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Temperature and Time Dependent Fatigue Crack Propagation in Ni-base Superalloys

A Thesis
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the Academic Faculty

by

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SUMMARY

Cast Ni-base superalloys are used for turbine blades and vanes in jet engines and gas turbines for power generation, and are subjected to a combination of the fatigue and creep loading along with time variation of the temperature. Under such thermo-mechanical fatigue conditions, fatigue cracks propagate and result in the failure of the components. In this study, the fatigue crack propagation behavior in the cast Ni-base superalloys was investigated focusing on effects of crystal orientation, grain boundary, temperature and creep deformation. To simplify the phenomena, these factors were separately evaluated by using different types of materials and experimental techniques.

The effects of the temperature and crystal orientation were investigated using a single crystal Ni-base superalloy, ICMSX-4. Fatigue crack propagation tests were conducted at room temperature, 450 °C, 700 °C and 900 °C under ΔK increasing conditions using four types of C(T) specimens with different combinations of the crystal orientations in loading and crack propagation directions. The crack was found to propagate in "shearing mode" along crystallographic slip planes at room temperature, whereas a transition from "opening mode" on non-crystallographic planes to the shearing mode occurred as the ΔK level increased at 450 °C and 700 °C. ΔK_I values at which the transition started were higher at 700 °C than at 450 °C. At 900 °C, the crack was found to propagate only in the opening mode. These phenomena were mainly attributed to distinctive temperature dependences of strength of γ matrix and γ' precipitates. Dependence of the transition behavior at 450 °C and 700 °C on the crystal orientation corresponded to that of fatigue crack propagation rates, da/dN, of the shearing mode crack at room temperature, which implied that the driving force of the shearing mode crack strongly affect the transition behavior. Difference in da/dN of the opening mode crack at 450 °C and at 700 °C depended on the crystal orientation in the loading direction. This was attributed to a difference in the configuration of the γ/γ' microstructure with respect to the loading and crack propagation directions.

For the next, the effect of the grain boundary was investigated using "two-dimensional" polycrystalline specimens extracted from a directionally solidified Ni-base superalloy, MGA1400. Fatigue crack propagation tests were conducted at room temperature, 700 °C and 900 °C under ΔK increasing conditions, and the distinctive crack propagation

behavior both in grain interiors and around the grain boundaries was observed in-situ using a high-resolution microscope. The crack propagation behavior in the grain interiors corresponded well with that in the single crystal superalloy. The crack propagated in the shearing mode at room temperature, whereas the crack transitioned from the opening to the shearing mode as the ΔK level increased at 700 °C. At 900 °C, the crack propagated only in the opening mode. The crack propagation in the shearing mode at room temperature and in the high ΔK region at 700 °C was retarded near the grain boundaries, whereas the opening mode crack in the low ΔK region at 700 °C was not observably affected by the grain boundaries. The retardation was attributed to a transition from the shearing to the opening mode induced by the slip plane incompatibility at the grain boundaries. At 900 °C, the crack propagated along high angle grain boundaries with higher da/dN than in the grain interiors. The acceleration was greater at the grain boundaries with larger misorientation, which was attributed to higher grain boundary energy. In high ΔK regions, secondary cracks were nucleated along the high angle grain boundaries ahead of the main crack tip. This was attributed to external stress normal to the grain boundaries and/or the strain incompatibility at the grain boundaries.

Finally, the effect of the creep deformation was investigated using the single crystal Ni-base superalloy, ICMSX-4. Unique creep-fatigue crack propagation tests were conducted at 700 °C and 900 °C by introducing single tension hold into fatigue loading to isolate the effect of the creep. When the tension hold of K_{max} of the prior fatigue loading was applied, a nascent crack was immediately initiated after the restart of the fatigue loading after the tension hold. Subsequently, da/dN rapidly decreased and remained low for a certain distance despite increasing ΔK, after which da/dN rapidly accelerated and converged to that under pure fatigue conditions. This transient crack propagation behavior was attributed to mechanisms based on two different concepts, i.e. residual stress and crack closure. From a viewpoint of the residual stress concept, material degradation at the crack tip was examined using scanning electron microscope (SEM), while the residual stress was quantified by elastic-plastic-creep finite element analysis (FEA) in combination with digital image correlation (DIC) technique. By the SEM observation, depletion of aluminum caused by the oxidation was found near the crack tip, which implied depletion of the γ' precipitates. From the FEA and DIC, the stress around the crack tip was found to be relaxed during the tension hold, and the relaxed stress was found to remain as residual compressive stress during the subsequent fatigue loading after the tension hold. Based on the calculation results of the residual compressive stress, it was possible to predict the retardation of the fatigue crack propagation after the tension hold.

Based on the above investigations, the effects of the crystal orientation, grain boundary, temperature and creep deformation on the fatigue crack propagation in the cast Ni-base superalloys were clarified. These fundamental properties of the fatigue crack may contribute to better understanding and predictions of the crack propagation under more complex conditions, i.e. the thermo-mechanical fatigue, in the actual turbines. Furthermore, the design of the turbine blade that has a better resistance to the fatigue crack propagation was proposed.