EFFECT OF TENSION HOLD IN CREEP-FATIGUE CRACK PROPAGATION IN NI-BASE SUPERALLOYS: TRANSITION FROM CRACK RETARDATION TO ACCELERATION

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Abstract

Effect of tension hold on crack propagation under subsequent fatigue loading during creep-fatigue crack propagation (CFCP) in single crystal (SC) and wrought Ni-base superalloys was investigated by conducting crack propagation tests with single tension hold applied during pure fatigue loading. Fatigue crack retardation occurred after the tension hold in the SC superalloy, whereas both retardation and acceleration occurred in the wrought superalloy depending on stress intensity factor, K. The retardation and acceleration were attributed to enhanced crack closure due to creep deformation and grain boundary (GB) embrittlement due to oxygen diffusion, respectively. Transition from the retardation to the acceleration was rationalized based on a comparison between sizes of residual compressive stress field and GB embrittlement area.

1. Introduction

Ni-base superalloys are used for gas turbine blades/disks and they are subjected to the creep-fatigue loading due to repeated turbine start-up/shut-down and steady-state operations. CFCP rate (da/dN) in the creep-brittle materials such as the superalloys is considered to be correlated with the ΔK since creep deformation tend to be confined to a small area near the crack tip (small-scale creep condition). However, some studies have reported anomalous crack propagation behavior that cannot be correlated with the ΔK [1,2]. A part of the reason for the insufficient understanding of the CFCP is the complex creep-fatigue interaction. In particular, the effect of creep loading on the crack propagation during subsequent fatigue loading has not been fully understood, which is thus to be clarified in this study. To isolate the effect of the creep loading, crack propagation tests are conducted by applying single tension hold during pure fatigue loading.

2. Results of single crystal superalloy, CMSX-4

C(T) specimens with 1 mm thickness were manufactured from a SC superalloy, CMSX-4. The crack propagation tests were conducted at 900 °C. Loading sequences consisted of (1) pure fatigue loading under ΔK = 20 MPam$^{1/2}$ constant condition, (2) tension hold at K_{max} = 33.3 MPam$^{1/2}$ for 90 or 180 minutes and (3) pure fatigue loading under ΔK increasing condition from 20 MPam$^{1/2}$. Crack length was monitored by the potential drop method and a microscope. No crack propagation was observed during the tension hold.

Fig. 1(a) shows the da/dN as a function of the crack length. In both tests, when the fatigue loading was restarted after the tension hold, the da/dN decreased from that before the tension hold and remained low for certain distances, after which the da/dN increased and converged on that under a pure fatigue condition. The distance of the crack retardation became larger with longer hold times. This crack retardation behavior is quite similar to what is caused by the single overload during fatigue loading. By this analogy, the crack retardation can be attributed to an enhanced crack closure induced by residual creep deformation created during the tension hold. We conducted elastic-plastic-creep FEA in combination with digital image correlation, and revealed strain evolution near the crack tip during the tension hold and resultant residual compressive stress (Fig. 1(b)). Assuming this residual stress works on crack faces during the subsequent fatigue crack propagation, the stress intensity caused by the residual stress was calculated using the weight function method, and the resultant ΔK_{eff} was quantified as per Willenborg et al. [3]. The calculated da/dN fairly agrees with the experimental result (Fig. 1(c)).

3. Results of wrought superalloy, IN718

The C(T) specimens were manufactured from a wrought superalloy, IN718. The crack propagation tests were conducted at 650 °C with the initial ΔK of 10, 12 or 15 MPam$^{1/2}$ and the corresponding K_{max} of 16.7, 20 or 25 MPam$^{1/2}$ at the tension hold. In these tests, the crack propagation occurred during the tension hold.

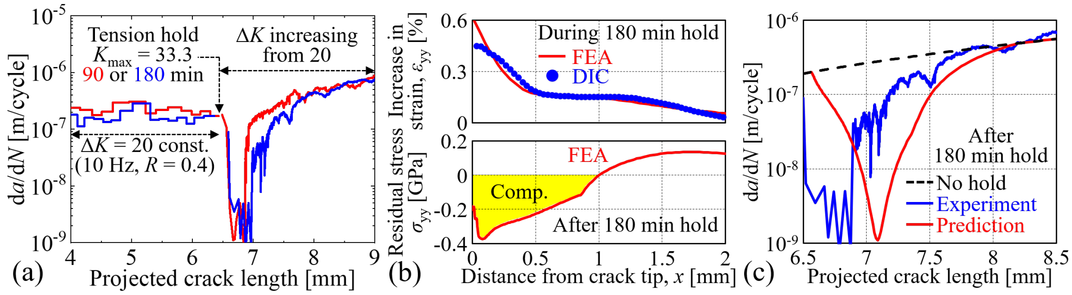

Fig. 1
Results of SC superalloy, CMSX-4.

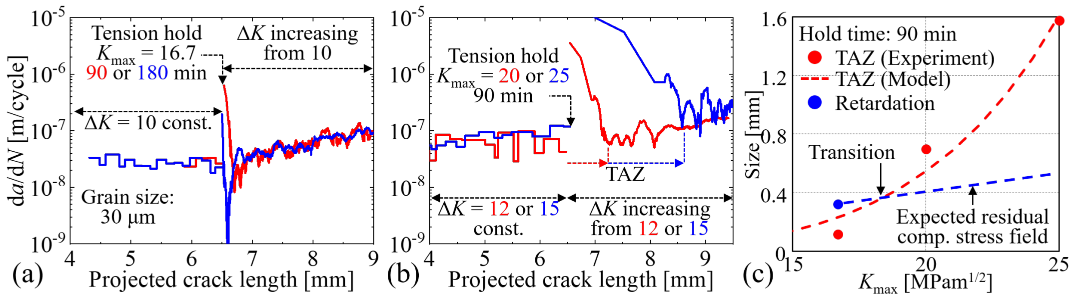

Fig. 2
Results of wrought superalloy, IN718.

When the initial ΔK was 10 MPam$^{1/2}$ (Fig. 2(a)), the crack retardation occurred after the tension hold as similar to the case of the SC superalloy. Throughout the tests, the crack propagated mostly transgranularly. In contrast, when the initial ΔK was 12 or 15 MPam$^{1/2}$ (Fig. 2(b)), the fatigue crack was accelerated along GBs for certain distances after the tension hold. Energy dispersive X-ray spectroscopy analysis on the fracture surfaces revealed high concentrations of oxygen in areas of the crack propagation during the tension hold and the subsequent acceleration. Thus, the crack propagation during these periods were attributed to the stress-assisted oxygen diffusion along GBs and the resultant GB embrittlement during the tension hold. The distance of the crack propagation during the tension hold was fit by the Paris law, and the distance where the acceleration continued was empirically fit by a K-dependent diffusion-based model by partially modifying an original model proposed by Johnson et al. [4]. A summation of these two distances was termed "thermally affected zone (TAZ) size" [4] and plotted as a function of the K in Fig. 2(c). The transition from the retardation to the acceleration is considered to be rationalized based on a simple comparison between sizes of the residual compressive stress field and the TAZ. To demonstrate this hypothesis, we are currently conducting the FEA to calculate the size of the residual compressive stress field which is expected to be as shown in Fig. 2(c). Furthermore, since the TAZ size should strongly depend on a density of the GBs, the transition behavior is considered to depend on the grain size: the retardation becomes easier to occur in larger grain sizes (in the single crystals, ultimately). This point is currently being studied.

The retardation observed in this study has also sometimes reported in the literature [1,2]. However, its mechanics and the transition to the acceleration have not been paid much attention. We believe that this study sheds light on their importance in thoroughly clarifying the CFCP mechanisms not only in the Ni-base superalloys but also in the creep-brittle materials in general.

4. Conclusions

The effect of the tension hold on the subsequent fatigue crack propagation during the CFCP in the Ni-base superalloys was studied via the crack propagation tests with the single tension hold applied during the pure fatigue loading. Both fatigue crack retardation and acceleration occurred after the tension hold depending on the K and grain size. Their mechanisms and the transition between them were described in detail.

References

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