta nia temperatura iha pontu koa nian

Rezultadu husi kalkulasaun no komparasaun husi feramenta nia temperatura iha pontu koa nian hatudu iha Fig. 5.21. Kompara ba temperatura feramenta nian wainhira la uza bé alkalina, temperatura tun too hela deit 48% wainhira uza bé alkalina no tun tan too hela deit 39% wainhira uza bé alkalina kahur micro-bolha. Tamba nee mak bele confirma katak makinazen iha bé alkalina nia laran efetivo tebes ba hatun temperatura koa nian.

5.4.3.2 Evaluasaun ba vida feramenta nian

Iha evaluasaun ba vida feramenta nian, prosesu koa performa to'o feramenta alcanca limitasaun iha ninia vida. Vida feramenta nian defini atu to'o rohan ona kuando nia tohik to'o 0.3 mm. Iha experimentu ida nee, konfigurasaun neebe normal iha mákina frais uza ba experimentu ida nee mak hatudu iha Fig. 5.22 ho kondisaun koa nian hatudu iha Tabela 6.5. Durante makinazen, feramenta (*tool chips*) frekuentamente hasai husi ninia fatin atu koko ninia tohik uza mikroskópio.

Tabela 5.6 Kondisaun kóá nian atu evalua vida feramenta nian

Kondisaun kóá nian	
Cutting speed	100 m/min
Feed speed	100 mm/min
Width of cut (axial)	2 mm
Depth of cut (radial)	3 mm
Peça	
Material	Ti6Al4V
Specific cutting force	3420 N/mm ²
Feramenta	
Material	Coated carbide
Rake angle	5°
Dimension	Diameter Ø25 × Length120

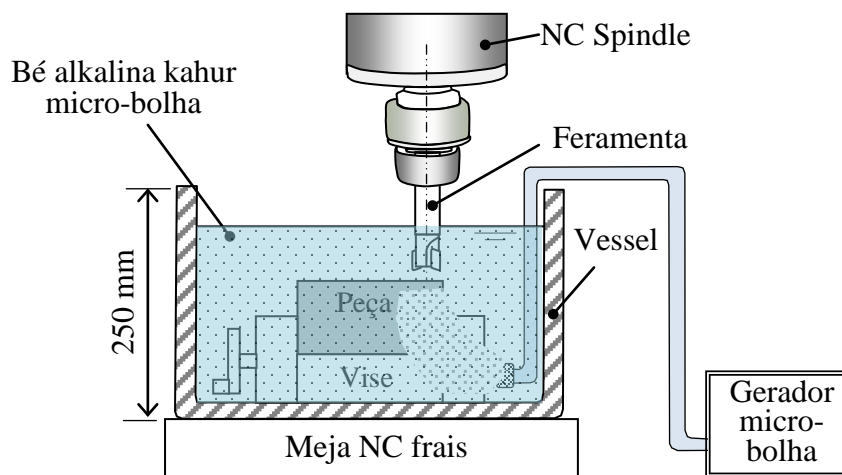


Fig. 5.22 Konfigurasaun experimentu nian atu evalua vida feramenta nian

Fig.5.23 apresenta rezultadu testu nian ba feramenta nia vida. Rezultadu nee hatudu katak, vida feramenta nian wainhira uza bé alkalina kahur micro-bolha prolunga dala 3 kompara ba wainhira lau bé alkalina no boot liu dala 2 kompara ba wainhira uza bé alkalina mesak. Tan nee mak, bele konsidera katak metodu resfriamentu hodi halao makinazen iha bé alkalina laran kahur micro-bolha kompatente ba halakon ou hatun manas neebe prodús wainhira koa materias neebe difisil atu koa. No mos, kondisaun koa nian neebe apresenta iha Tabela 5.6 nee bai-bain uza ba prosesaun ikus nian ba peça aço S45C. Normalmente, wainhira koa uza kondisaun ida nee ba iha material Ti6Al4V, feramenta sei manas lalais tamba kondisaun koa nian neebe la adekua. Maibe uza metodu neebe ami propoin, bele hamenus temperatura no prolunga vida feramenta nian. Nunee mak metodu propostado nee konsidera efetivu ba produktividade no kualidade neebe aas.

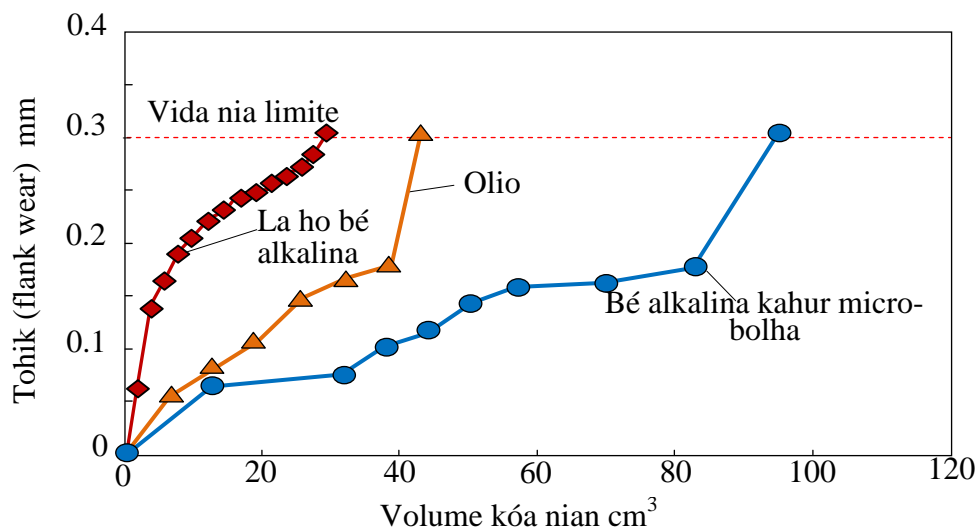


Fig.5.23 Rezultadu testu nian ba ferramento nia vida

5.4.3.3 Evaluasaun ba rugosidade superfície peça nian

Iha medisaun ba *rugosidade superfície* peça nian, medisaun ba area koa nian tenke iha linya perpendicular ho diresaun koa nian uza intrumentu ho tipu probe. Instrumentu husi Mitutoyo ho modelu SJ-400 mak uza hodi sukat

rugosidade peça nian. Fotografia husi instrumentu nee hatudu iha Fig.5.24. Rugosidade peça nian sukat depois de koa primeiro nian no mos depois de feramenta alkansa ba ninia vida uzo nian. Fig. 5.25 apresenta rezultadu husi mediasaun rugosidade R_z nian wainhira koa uza resfriamentu neebe vário. Rezultadu nee hatudu katak uza metodu neebe propoin, rugosidade sai diak 70% no 89% tui-tuir malu kompara ba metodu konvensional uza olio no la uza resfriamentu ruma. No mos variasaun iha rugosidade mos kiik. Tamba nee bele konsidera katak deformasaun térmika husi feramenta no mákina produsaun suprimi ho diak, no mos akurasaun husi rezultadu koa nian sai diak liu tan.



Fig. 5.24 Fotografia instrumentu hodi sukat rugosidade

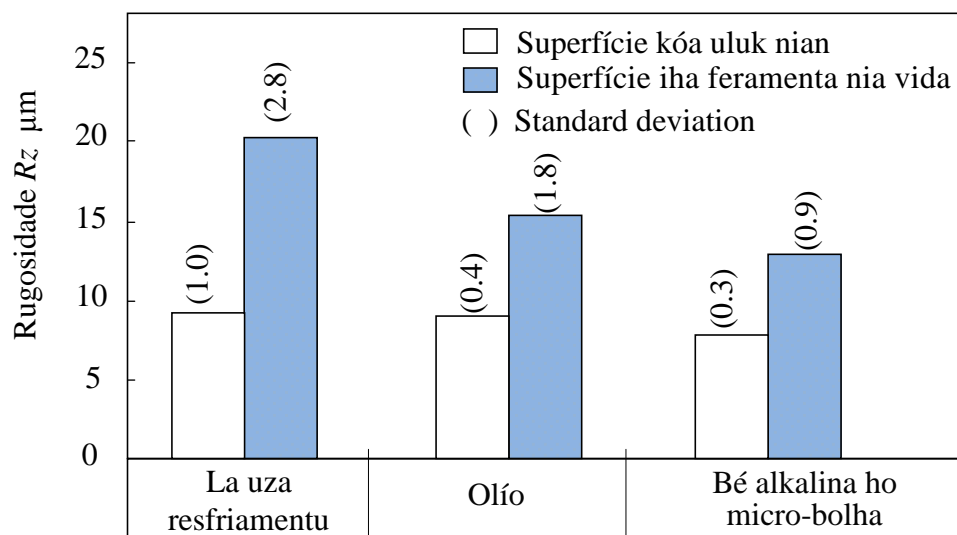


Fig. 5.25 Rezultadu medisaun ba rugosidade

5.5 Rezumu

Rezultadu husi estudu iha kapitulu ida nee nian rezumu hanesan tuir mai nee:

- (1) Valor husi transferensia calor nia koeficiente wainhira uza bé alkalina mak 400 W/m²K no sae ba 2350 W/m²K wainhira opera mákina iha bé alkalina lara ho rotasaun 3600 rpm, no sae tan ba to'o 2550W/m²K wainhira aumenta ho micro-bolha, nune konsidera nudar resfriamentu neebe excelente.
- (2) Ho kondisaun neebe submerge, feramenta nia temperatura bele redús 60%, dezlokamentu relativa redús quaze 89%, dezlokamentu angular redús quaze 86%, vida feramenta nian prolonga kuaze dala 3.6, no rugosidade peça nian sai diak dala 2/3 kompara ba prosesu koa la uza resfriamentu.
- (3) Kuaze materiais sira neebe relasiona ba mákina produsaun, exclui alumínio, la feruzu wainhira enfrente ho bé alkalina neebe forte, tan nee mak bé alkalina neebe forte bele uza ba resfriamentu durante makinazen.

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Kapítulu (6)

IMPAKTU BA AMBIENTE HUSI UTILIZASAUN REFRIGERANTE BÉ ALKALINA IHA MAKINAZEN

6.1. Introdusaun

Iha tempo agora nian, konserva ambiente sai hanesan fatór ida neebe importante tebes ba iha dezenyu produktu nian no prosesu fabrikasaun. Fabrikasaun neebe *eco-amigáveis* (*eco-friendly*) asosiadu ho preservasaun ba energia mos sai hotu nudar pedido jerál ba iha produsaun no makinazen. ^{[6-1],[6-2]} Eleva exekusaun makinazen nian ba hadiak produktu nia qualidade, preserva tempu no kustu gastu nian neebe kiik esensial tebes iha fábriku no makinazen. ^[6-3] Maibe, konsumo energia neebe boot, kontaminaun ba bé, no emisaun durante fabrikasaun eleva tiha ona nível toxisidade nian iha ambiente. ^{[6-4],[6-5]} Enkuanto, iha tinan ikus-ikus nee, ho industrializasaun neebe komesa diak ona iha fatin barak, hamenus utilizaun ba energia no konsumo ba ninia fonte sira sai hanesan ona objetivu primáriu neebe presiza fó atensaun hodi nunee bele contribui ba hamenus impaktu ba ambiente. Iha parte seluk, kuantidade husi emisaun CO₂ nian neebe asosiadu ho uzo energia nian sai ona hanesan problema neebe boot ba indúz *aquecimento global* (*global warming*). Nunee, ho konsiderasaun ba problema ambiente neebe global ^{[6-6],[6-7]}, fabrikasaun produktu ida nian tenke konsidera hotu ba ninia impaktu ba ambiente no natureza. Atualmente, peskizadores barak inventiga no halo dezenyu ona ba mákina sira neebe amizável no iha impact neebe uituan ba iha ambiente hodi hamenus resíduos ^{[6-8],[6-9],[6-10]}. Balun halao ona estudu kona ba oinsa bele hadiak qualidade graxa no lubrifikaun hodi bele uza ba tempu naruk ^[6-11]. Balun fali interese ba kondúz investigasaun relasiona ho managementu

produsaun nian iha fabrikasaun ^[6-12]. Entretantu, otimizasaun presiza tebes hodi avalia vida ciclo produktu nian no prosesu fabrikasaun atu bele minimiza sira nia impaktu ba iha ambiente no ema nia saude. Nunee, *Avaliação do Ciclo de Vida (Life Cycle Assessment, LCA)* importante tebes ba dezenho produktu nian no prosesu fabrikasaun. Avaliasaun bazeia ba metodologia LCA uza barak tiha ona iha area oi-oin ^{[6-13], [6-14], [6-15]}, maibe relatório avaliasaun ba makinazen quase laiha liu. Iha tempu neebe hanesan, tan teknolojia fabrikasaun nian evolve tiha ona ho objetivu hasae produktividade, akurasaun no hamenus kustu, konsiderasaun ba ambiente presiza hotu iha dezenyu produktu nian no prosesu fabrikasaun nia laran. Tamba nee mak iha estudu ba kapitulu ida nee nian, avaliasaun simples ida halo ba makinazen uza bé ba resfriamentu ho konsiderasaun ba aspeitu ambiente no ninia konservasaun. Mákina produsaun sira neebe uza iha kapitulu sira liu ba mak sei uza hodi halao avaliasaun ba sira. Nivel emisaun nian ba mákina ida-idak wainhira uza bé ba resfriamentu sei kompara ho uza konvensional resfriamentu.

6.2. Metodu estudu nian ba avaliasaun bé alkalina neebe forte

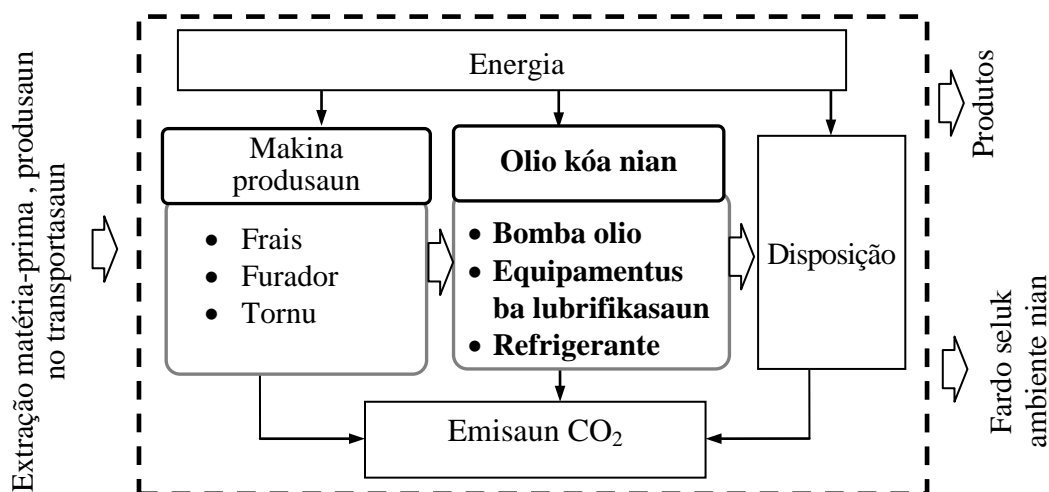
6.2.1 Objetivu and eskopu estudu nian

Objetivu husi estudu nee mak atu evalua ciclo vida nian husi utilizaun bé alkalina neebe forte nudar resfriamentu iha mákina produsaun ba hamenus residuos (*waste*) neebe estraga ambiente. Estudu ida nee halao evaluasaun LCA ba peskiza sira neebe halao no esplika tiha ona iha kapitulu sira anterior hanesan: perfurasaun iha bé alkalina nia laran no imerge mákina iha bé alkalina nia laran. Kuantidade bé nian neebe uza iha avaliasaun ida nee depende ba mákina ida-idak. Ba protesaun ambiente nian, estudu ida nee foka liu ba halao avaliasaun atu hatene kuantidade CO₂ nian hira mak sei emiti ba ambiente wainhira uza bé alkalina durante makinazen kompara ho olio no lubrifikante seluk. Tan kuaze buat hotu-hotu iha ita nia sor-sorin emiti CO₂, tan nee avaliasaun iha estudu nee

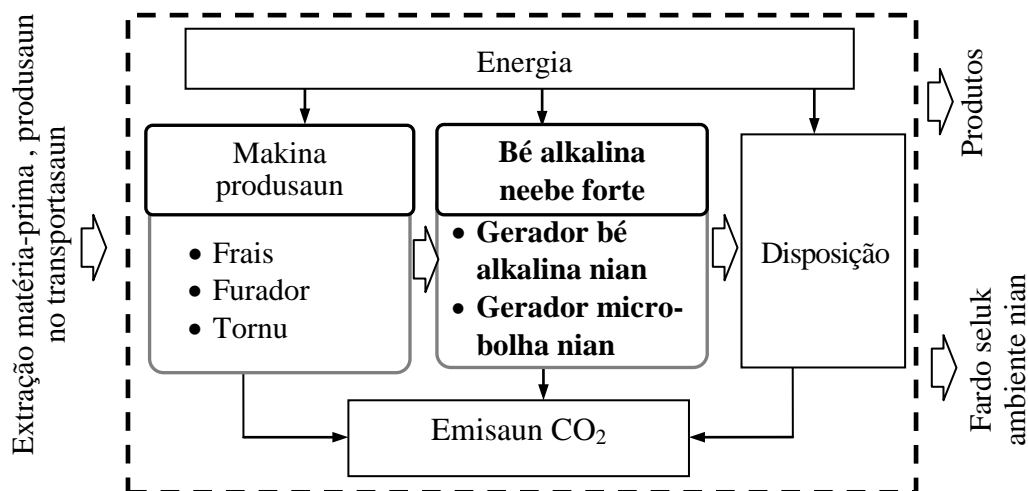
sei limitu ba iha sasan no prosesu sira neebe emiti CO₂ durante prosesu makinazen. Tan nee mak bazeia ba estudu iha kapitulu anterior nian, kalkulasiun halo ba evalua residuos, olio, prosesu makinazen neebe konvensional, mákina NC frais, gerador micro-bolha nian, gerador ba bé alkalina, bomba bé, no mákina tornu bancada. Fig.6.1 apresenta *flowchart* simples husi ciclo vida nian ba makinazen ho resfriamentu konvensional no resfriamentu uza bé alkalina neebe forte. Sistema fronteira husi LCA nee inklui atividade hotu-hotu neebe involve iha produsaun POCA (K₂CO₃) nian, maibe extrasaun matéria-prima (*raw material*) ba peça no fermenta no mos ba *óleo bruto* (*crude oil*) sei la evalua no la halo análise inventário ba sira. Tráfiku husi transportasaun mákina nian no konsumível ba makinazen mos exklui iha avaliasaun ida nee. Fardo ambiental (environmental burden) CO₂ sei kalkula iha estudu nee. Kalkulasiun halo hodi kalkula no kompara total konsumo elétriku nian ba ekipamentu ida-idak durante halao makinazen la uza resfriamentu, uza resfriamentu konvensional, no uza resfriamentu bé alkalina neebe forte kahur micro-bolha ba tinan ida nia laran.

6.2.2 Metodu estudu nian

Metodu LCA nian neebe uza ba avaliasaun iha estudu ida nee mak metodu *unit process analysis* no *input-output analysis*. Iha nee, bé uza nudar objeto estudu nian ba mákina tornu bancada no furador. Tabela relasaun entre *inter-industry* (*input-output*) ba makinazen konsidera atu uza ba halao estimasaun ba impaktu direto no indireto ba element ida-idak iha ambiente. Emisaun CO₂ nian kalkula husi prosesu makinazen uza mákina tornu no mákina furador. No mos, total energia neebe konsume no olio neebe deskarte mos sei kalkula hotu. Hodi konsidera pontu sira nee, ami adota *metodu input-output analysis* ba iha estudu ida nee hodi halo avaliasaun ba utilizasaun bé durante makinazen no sei kompara ba makinazen ho resfriamentu konvensional uza olio no solvente sira seluk.



(a). Flow chart LCA ba resfriamentu convencional



(b). Flow chart LCA ba resfriamentu uza bé alkalina neebe forte

Fig. 6.1 Flow chart LCA ba resfriamentu convencional no uza bé alkalina neebe forte

6.2.3 Aproximasaun kalkulasaun nian

Kalkulasaun performa hodi kalkula gas oi-oin neebe emiti ba ambiente ho ninia impacto potencial ba aquecimento global no saude ema nian. Kalkulasaun ba avaliaun halao hodi kalkula emissasaun husi energia no eletricidade neebe konsumo, no mos disposisaun olio nian durante mainazem. Emisaun husi energia neebe consume durante makinazen kalkula uza equasaun (6.1). Iha equasaun nee,

W_E mak kuantidade energia neebe konsumo iha oras ida nia laran. Emisaun husi uzo ba olio no ninia disposisaun kalkula uza ekuasaun (6.2).

$$CL_{CO_2} = 0.468 \text{ (kg-CO}_2\text{/kWh)} \times W_E \text{ (kWh)}. \quad (6.1)$$

$$\begin{aligned} \text{CO}_2 \text{ emission (kg-CO}_2\text{)} = & \text{Disposed oil kl} \times \text{Calorific value GJ/kl} \\ & \times \text{EF (t-C/TJ)} \times (44 \div 12). \end{aligned} \quad (6.2)$$

Iha kalkulasaun nee mos, ba energia elétrica neebe consume durante makinazen, fatór emisaun nian (emission factor) foti bazeia ba gas nia kuantidade neebe emite per kWh, enkuantu emisaun fatór ba disposisaun olio nian foti bazeia ba kuantidade gas sira neebe emiti durante prosesu *incineração*.

6.3 Avaliasaun simples ba makinazen uza bé alkalina neebe forte

6.3.1 Inventário ba teknolojia koa nian iha bé alkalina neebe forte nia laran kahur micro-bolha

Titânio alloy no niquel alloy uza barak iha mákina aeronáutika no astronáutika nia elementus. Teknoljia makinazen ho akurasaun neebe aas ba materiais sira nee sei iha prosesu investigasaun nia laran ^{[6-16],[6-17],[6-18]}. Maibe, materiais ho tipo rua nee iha konduktividade térmiku neebe kiik los, tamba nee wainhira performa koa ba materiál sira nee, manas husi koa nian sei kondúz fali ba feramenta laran. Tan manas sira kondúz hotu ba feramenta laran, feramenta ninia temperatura sei sai aas los, nunee hamenus ninia dureza, neebe mak bele hamenus efisiensia no akurasaun makinazen nian. Tan estudu ba problema ida nee investiva no evalua tiha ona uza resfriamentu forsadu hodi bé alkalina neebe forte, impaktu husi utilizaun bé

alkalina nian sei evalua hodi halao kalkulasaun ba CO₂ neebe emiti. Iha kalkulasaun nee, rezultadu total CO₂ nian husi makinazen uza resfriamentu bé alkalina sei kompara ho makinazen uza resfriamentu konvensional. Emisaun neebe emiti husi eletrisidade durante makinazen no disposisaun ba olio sei kalkula no halao komparaun. Kuantidade CO₂ nian neebe emiti sei kalkula husi utilizaun eletrisidade husi bomba olio, compressor anin nian, gerador micro-bolha nian, gerador bé alkalina nian, no bomba neebe uza ba hamoos restu koa (*chip*) nian.

Tabela 6.1(a) apresenta kalkulasaun ba emisaun CO₂ nian husi makinazen uza resfriamentu konvensional. Iha kalkulasaun nee, avaliaun ba utilizaun energia elétrico nian no disposisaun olio nian halao. Energia neebe uza husi mákina NC frais no bomba refrigerante nia (1.2 kW) sura ba total loron servisu nian ba tinan ida (250 days). Asumi katak oras servisu nian mak oras 8 iha loron ida nia laran, nunee total elétrico mak 2400 kW (1.2 kW×8 h×250 days) ba tinan ida. Ho total elétriku nee, kuantidade husi emisaun CO₂ nian sei sura uza ekuasaun (6.1). Fatór emmisaun nian uza ba kalkulasaun nee mak 0.468 kg-CO₂/kWh⁽⁶⁻¹⁹⁾. Ho ida nee, total husi emissun CO₂ ba makinazen uza resfriamentu konvensional mak 1123.2 kg-CO₂. Tuir mai, kuantidade emisaun CO₂ husi disposisaun olio sei kalkula. Iha kalkulasaun nee, olio koa nian ho litru 340 konsidera uza ba makinazen no sei troka kada fulan 6. Nunee, total disposisaun olio nian ba tinan ida mak 680 ℓ/tinan. No mos, tan olio presiza atu aumenta wainhira nia menus, olio litru 30 sei uza ba aumenta kada fulan (30ℓ×12 month=360 ℓ/year), nunee mak total husi kuantidade disposisaun ba olio ba tinan ida nia laran mak 1040 ℓ. Ho ida nee, emisaun CO₂ nian bele kalkula uza ekuasaun (6.2)⁽⁶⁻²⁰⁾. Ba kalkulasaun ida nee, valor calorífiku (*calorific value*) husi disposisaun olio nian mak 40.2 GJ / kℓ, no ninia fatór emisaun mak 19.22 t-C / TJ⁽⁶⁻²¹⁾. Hodi ekuasaun (6.2), total emisaun CO₂ nian husi disposisaun ba olio mak 2946.3 kg-CO₂. Nunee, total kuantidade husi CO₂ neebe emiti husi makinazen uza resfriamentu konvensional no disposisaun olio nian hamutuk mak 4069.5 kg-CO₂.

Tabela 6.1 Emisaun CO₂ nian husi makinazen uza resfriamentu konvensional no resfriamentu uza bé alkalina kahur micro-bolha

(a). Emisaun CO₂ nian husi makinazen uza resfriamentu konvensional

Bomba olio		Disposisaun residuo olio nian	
Energia elétriku	kW	1.2	Olio kóá nian ℓ/tinan 680
Condisaun uza nian	/tinan	8 h ×250 days	Olio troka nian ℓ/tinan 360
Elétrico neebe konsumo	kWh	2400	- -
Emisaun CO ₂	kg- CO ₂ /tinan	1123.2	Emisaun CO ₂ kg- CO ₂ /tinan 2946.3
Total emisaun CO ₂	kg- CO ₂ /tinan	4069.5	

(b). Emisaun CO₂ nian husi makinazen resfriamentu uza bé alkalina kahur micro-bolha

Fatór kalkulasaun nian	Compressor anin nian	Gerador micro-bolha	Bomba atu hamos chip	Gerador bé alkalina nian
Energia elétriku kW	0.95	0.56	0.0132	0.75
Kuantidade bé alkalina neebe mak uza ℓ	-	-	-	20
Ciclo troka nian	-	-	-	Kada fulan
Bé alkalina neebe prodúz ℓ	-	-	-	20
Kondisaun uza nian /tinan	8 h ×250 loron	8 h ×250 loron	8 h ×250 loron	25h
Elétriku neebe konsumo kWh	1900	1120	26.4	75
Emisaun CO ₂ kg- CO ₂ /tinan	889.2	524.2	12.4	8.8
Total emisaun CO ₂ kg- CO ₂ /tinan	1434.6			

Tabela 6.1(b) apresenta kalkulasaun ba emisaun CO₂ nian husi makinazen uza resfriamentus bé alkalina neebe forte kahur micro-bolha. Emisaun CO₂ husi kompressor anin nian neebe assume hidi halao oras 8 kada loron no loron 250 ba tinan ida, total eletrisidade neebe uza mak 1900 kWh ($0.95 \text{ kW} \times 8 \text{ h} \times 250 \text{ days}$). Uza fatór emisaun $0.468 \text{ kg-CO}_2/\text{kWh}^{(4-19)}$ neebe fó husi kompania *Tokyo electricity*, kuantidade emisaun CO₂ nian ba operasaun kompressor nee kalkula uza ekuasaun (6.1) mak 889.2 kg-CO₂. Ho kalkulasaun neebe hanesan, ita nele hetan emisaun CO₂ ba halao operasaun uza gerador micro-bolha no bomba bé nian tui-tuir malu mak 524.2 kg-CO₂ no 12.4 kg-CO₂. Adisionalmente, emisaun gerador bé alkalina nian mos kalkula hotu. Kuantidade husi bé alkalina neebe uza iha prosesu nee mak 20ℓ. Ho kondisaun uzo nian loron 250 kada tinan no mos bé alkalina konsidera sei troka kada fulan ida, nunee kuantidade bé nian neebe presiza ba tinan ida mak mais ou menus 250 ℓ. Tan gerador nee presiza oras 2 atu bele prodús bé alkalina litru 20, total oras neebe presiza atu prodús bé alkalina ba tinan ida mak oras 25. Nunee total elétiku neebe uza mak 18.8 kWh ($0.75 \text{ kW} \times 25 \text{ h}$). Uza ekuasaun (6.1), emisaun CO₂ nian ba produsaun bé alkalina iha tinan ida nia laran mak 8.8 kg-CO₂. Ho ida nee, ita bele hetan total emisaun ba makinazen uza resfriamentu bé alkalina kahur micro-bolha kada tinan hamutuk 1434.6 kg-CO₂.

6.3.2 Inventário ba teknolojia perfurasaun uza bé alkalina neebe forte kahur micro-bolha

Relasiona ba estudu iha Kapítulu 4, teknolojia perfurasaun uza bé alkalina neebe forte kahur micro-bolha, avaliasaun tekniku nee nian atu hatene ninia impatu ba ambiente avalia hodi kalkula kuantidade CO₂ neebe mak emiti. Iha kalkulasaun nee, emisaun CO₂ husi makinazen uza

resfriamentu konvensional no resfriamentu uza bé alkalina kahur micro-bolha sei kalkula no kompara ba malu. Iha makinazen uza resfriamentu konvensional, emisaun CO₂ nian kalkula husi mákina NC frais, bomba olio nian, no emisaun husi tratamento no disposisaun olio nian. Iha parte seluk, emisaun durante perfurasaun uza resfriamentu bé alkalina kahur micro-bolha kalkula husi uzo ba mákina NC frais, gerador micro-bolha, gerador bé alkalina, no bomba bé neebe uza ba fornese bé alkalina ba broca.

Tabela 6.2 apresenta inventário no rezultadu kalkulasaun emisaun CO₂ nian ba perfurasaun uza resfriamentu konvensional no bé alkalina kahur micro-bolha. Rezultadu kalkulasaun emisaun CO₂ nian ba perfurasaun uza resfriamentu konvensional hatudu iha Tabela 6.2(a). Iha kalkulasaun nee, mákina NC frais ho kapasidade 3.6 kW no bomba olio 1.2 kW neebe uza atu fronece olio ba broca konsidera opera oras 8 lora ida no lora 250 ba tinan ida. Nunee, energia elétriku nian neebe konsumo mak 9600 kW ($74.8\text{kW} \times 8\text{h} \times 250\text{ days}$). Ho fatór konversaun emisaun CO₂ nian mak uza 0.468 kg-CO₂/kWh, emisaun CO₂ nian wainhira opera mákina frais no bomba olio ba tinan ida nia laran kalkula uza ekuasaun (6.1) mak 4492.8 kg-CO₂/year.

Tuir mai, kalkulasaun halao fali ba emisaun CO₂ husi disposisaun ba olio residuos nian. Iha kalkulasaun nee, olio ho kapasidade 340 ℓ konsidera uza ba perfurasaun no sei troka dala rua iha tinan ida nian laran. Tan kada fulan olio nee komesa menus, nunee olio litru 30 konsidera sei aumenta fula-fulan ba tinan ida nia laran ho total 360ℓ ($30\text{ ℓ} \times 12\text{ month}$). Tan nee total olio neebe uza ba tinan ida nia laran hamutuk 1040 ℓ. Uza ekuasaun (6.2), calor calorífico 40.2GJ/ℓ, no fatór emisaun karbonu nian 19.22 t-C/TJ, emisaun CO₂ nian ba prosesaun no disposisaun olio nian iha tinan ida nia laran mak 2946.3 kg-CO₂. Ho ida nee, total emisaun ba perfurasaun uza resfriamentu konvensional mak 7439.1 kg-CO₂/tinan.

Tabela 6.2 Emisaun CO₂ nian husi perfurasaun uza resfriamentu konvensional no resfriamentu uza bé alkalina kahur micro-bolha

(a). Emisaun CO₂ nian husi perfurasaun uza resfriamentu konvensional

NC frais no boba olio nian			Disposisaun residuo olio nian		
Energia elétriku	kW	4.8	Olio kóá nian	ℓ/tinan	680
Kondisaun uza nian	/tinan	8 h ×250 days	Olio troka nian	ℓ/tinan	360
Elétriku nebe konsumo	kWh	9600	-		-
Emisaun CO ₂	kg- CO ₂ /tinan	4492.8	Emisaun CO ₂	kg- CO ₂ /tinan	2946.3
Total CO ₂ emisaun		kg-CO ₂ /year	7439.1		

(b). Emisaun CO₂ nian husi perfurasaun uza resfriamentu uza bé alkalina kahur micro-bolha

Fatór kalkulasaun nian	NC Frais	Gerador micro-bolha	Bomba bé nian	Gerador bé alkalina nian
Energia elétriku kW	3.6	0.56	0.75	0.75
Kuantidade bé alkalina neebe mak uza ℓ	-	-	-	20
Ciclo troka nian	-	-	-	Kada fulan
Bé alkalina neebe prodúz ℓ	-	-	-	20
Kondisaun uza nian /tinan	8 h ×250 loron	8 h ×250 loron	8 h ×250 loron	25h
Elétriku neebe konsumo kWh	7200	1120	1500	18.8
Emisaun CO ₂ kg- CO ₂ /tinan	3369.6	524.2	702	8.8
Total emisaun CO ₂ kg-CO ₂ /tinan	4604.6			

Inventário no rezultadu kalkulasaun emisaun CO₂ nian ba perfurasaun uza resfriamentu bé alkalina kahur micro-bolha mak hatudu iha Tabela 6.2(b). Hanesan mos uza iha perfurasaun uza resfriamentu konvensional, máquina NC frais mos uza hotu iha nee. Uza kondisaun operasaun neebe hanesan (operasaun ba oras 8 kada loron no loron 250 kada tinan), total energia elétriku neebe consume mak 7200 kWh ($3.6 \text{ kW} \times 8 \text{ h} \times 250 \text{ days}$). Uza ekuasaun (6.1), emisaun CO₂ husi perfurasaun uza bé alkalina kahoe micro-bolha mak 3369.6 kg-CO₂ ba tinan ida nia laran. Adisionalmente, tan gerador micro-bolha nian no bomba bé nian mos uza hotu iha perfurasaun nee, emisaun neebe emitu husi máquina rua nee tui-tuir malu mak 524.2 kg-CO₂ and 702 kg-CO₂. Nunee mos, emisaun CO₂ husi gerador bé alkalina nian mos kalkula hotu. Kapasidade tanque neebe uza hodi tau bé alkalina mak 16.1ℓ ($350 \times 230 \times 200 \text{ mm}$), enkuantu ba tanque neebe uza atu fornese micro-bolha, ninia kapasidade mak 3.9 ℓ. Tan nee presiza bé alkalina ho kuantidade 20 ℓ. Konsidera katak máquina NC frais sei opera ba loron 250 kada tinan, enkuantu bé alkalina sei troka kada fulan ida, kuaze bé alkalina 250ℓ mak presiza ba perfurasaun durante tinan ida nia laran. Tamba presiza oras 2 atu bele prodús bé alkalina 20 ℓ (kuaze oras 25 iha tinan ida nia laran), total energia elétriku neebe konsumo mak 18.8 kWh ($0.75 \text{ kW} \times 25 \text{ h}$). Uza ekuasaun (6.1), rezultadu emisaun mak 8.8kg-CO₂. Nunee, total emisaun CO₂ durante perfurasaun uza resfriamentu bé alkalina neebe forte kahur micro-bolha ba tinan ida nia laran mak hamutuk 4604.6 kg-CO₂.

6.3.3 Inventário ba imersaun máquina tornu bankada no halao operasaun iha bé alkalina nia laran atu redús CO₂

Avaliasaun impaktu husi utilizaun metodu imersaun no halao operasaun ba máquina iha bé alkalina laran performa hanesan hotu makinazen neebe halao iha sesaun 6.3.1 no 6.3.2. Evaluasaun neebe simples halo ba prosesu makinazen hodi

immerse mákina iha ba alkalina kahur micro-bolha laran hodi ezamina no kalkula prosesu nee ninia emisaun CO₂. Iha kalkulasaun nee, gas CO₂ neebe emiti husi operasaun mákina tornu bankada uza la uza imersaun no uza imersaun investiga no kompara ba malu. Wainhira la halo imersaun, CO₂ neebe mak emiti sura husi mákina produsaun, bomba olio, refrigerador no disposisaun residuo olio nian. Iha parte seluk, wainhira halao imersaun, emisaun CO₂ kalkula husi energia electric neebe konsume husi gerador micro-bolha nian, gerador bé alkalina nian no bomba atu hamos restu chips nian. Tabela 6.3 apresenta inventário no resultdo husi kalkulasaun ba makinazen la uza imersaun no halao imersaun iha bé alkalina neebe forte kahur micro-bolha nia laran. Resultadu emisaun CO₂ husi makinazen la uza imersaun mak hatudu iha Tabela 6.3(a). Iha makinazen konvensional (la uza imersaun), mákina sira hanesan NC frais (3.6 kW), bomba olio (1.2 kW) no refrigerador (2.2 kW) ho total energia 7.0 kW konsidera uza no opera oras 8 kada laron ida no laron 250 ba tinan ida, nune total energia elétric neebe mak konsumo iha tinan ida nia laran mak 14000 kW (7.0 kW×8 h×250 days). Hanesan esplika tiha ona iha sesaun rua liu ba, fatór konversaun ba emisaun CO₂ nian husi eletrisidade foti ba kalkulasaun mak 0.468 kg-CO₂/kWh. Ho valor ida nee, kuantidade emisaun CO₂ neebe emiti ba tinan ida bele kalkula uza ekuasaun (6.1). Nune, total emisaun CO₂ husi eqkipamentus sira neebe uza iha makinazen konvensional ba tinan ida nia laran mak 6552 kg-CO₂. Tuir mai, emisaun husi disposisaun ba residuo olio nian mos evalua no kalkula. Hanesan hotu iha sesaun 6.3.2 perfurasaun nian, iha nee olio ho kapasidade 340 ℓ mos konsidera uza ba makinazen no sei troka dala rua iha tinan ida nian laran. Tan kada fulan olio nee komesa menus, nune olio litru 30 konsidera sei aumenta fula-fulan ba tinan ida nia laran ho total 360ℓ (30 ℓ × 12 *month*). Tan nee total olio neebe uza ba tinan ida nia laran hamutuk 1040 ℓ. Uza ekuasaun (6.2), calor calorífiku 40.2GJ/ℓ, no fatór emisaun karbonu nian 19.22 t-C/TJ,

emisaun CO₂ nian ba prosesaun no disposisaun olio nian iha tinan ida nia laran mak 2946.3 kg-CO₂. Ho ida nee, total emisaun ba makinazen konvensional la uza imersaun mak 9498.3 kg-CO₂/tinan.

Tabela 6.3(b) apresenta inventário no rezultadu kalkulasaun emisaun CO₂ nian husi makinazen hodi immerse mákina tornu bankada iha bé alkalina neebe forte nia laran. Durante halao experiment ba metodu ida nee hanesen esplika tiha ona iha Kapítulu 5, tamba difisil tebes halao operasaun koa ho mákina tornu banku iha bé alkalina laran, nunez iha experimentu neeba, uza fali mak mákina NC frais ba halao evaluasaun. Bazeia ba ida nee, iha avaliasaun ida nee emisaun CO₂ nian sei sura husi oras uzo ba mákina NC frais. Nunez, mákina NC frais ho kapasidade 3.6 kW konsidera uza oras 8 ba loron ida no loron 250 ba tinan ida, ninia energia total neebe mak konsumo ba tinan ida mak 7200 kWh ($3.6 \text{ kW} \times 8 \text{ h} \times 250 \text{ days}$). Uza fatór konversaun emisaun CO₂ nian husi utilizaun eletrisidade nian ho valor 0.468 kg - CO₂/kWh, kuantidade husi CO₂ neebe mak emiti husi operasaun mákina NC frais ba tinan ida kalkula uza ekuasaun (6.1) mak 3370 kg-CO₂. Ho metodu kalkulasaun neebe mak hanesan, emisaun husi gerador micro-bolha nian no bomba bé nian tuituir malu mak 524 kg-CO₂, 12 kg-CO₂. Nunez mos, kalkulasaun emisaun husi gerador bé alkalina nian halo hotu. Iha nee, bé alkalina ho total litru 26094 konsidera uza ba makinazen durante tinan ida nian laran. Kuantidade bé alkalina ida nee hetan husi kuantidade bé alkalina neebe mak enxe ba kontainer laran inklui ho bé alkalina neebe sei uza hodi aumenta ful-fulan. Wainhira immerse mákina ida, mákina nee tenke taka tomak ho bé, nunez kontainer neebe mak uza tenke mos tenke boot liu mákina nee. Iha avaliasaun nee, total volume husi bé alkalina no mákina frais iha kontainer laran hamutuk 27000 ℓ ($=W3000 \text{ mm} \times D3000 \text{ mm} \times H3000 \text{ mm} \times 10^{-6}$). Volume husi parte hot-hotu mákina NC frais nian mak 1026 ℓ ($=\text{Máquina NC frais nia todan } 8000 \text{ kg} \div \text{Densidade aço nian } 7800 \text{ kg/m}^3 \times 10^3$). Nunez volume bé alkalina neebe enxe ba iha kontainer atu nunez

Tabela 6.3 CO₂ Emisaun CO₂ nian husi makinazen la uza imersaun no imersaun iha bé alkalina kahur micro-bolha nia laran

(a). Emisaun CO₂ nian husi makinazen konvensional (la halo imersaun)

Makina NC frais no bomba olio			Disposisaun residuo olio nian		
Energia elétriku	kW	7.0	Olio kóá nian	ℓ/tinan	680
Kondisaun uza nian	/tinan	8 h ×250 loron	Olio troka nian	ℓ/tinan	360
Kuantidade elétriku neebe konsume	kWh	14000	-		-
Emisaun	kg-CO ₂ /tinan	6552	Emisaun	kg-CO ₂ /tinan	2946
Total emisaun CO ₂	kg- CO ₂ /tinan	9498			

(b). Emisaun CO₂ nian husi makinazen ba imersesaun iha bé alkalina kahur micro-bolha nia laran

Fatór kalkulasaun nian	NC Frais	Gerador micro-bolha	Bomba bé nian	Gerador bé alkalina nian
Energia elétriku kW	3.6	0.56	0.0132	0.75
Energia elétriku ba bé alkalina 1 ℓ kWh/ ℓ				0.075
Ciclo troka nian	-	-	-	Kada fulan
Kuantidade bé alkalina nian ℓ	-	-	-	26094
Kondisaun uza nian /tinan	8 h ×250 loron	8 h ×250 loron	8 h ×250 loron	24h×365 dloron
Kuantidade elétriku neebe konsumo kWh	7200	1120	26.4	1957
Emisaun CO ₂ kg-CO ₂ /tinan	3370	524	12	916
Total emisaun CO ₂ kg- CO ₂ /tinan	4822			

bele taka tomak mákina frais mak 25974 ℓ (= Volume bé alkalina ho mákina frais – volume husi mákina frais). Ba aumenta nian, bé alkalina litru 10 konsidera uza hodi aumenta ba iha kontainer laran atu nunee bele matein nivel bé alkalina nian iha kontainer laran. Tan nee, presiza bé alkalina litru 120 ($= 10 \text{ ℓ/month} \times 12 \text{ month}$) ba tinan ida nia laran. Gerador ba produsaun bé alkalina iha kapasidade 0.75 kW. Tan gerador nee bele prodús bé alkalina litru 10 iha oras ida nia laran, nunee, energia elétrika neebe presiza atu prodús bé alkalina litru ida mak 0.075 kW/ℓ ($0.75 \text{ kW} \times 1 \text{ h} \div 10 \text{ ℓ}$), no kuaze 1957 kW iha tinan ida nia laran. Husi energia neebe konsume nee, emisaun husi produsaun bé alkalina nian iha tinan ida nia laran mak 916 kg-CO₂. Nunee, total emisaun ba makinazen hodi immerse mákina iha bé laran durante tinan ida nia laran mak hamutuk 4822 kg-CO₂.

6.4 Análize impaktu makinazen uza resfriamentu bé alkalina neebe forte

6.4.1 Impaktu ba ambiente

Iha sesaun ida nee sei halao diskusaun kona ba impaktu husi makinazen uza resfriamentu bé alkalina neebe forte ba iha ambiente. Komparasaun impaktu husi makinazen uza resfriamentu konvensional no uza bé alkalina neebe forte sei halao atu hatene ida neebe mak efektivu ba konserva ambiente, liu-liu ida nebe mak la fo kontribuisaun neebe boot ba *aquecimento global*.

Komparasaun husi emisaun CO₂ nian husi prosesu makinazen tolu neebe esplika tiha ona iha sesaun 6.3 mak apresenta tui-tuir malu iha Fig. 6.2, Fig. 6.3, no Fig. 6.4 ba teknolojia ba makinazen iha bé alkalina kahur micro-bolha nia laran, teknolojia perfurasaun uza be alkalina neebe forte kahur micro-bolha, no makinazen hodi immerse mákina produsaun iha bé alkalina neebe forte kahur micro-bolha nian laran. Komparasaun emisaun CO₂ neebe mak emiti durante makinazen uza resfriamentu konvensional no makinazen iha bé alkalina nia laran mak hatudu iha Fig 6.2. Husi rezultadu nee ita bele haree katak kuantidade

emisaun CO₂ nian redús kuaze 2634.9 kg-CO₂ (64.7 % redusaun) iha tinan ida nia laran wainhira uza bé alkalina neebe forte ba resfriamentu kompara ba uza resfriamentu konvensional. Redusaun iha emisaun neebe boot nee tamba la presiza olio wainhira uza resfriamentu bé alkalina. Nunee ita bele hateten katak tékniku resfriamentu nee efetivu tebes no bele redús emisaun.

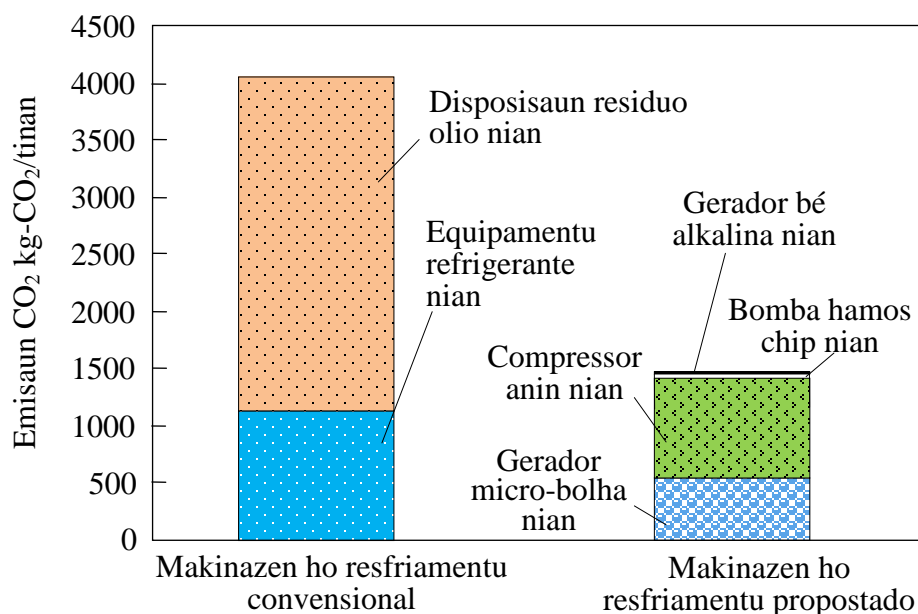


Fig. 6.2 Komparasaun emisaun CO₂ neebe mak emiti durante makinazen uza resfriamentu konvensional no iha bé alkalina nia laran

Komparasaun emisaun CO₂ neebe mak emiti durante perfurasaun uza resfriamentu konvensional no perfurasaun uza bé alkalina neebe forte kahur micro-bolha hatudu iha Fig. 6.3. Husi rezultadu nee ita bele haree katak kuantidade emisaun CO₂ nian redús kuaze 2834.5 kg-CO₂ (38.1 % redusaun) iha tinan ida nia laran wainhira uza bé alkalina neebe forte ba resfriamentu iha perfurasaun kompara ba perfurasaun uza resfriamentu konvensional. Hanesan esplika uluk tiha ona iha leten, redusaun ida nee tamba resfriamentu uza bé

alkalina neebe forte la uza no la presiza olio durante makinazen, nunee mak bele redús emisaun signifkativamente.

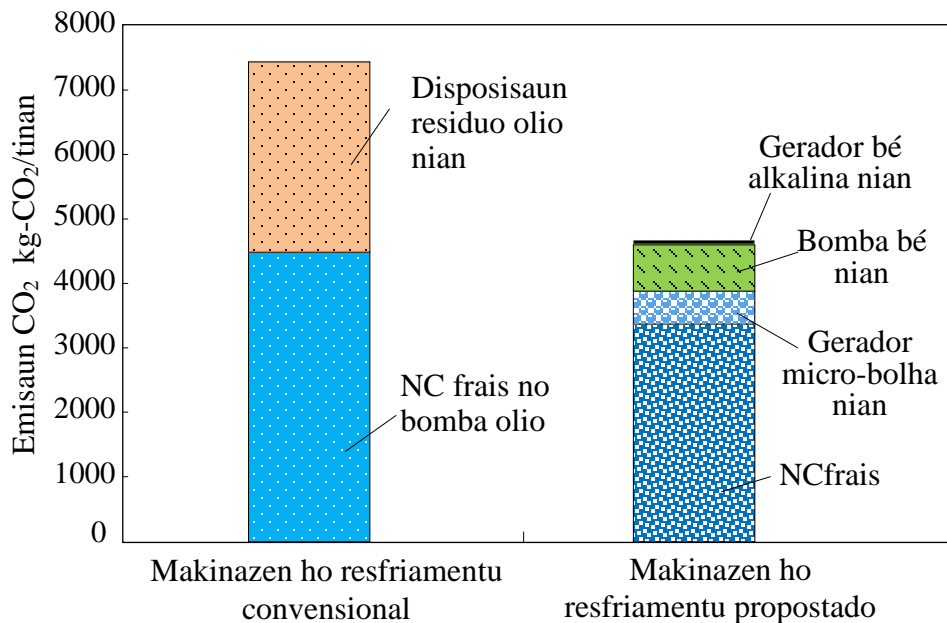


Fig. 6.3 Komparasaun emisaun CO₂ neebe mak emiti durante perfursaun uza resfriamentu konvensional no uza bé alkalina neebe forte

Fig.6.4 hatudu komparasaun emisaun CO₂ neebe mak emiti durante makinazen uza resfriamentu konvensional no makinazen hodi immerse mákina iha bé alkalina neebe forte nia laran. Husi rezultadu nee ida nee mos ita bele hare katak kuantidade emisaun CO₂ nian redús kuaze 4678 kg-CO₂ (49.2 % redusaun) iha tinan ida nia laran wainhira halao makinazen hodi immerse mákina iha bé alkalina neebe forte nia laran kompara ba makinazen uza resfriamentu konvensional. Tan ekipamentus sira neebe uza iha makinazen ho resfriamentu husi bé alkalina konsumo energia elétiku neebe uituan, nunee emisaun mos emiti uituan deit. No mos, tan iha resfriamentu uza bé alkalina la presiza olio no graxa, nunee emisaun kiik liu fali duque wainhira uza olio no graxa. Tamba nee mak

wainhira uza bé alkalina neebe forte nudar refrigerante, emisaun neebe boot emiti husi prosesu no disposisaun olio nian bele hamenus, limpeza depois de makinazen la presiza nunee bele hamenus impaktu ba ambiente, no mos metodu resfriamentu uza bé alkalina neebe forte konsidera efetivu ba aplikasaun iha fabrikasaun no makinazen.

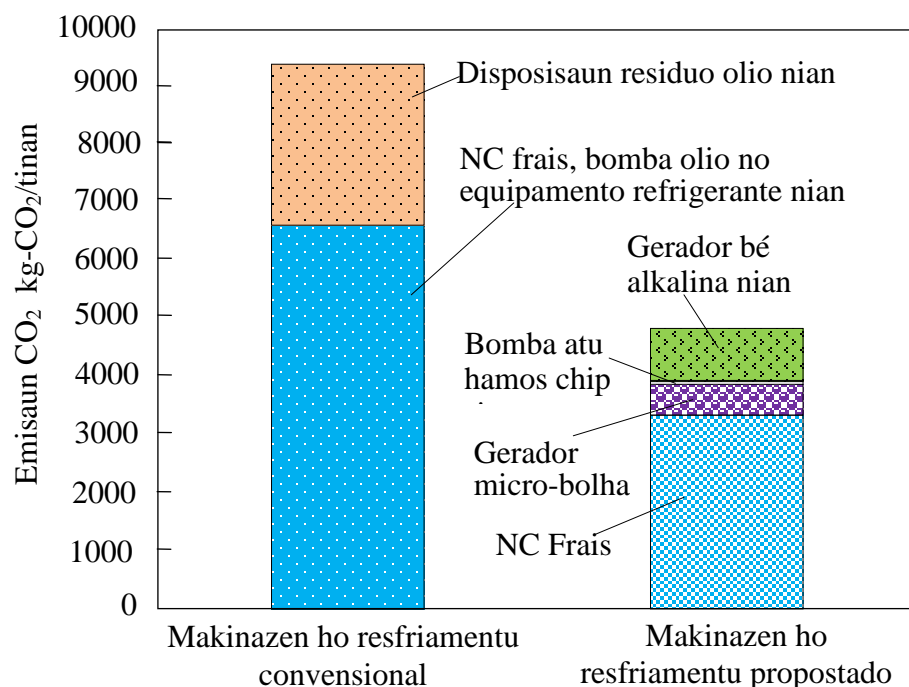


Fig. 6.4 Komparasaun emisaun CO₂ neebe mak emiti durante makinazen uza resfriamentu konvensional no makinazen hodi immerse makina iha bé alkalina neebe forte nia laran

Wainhira prosesu makinazen tolu nee halao dala ida iha tempu neebe hanesan, emisaun CO₂ durante operasaun mákina sira nee ba tinan ida sai sai boot los. Nunee, sira nia impaktu ba ambiente bele simplifika hodi kalkula potensial impaktu ba *aquecimento global*. Fig.6.5 hatudu komparasaun prosesu makinazen husi prosesu tolu iha leten ba *aquecimento global*. Rezultadu kalkulasaun nian hatudu katak wainhira halao makinazen uza

resfriamentu konvensional, prosesu nee sei contribui kuaze 21006 kg-CO₂-eq/year ba akontesementu *aquecimento global* nian. Iha parte seluk, wainhira halao makinazen uza resfriamentu husi bé alkalina neebe forte, prosesu nee kontribui deit kuaze 10861 kg-CO₂-eq kada tinan ba *aquecimento global*, ida neebe kuaze 48% redusaun husi makinazen uza resfriamentu konvensional. Tamba emisaun CO₂ redús makaas, gas sira seluk hanesan CH₄ no N₂O neebe mak halao diskusaun iha estudu nee konsidera redús hotu. Tan nee, impaktu husi gas sira nee ba ambiente hanesan *acidification*, *ozone depletion*, *smog formation* no *eutrophication* mos konsidera redús.

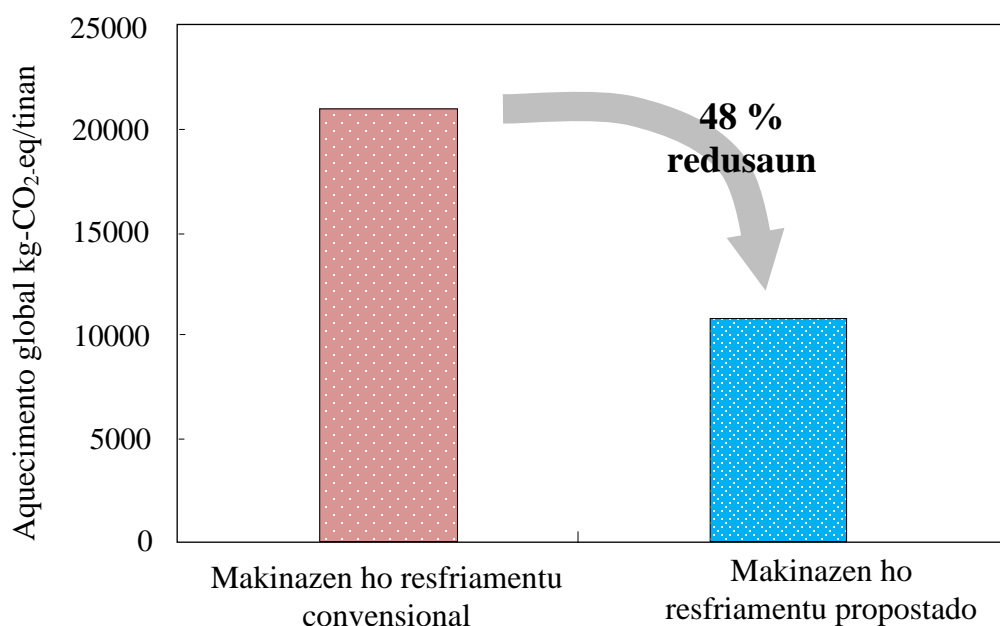


Fig. 6.5 Comparasaun impacto husi prosesu makinazen no utilizaun resfriamentu nian ba aquecimento global

6.4.2 Impaktu ba ema nia saude

Além de importancia ba conserva ambiente, saude ema nian nudar prioridade neebe importate tebes atu fó atensaun neebe máxima. Tamba nee mak avaliaun husi efeito bé alkalina neebe forte ba ema nia saude mos halao. Hanesan hatudu

iha Tabela 6.4, kompostu solúvel neebe uza ba prodús bé alkalina mak 2.18 g/litru husi potássio carbonato (K_2CO_3). Tamba kompostu nee kontribui 2.18 grama ba bé alkalina, nune nia kuaze 0.1% deit husi total bé alkalina neebe mak prouúz. Tan nee, bé alkalina neebe forte nee konsidera 99.9% nee bé bai-bain. Tabela 6.5 fó hatudu efeito husi bé alkalina ba ema nia saude. Hanesan esplika tiha ona iha leten katak, tamba kuaze 99.9% husi bé alkalina nee bé bai-bain, nune respira no kontaktu ho ema nia kulit durante uza bé alkalina neebe forte konsidera seguru. Maibe, tan sensibilidade husi ema ida-idak nia kulit la hanesan,

Tabela 6.4 Propriedade bé alkalina neebe forte nian

Propriedade husi bé alkalina neebe forte	
Komposto auxiliar	Potássio Carbonato (K_2CO_3)
Koncentrasaun	99.9% bé, 0.1% K_2CO_3
pH	12.5
Viscosidade dinâmica (<i>Dynamic viscosity</i>)	1.002×10^{-3} kg/m.s
Calor espesífiku (<i>Specific heat</i>)	4.184 J/g°C
Kór	Laiha kór
Aspeito olio nian	Laiha

Tabela 6.5 Efeito bé alkalina neebe forte ba saude

Atividade	Efeito ba saude
Horon	○
Kontaktu	○
Respira	○
Hemu	Δ no ×

○ : La problema Δ : Evita × : Bandu

nunee iritasaun bele akontese ba ema balun. Atu prevene kondisaun nee, ami sugere no rekomenda atu uza mascara no mos fase mos liman no oin depois de uza bé alkalina neebe forte. No mos, hemu bé alkalina neebe forte ne konsidera la seguro, nunee tenke evita. Tan nee, investigasaun no experimentu neebe klean no espesífiku liu tan presiza tebes atu bele hatene didiak impaktu husi bé alkalina neebe forte ba saude ema nian.

6.5 Rezumu

Olio koa nian neebe mak uza durante makinazen hodi resfriamentu konvensional prodús residuo barak no emisaun neebe boot, nunee sempre hamosu diskusaun no debate sobre problema nee ba importansia ambiente nian. Enkuantu, uzo bé alkalina neebe komesa barak ba bei-beik, komesa konsidera ona nuda alternative refrigerante nian neebe la fó impaktu ba ambiente. Rezultadu estudu nee nian hatudu katak avaliasaun komparativa konsidera hanesan solusaun neebe efetivu tebes hodi fó hatudu katak resfriamentu husi bé alkalina neebe forte preferível liu doque resfriamentu konvensional husi olio. Rezultadu husi estudu nee nian mos hatudu katak bé alkalina neebe forte ladun prejudika ambiente no ema nia saude. Maske bé alkalina neebe forte nee konsidera seguru wainhira kona kulit no respira, presiza fó atensaun no tuir rekomendasaun neebe esplika tiha ona iha leten. Aumenta liu tan, investigasaun neebe klean liu presiza atu halao iha futuru hodi nunee bele avalia impaktu bé alkalina neebe forte nian ho espesífiku liu tan. Kompara ba makinazen hodi resfriamentu konvensional, uza bé alkalina neebe forte nudar refrigerante bele hamenus impaktu ba *aquecimento global* kuaze 48%. Tan nee mak ita bele hateten katak *além de* bele evita korosaun, prolonga vida feramenta nian, no hadiak rugosidade peça nian, bé alkalina neebe forte mos amizável ba ambiente.

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Kapítulu (7)

KONKLUZAUN

Iha estudu nee, teknolojia uza bé alkalina neebe forte nudar refrigerante durante makinazen estuda no evalua. Kontrolu mákina produsaun nia frekuensia resonansia uza bé alkalina kahur polimer, halao perfurasaun uza resfriamentu bé neebe forte, no halo makinazen ba mákina neebe immerse tomak iha bé alkalina laran dezenvolve no evalua. Rezultadu evaluasaun no konkluzau husi kapítulu ida-idak estudu nee mak hanesan tuir mai nee.

Kapítulu (3) : Tekniku kontrolu ba kontrola frekuensia resonansia mákina nian dezenvolve atu bele mantein no estabeleze kondisaun koa nian neebe ótimu. Fatór kontrolu nian hanesan kontrola densidade, rigidez no posisaun suporta mákina nian evalua iha estudu nee. Tamba iha kontramedidas barak nebe mak bele uza iha estudu nee, análise CAE nian halao uluk atu hatene kontramedida sira neebe mak adekua uza ba etudu nee no elimina kontramedida sira neebe konsidera la adequa. Depois, rezultadu husi análise CAE nian evalua liu husi experimentu atu hatene kombinasau kontrolu nian neebe ótimu. Kombinasau kontrolu neebe ótimu nee sai hanesan metodu propostado estudu nee nian no sei aplika ba iha prosesu makinazen atu bele avalia ninia efikásia ba rezultadu final koa nian. Haree husi rezultadu experimentu nian iha kapítulu, ita bele hateten no konklui katak,

- (1) Metodu ba kontrola frekuensia resonansia iha mákina produsaun estabeleze tiha ona hodi muda densidade estrutura mákina nian, rigidez no posisaun suporta nian.
- (2) Hodi preenxe bé kahur ho polimer ba iha estrutura mákina nian, bele redús frekuensia resonansia no alkansa *damping ratio* sai boot liu.

- (3) Aplikasaun husi metodu propostado ba iha mákina tornu bankada bele prevene resonansia ho diak, no hadiak peça nia rugosidade sai diak liu tan.

Kapítulu (4) : Iha estudu nee, tecnologia uza refrigerante bé alkalina neebe forte dezenvolve atu redús manas neebe kria iha broca nia tutun durante perfurasaun. Tamba bé geralmente halo feruzu kuaze metal barak industia nian, nunez resisténsia ba korosaun husi materiál sira neebe bai-bain uza ba makinazen halao no avalia. Nunez mos, tan bé alkalina neebe forte sei lakon ninia alkalinidad no sai fali bé bai-bain wainhira rai kleur, ninia mudansa iha pH evalua hosi tau nia iha fati ho temperatura neebe la hanesan. Revela husi testu nee katak bé alkalina neebe forte nia pH tun deit 0.1, 0.3 no 0.5 wainhira tau iha ambiente ho temperatura $12\pm 1^{\circ}\text{C}$, $20\pm 1^{\circ}\text{C}$ no $40\pm 1^{\circ}\text{C}$, konsektivamente. Atu hadiak efisiensia resfriamentu nian, metodu hodi fornese micro-bolha ba bé alkalina laran mos dezenvolve no investiga. Efikásia husi metodu propostado nee evalua liu husi ninia aplikasaun iha experimentu perfurasaun nian. Haree husi rezultadu experimentu nian iha kapítulu nee, ita bele hateten no konklui katak,

- (1) Wainhira aumenta micro-bolha ba iha bé alkalina nia laran, bele prodús efeito resfriamentu forsadu neebe boot ho ninia *coeficiente de transferência de calor* neebe aas tebes ho valor too $2500\text{W/m}^2\text{K}$.
- (2) Uza metodu propostado, temperatura broca nian bele hamenus to'o 70%, peça nia *rugosidade* bele sai diak to'o 30%, no vida broca nian bele prolunga dala 6.5 kompara ba la uza resfriamentu.
- (3) Metodu resfriamentu forsadu uza bé alkalina neebe forte kahur micro-bolha konsidera efetivu ba konserva meio ambiente.

Kapítulu (5) : Iha estudu kapítulu nee nian, mákina nia estrutura tomak, sistema koa nian, ferrameta koa nian, no peça hatama tomak ba bé alkalina neebe forte nia laran, depois evaporasaun bé nian ba resfriamentu forsadu kria ba iha mákina

nia estutura. Atu aumenta efisiensia resfriamentu nian, mirco-bolha aumenta ba bé alkalina laran hodi nune bele hamenus manas iha broca nian tutun diak liu tan. Tamba iha Kapítulu (4), materiais balun deit mak uza ba testu sira nia rezisténsia korosaun nian, iha Kapítulu (5) nee, matriais sira hotu neebe mak uza iha industria no makinazem identifika hotu no halao evaluasaun ba korosaun iha bé alkalina neebe forte nian laran. Efikásia husi metodu imersaun ida nee evalua liu husi experimentu hodi sukat deformasaun térmika no vibraasaun mákina tornu bankada nian. No mos, vida feramenta nian no rugosidade peça nian mos sukat hotu. Haree husi rezultadu experimentu nian iha kapítulu nee, ita bele hateten no konklui katak,

- (1) Valór husi transferensia calor nia koeficiente wainhira uza bé alkalina mak $400 \text{ W/m}^2\text{K}$, no sae ba $2350 \text{ W/m}^2\text{K}$ wainhira opera mákina iha bé alkalina lara ho rotasaun 3600 rpm, no sae tan ba to'o $2550 \text{ W/m}^2\text{K}$ wainhira aumenta ho micro-bolha, nune konsidera nudar resfriamentu neebe excelente.
- (2) Ho kondisaun neebe submerge, feramenta nia temperatura bele redús 60%, dezlokamentu relativa redús kuaze 89%, dezlokamentu angular redús kuaze 86%, vida feramenta nian prolonga kuaze dala 3.6, no rugosidade peça nian sai diak dala 2/3 kompara ba prosesu koa la uza resfriamentu.
- (3) Kuaze materiais sira neebe relasiona ho mákina produsaun, exclui alumínio, la feruzu wainhira enfrente ho bé alkalina neebe forte, tan nee mak bé alkalina neebe forte bele uza ba resfriamentu durante makinazen.

Kapítulu (6) : Iha kapítulu nee, diskusaun impaktu husi utilizasaun bé alkalina neebe forte iha makinazen ba ambiente no saude ema nian halao no avalia. Avaliasaun halao ba prosesu makinazen tolu hanesan fresazen (*milling*) , perfurasaun (*drilling*), no tornu (*turning*), neebe uza bé alkalina neebe forte nudar refrigerante. Emisaun CO_2 nian kalkula bazeia ba kuantidade

energia elétriku neebe konsumo no disposisaun ba residuo olio nian. Atu hatene efikásia makinazen uza bé alkalina diak liu tan, impaktu potensial ba *aquecimento global* evalua no kompara ho makinazen uza resfriamentu konvensional. Diskusaun kona ba impaktu ba ema nia saude mos halao no apresenta hotu. Maske bé alkalina konsidera laiha problema wainhira kona ita nia kulit ou respira, seguransa hanesan uza mascara no fase liman no oin depois de uza bé alkalina neebe forte presiza tebes. No mos investigasaun neebe klean liu iha future presiza tebes atu bele avalia efeitu bé alkalina neebe forte espesífiku liu tan. Rezultadu avaliasaun nian hatudu katak impaktu potensial ba *aquecimento global* redús 48% wainhira halao makinazen uza bé alkalina neebe forte nudar refrigerante kompara ba makinazen uza resfriamentu konvensional. Nunee, ita bele hateten katak bé alkalina neebe forte nee amigável ba ambiente.

Hanesan mensiona iha leten, kontramedida no metodu oi-oin uza bé alkalina neebe forte mak dezenvelope no halao tiha ona diskusaun. Nunee, rezumu no konkluziun husi estudu nee nian mak esplika hanesan tuir mai nee. Primerio, iha Kapítulu (3), kontrolu tekniku neebe simples, fasil atu opera no efetivu dezenvelope atu bele mantein kondisaun koa nian neebe ótimu. Iha estudu ida nee nian, metodu hodi uza bé atu bele kontrola resonansia mákina nian sai hanesan metodu propostado. Maibe tamba uza bé deit ladun efetivu ba muda mákina nia resonansia, nunee, investigasaun halao hodi kombina metodu uza bé nian ho metodu seluk hanesan reforca mákina nia estrutura no muda posisaun suporta mákina nian. Nunee mos, husi rezultadu evaluasaun nian hatudu katak wainhira uza bé, mákina nia resonansia bele hatun maibe ninia amplitudu aumenta boot tan deit, nunee ami aumenta polymer PEO ba bé laran ho objetivu atu hasae bé nia *damping ratio*. Hodi mistura nee, rezultadu hatudu katak amplitudu vibraun nian redús ho efetivu. Aumenta liu tan, atu bele

muda mákina nia resonansia no amplitude vibraun nian ho efetivu, experimentu ida hodi buka kombinasun neebe ótimu iha rotasaun espidulu neebe vário entre fatór control tolu neebe propoin mos halao. Rezultadu husi estudu ida nee hatudu katak uza metodu neebe propoin, mákina nia resonansia bele muda, vibraun bele hamenus, no rugosidade peça nian bele sai diak liu tan sem muda kondisaun koa nian wainhira opera mákina koinside ho frekuensia resonansia mákina nian. Tuir mai, hare husi rezultadu estudu nian katak bé bele muda mákina nia resonansia no hatun vibraun, ami konsidera atu uza bé nudar refrigerante ba makinazen. Nunee, iha Kapítulu (4), ami desenvolve no propoin metode refrigerante foun uza bé alkalina neebe forte ba resfriamentu iha perfurasaun. Tamba bé bai-bain too agora sei evita atu uza iha makinazen ho razaun nia halo feruzu metal sira, nunee ami propoin atu uza mak bé alkalina neebe forte. Rezultadu husi evaluasaun rezisténsia ba korosaun husi materiais sira iha bé alkalina neebe forte nia laran hatudu katak, materiais barak la feruzu wainhira kona bé alkalina, exclui aluminium mesak. Nunee, bele konsidera katak bé alkalina bele uza nudar refrigerante iha makinazen. Atu hasae kapasidade resfriamentu nian, ami aumenta micro-bubble ba bé alkalina laran hodi nunee bele ajuda hasae ninia efeitu evaporasaun. Metodu neebe propostado depois evalua liu husi experimentu perfurasaun nian atu hatene ninia efisiensia. Rezultadu husi estudu ida nee hatudu katak, wainhira uza metodu neebe propoin, manas neebe kria iha broca nian tutun bele hamenus, vida broca nian bele prolonga, no hadiak akurasaun koa nian, neebe rezulta ba iha rugosidade neebe diak. Dala barak, deformasaun térmika neebe rezulta husi manas rolamentus ou movimento husi meza mákina nian fo impaktu negative ba presisaun koa nian. Nunee, iha Kapítulu (5), ami konsidera halao estudu ba hamenus deformasaun térmika iha mákina tornu bankada atu nunee bele hadiak presisaun koa nian hodi

submerge mákina iha bé alkalina neebe forte nia laran. Iha estudu nee, mákina nia estrutura tomak, sistema koa nian, ferameta koa nian, no peça hatama tomak ba bé alkalina neebe forte nia laran. Ho metodu ida nee, efeito resfriamentu husi bé alkalina neebe forte bele suprimi manas neebe rezulta husi rolamentus no parte mákina nian neebe movél. Atu hadiak liu tan efeito resfriamentu nee, micro-bolha forneche ba bé alkalina laran. Efikásia husi metodu nee nian investiga liu husi experiementu hodi sukat deformasaun térmika, mudansa iha temperatura, vida feramenta nian no peça nia rugosidade. Rezultadu husi estudu nee hatudu katak wainhira uza metodu imersaun, deformasaun térmika mákina ida nian bele minimiza, vida feramenta nian bele prolonga, no rugosidade peça nian bele sai diak liu tan. Ikus liu, husi Kapítulu (3), (4) no (5) ita bele hateten katak bé alkalina neebe forte efetivu tebes uza iha makinazen, nune iha Kapítulu (6), avaliasaun ba impaktu husi utilizaun bé alkalina neebe forte durante makinazen ba ambiente no ema nia saude halao no investiga. Iha estudu ida nee, avaliasaun halao hodi kalkula emisaun CO₂ nian durante makinazen no disposisaun ba residuo olio nian. Nune mos, impaktu potensial ba *aquecimento global* mos kalkula hotu no kompara entre makinazen uza resfriamentu bé alkalina ho uza resfriamentu konvensional. Rezultadu husi estudu nee nian hatudu katak bé alkalina neebe forte amizável liu ba ambiente doque resfriamentu konvensional uza olio. No mos, tamba bé alkalina neebe forte 99% bé bai-bain, nune ninia efeito ba ema nia saude konsidera minimu liu. Maibe atensaun hanesan uza mascara no fase liman no oin depois de uza bé alkalina presiza tebes atu nune bele prevene problema neebe ita la espera.

Husi estudu sira neebe halao no esplika tiha ona iha leten, peskiza ida nee, ‘Estudu ba Akurasun neebe Boot no Fabrikasaun neebe Eficiente Utiliza Bé ho Kompostu atu Konserva Ambiente’ konsidera efetivu no aplikável ba iha industria no makinazen.