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論 文 内 容 の 要 旨

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Heat resistant materials such as Ni-base superalloys possess a remarkable capability to hold their properties at elevated temperature conditions. They have been widely used in the hot section components of modern aircraft and power generation gas turbine engines. Especially, turbine blades are one of the most sophisticated components of a gas turbine which convert the thermal energy of combustion gases into mechanical energy. Here, turbine blades are casted as single crystals of Ni-base superalloys due to their higher tolerance to creep and low cycle fatigue exposure. Consequently, single crystal blades exhibit high elastic anisotropy, i.e. their mechanical properties vary with crystallographic orientation.

Single crystal blades are mounted on turbine disks, manufactured from polycrystalline Ni-base superalloys by means of dovetail connections or fir-tree arrangements. Cyclic friction and fretting between the single crystal blade and polycrystalline disk occur due to small oscillating relative displacements during engine operation. Key research focus should be laid on the clarification of crystallographic orientation dependence on high temperature strength of single crystal superalloy. Specifically, the effect of secondary crystallographic orientation of rotor blades with respect to disk contact surface on the mechanical strength and reliability needs to be clarified to achieve further improvements in microstructure design and development of advanced superalloys.

The aim of the present study is to investigate the influence of crystallographic orientation of contacting single crystal vs polycrystalline superalloys used in gas turbine blades and disks, respectively. To achieve this, the role of crystallographic orientation of single crystal rotor blade material (CMSX-2/4) with respect to polycrystalline disk material (IN718) on the cyclic sliding friction (CSF) and fretting fatigue (FF) behavior was investigated at ambient and high temperatures.

First, anisotropic frictional response of contacting superalloys during cyclic sliding under gross slip conditions has been investigated. A significant influence of crystallographic contact plane (crystallographic orientation of sliding surface) and sliding orientation (crystallographic orientation toward the sliding direction) on the coefficient of friction (COF) was found. At room temperature, a normal load depended anisotropic tribological behavior was observed. On a given contact surface orientation, a specific effect of sliding direction was also established. This anisotropic behavior was found to be independent of test temperature. Discussions were made on the above experimental results. It was shown that both the stress and the deformation field near the contact area which are closely influenced by the anisotropic mechanical properties in longitudinal and transverse elastic moduli and in yield strength would play extrinsic roles there.

Second, fretting fatigue tests were carried out under partial slip conditions. Significant differences in fretting fatigue lives with respect to contacting superalloy combinations were found experimentally. These differences were found to be controlled by material dependent tangential force coefficient (TFC) evolution during fretting fatigue loading. A slight improvement of life at 600°C was observed under lower stress amplitudes. Significant changes in the fretting induced subsurface microstructure was characterized using SEM and EBSD techniques. Experimentally measured TFC values were correlated with an analytical approach based on a crack analogue model for the estimation of fretting fatigue crack propagation life. Also, the influence of secondary crystallographic orientation of single crystal superalloy on the TFC, and in turn, the fretting fatigue life was highlighted. Notable differences in fretting contact stress field induced multiple slip systems and crack initiation behavior were observed.

With respect to the above experimental investigations, a mechanism-based numerical model was proposed to analyze the crack initiation stress state due to fretting forces on single crystal slip systems. A competition between resolved shear stresses (shear mode) and resolved normal stresses (opening mode) was found to be controlled by the secondary crystallographic orientation. It was also found by quantitative calculation that the magnitude of TFC at the contact interface and resolved normal stresses on slip planes play a critical role in accelerating crack initiation and propagation with increasing misorientation angle. An equivalent stress range parameter was proposed to incorporate the effect of varying resolved normal stresses with secondary orientation and TFC. The proposed model enables us to estimate the effect of crystallographic orientation on TFC and resolved normal stresses acting on single crystal slip planes. Those estimations are in agreement with the experimental results.

The present experimental and analytical studies on the crystallographic orientation based on the variation of surface tractions and sub-surface stress state under the influence of fretting forces can be useful in fretting fatigue strength design of SC/PC mating parts such as gas turbine SC blades and PC disk assemblies, where friction/fretting induced stress concentration leads to early fatigue crack nucleation and growth, resulting in premature failure of components.