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Micro-Scale Damage Mechanisms and Life Prediction Method of the Fourth-Generation Single Crystal Superalloy During Thermal-Mechanical Fatigue

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Abstract
Thermal-mechanical fatigue (TMF) is considered as an important damage mode for single crystal superalloys during real service. It is of great significance to uncover the damage mechanisms of the alloy and establish fatigue life prediction method for enhancing the service reliability of the alloys. Therefore, in this work, the TMF behavior and damage mechanisms of the single crystal superalloy DD91 has been systematically clarified via advanced analysis methods. The results showed that during the TMF deformation, the high-level of stress concentration existed in the vicinity of micro-pores and fatigue cracks, which led to the presence of deformation bands and brought about micro-scale plastic damage to the alloy, thereby affecting the overall fatigue life of the alloy. In addition, the process of γ′-degradation would be accelerated by the introduction of local micro-defects. Under in-phase cycling condition, plenty of superdislocations would shear into the γ′ particles, while for out-of-phase cycling condition, the deformation twins would extend through both γ and γ′ phases. Based on the micro-scale plastic deformation mechanisms, a TMF life prediction method has been proposed through considering both plastic strain energy and elastic strain energy. These findings have provided useful guidance for the safe service of the fourth-generation single crystal superalloys.
Keywords: Fourth-generation single crystal superalloy; Thermal-mechanical fatigue; Local micro-scale damage mechanism; Life prediction method.

Introduction
During the real service of single crystal (SX) turbine blades of aircrafts, they would definitely undergo the cyclic mechanical stress and thermal stress during the stages of starting-up, accelerating, decelerating and shutting-down. Hence the potential failure mode of thermal-mechanical fatigue (TMF), which poses a threat to safe service of SX superalloys, would be introduced [1]. During TMF process, the presence of SF bands is common in the first- and second-generation SX superalloys under out-of-phase (OP) cycling [2]. When it was transformed into in-phase (IP) cycling, the creep damage played a vital role during the TMF deformation [3]. Due to the reduced stacking fault energy of the fourth-generation SX superalloy, it might be thus considered that the primary mechanisms during fatigue deformation would be different. In addition, another pivotal factor which would promote the fatigue failure and might even control the fatigue life is the local micro-defects [4]. Moreover, the elevated service temperature and long-term solution treatments would undoubtedly lead to the formation of excessive oxidation cracks and micro-pores in alloys, respectively. Therefore, the TMF experiments concerning the fourth-generation SX superalloy and the systematic clarification of damage mechanisms based on local micro-defects are in demand.
In the present work, therefore, systematical fatigue experiments had been carried out on a fourth-generation SX superalloy. The fatigue behaviors, overall deformation mechanisms and local micro-scale damage mechanisms during TMF deformation were characterized and clarified. Subsequently, based on the local micro-scale plastic damage mechanisms, a novel TMF life prediction method has been proposed and verified.

Experimental procedure
The fourth-generation SX superalloy DD91 with the excellent high-temperature properties was selected. For TMF experiments, the temperature range was determined ranging from 600 °C to 1000 °C and the frequency of 1/200 Hz were adopted. Both IP- and OP-TMF tests were carried out at different strain amplitudes. In-depth dislocation configurations and deformation mechanisms were analyzed via transmission electron microscopy of Talos F200X and aberration-corrected microscopy.

Result and discussion
1. TMF damage mechanisms based on local defects
As shown in figure 1, during IP-TMF process of the DD91 alloy, the common dislocation configuration was γ/γ′ interfacial dislocation networks. The matrix dislocations would overcome the γ′ particles via the method of Orowan by-passing. While in regions near pores or surface oxidation cracks, plenty of long and curved superdislocations were observed to shear into γ′ phase directly. While for OP-TMF process, the primary deformation mechanism was still Orowan by-passing. Nevertheless, when the local defects were introduced, the local stress concentration had on the one hand facilitate the decomposition of a/2<110> matrix dislocations, hence

a large number of a/6<111> twinning dislocations would be generated in the matrix. On the other hand, the viscous slipping of {111}<112> systems would also be activated. Consequently, the deformation twins would gradually take shape, as shown in figure 1. To sum up, the introduction of local micro-defects would promote the processes of dislocations entering γ′ particles, thereby leading to severe local micro-scale damage to the alloy.

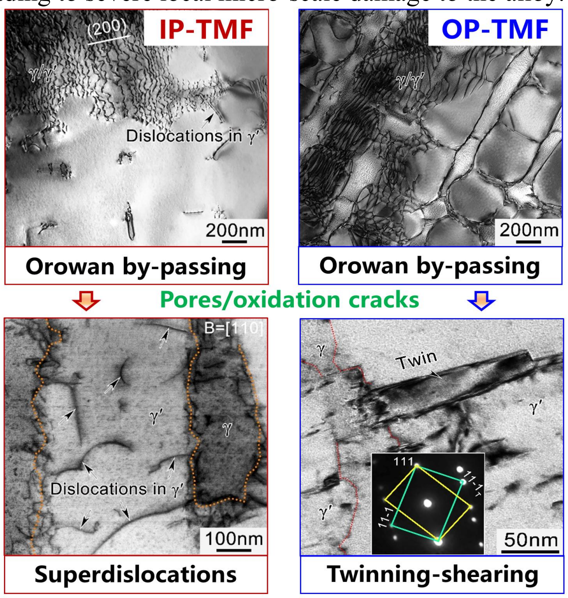

Figure 1. Evolution of dislocation configurations when pores or oxidation cracks were introduced during TMF.

2. Life prediction method based on local defects

In this work, the energy model was used to achieve TMF life prediction. The key point lies in correlate the different energy part to the damage modes. Based on the micro-scale plastic damage mechanisms, the schematic diagram of the total strain energy model is demonstrated in Figure 2. It could be seen that the first part was hysteresis strain energy (Wp), which was reflected by the widespread deformation bands or twinning bands (not much dependent on the local micro-defects). Apart from that, the energy compositions of We^{+} and We^{-} are corresponded to the micro-scale plastic damages generated in tensile and compressive half-cycles, respectively. On this basis, a high-accuracy fatigue life prediction results were obtained through data calculations.

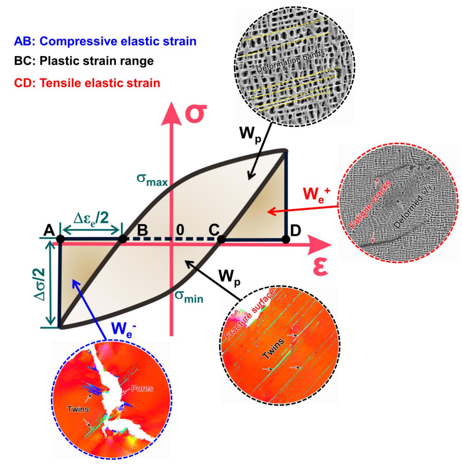

Figure 2. Schematic diagram of the calculation method of total strain energy as well as the relationship between the energy composition and typical deformed microstructures.

Conclusion

During the TMF deformation of fourth-generation SX superalloy, the local micro-scale damage was verified to exist near micro-pores and oxidation crack. The process of γ′-degradation would be accelerated by the introduction of local micro-defects while the entire TMF life would be affected. At high strain amplitude conditions, the alloy was subjected to the severe macroscopic plastic deformation damage. While for low strain range conditions, the alloy sustained oxidation damage and considerable micro-scale plastic deformation damage, which was induced by the excessive superdislocations (IP-TMF) as well as stacking faults and deformation twins (OP-TMF) shearing γ′ precipitates. Based on the micro-scale plastic damage mechanisms, an optimized energy model (total strain energy model) considering both plastic and elastic strain energy had been proposed for fatigue life prediction. In comparison to conventional model, a much higher predicting accuracy was obtained when the optimized model was applied.

References

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