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Finite element analysis and life modeling of a notched superalloy under thermal mechanical fatigue loading

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ABSTRACT

Notched thermal mechanical fatigue (TMF) of a directionally solidified (DS) superalloy applied for turbine blades has been studied experimentally and numerically. The test results, failure analysis, constitutive model and life prediction method of the notched superalloy were presented. Two types of notched specimens with the theory stress concentration (Kt) of 1.5 and 2 were designed. The temperature applied to the specimens ranged from 500 to 1000 °C. With a developed constitutive model for TMF, the cyclic stress and strain responses at the notches were analyzed. The dominated damage area which was defined as 1 mm zone was identified with the basis of the scanning electron microscope (SEM) observations as well as the finite element analysis results. Finally, an averaged stress based life model corresponding to the damage process zone was proposed with good accuracy to prediction TMF lives with or without notches.

1. Introduction

With the gas turbine entry temperature reaching to a level of 1800K, turbine blades with complex cool structure features are widely applied for the high pressure turbine sections of modern aircraft engines and gas turbines. Due to engines startup and shutdown, these components undergo extremely complex TMF loadings in an aggressive oxide and corrosion gas environments [1]. As a result of the non-uniform inlet gas temperature distribution combined with the inner cool air, a dramatic temperature gradient and its transient effect exist and tend to result in various TMF cycles depending on the locations along the turbine blades. Additionally, the stress concentrated regions, including cool holes and shrouds, were inevitably designed in these components for special functions. Stress concentrations involved in these geometry features will further weaken the components, and cause early TMF cracks. Fractographic studies of failed service components revealed cracks initiated from these stress concentrated regions as well as ‘hot spots’ experienced severe thermal gradients, which often lead to premature retirement of the rotor blades [2].

Though various high temperature fatigue studies performed for superalloys, the impact of notch severity under TMF loadings on DS superalloy behavior is still not entirely understood. The effect of notch severity on TMF behaviors has become an important engineering and scientific problem to be solved urgently [2–4]. Kersey et al. [3] studied the thermomechanical fatigue crack growth of single crystal nickel based superalloy PW1484. Laser drilled holes were machined at the gage section of hollow cylinder specimens to simulate the notch severity at cool holes in turbine airfoils. The results showed the lives of TMF specimens with notches were 4 times shorter than the ones on smooth gage section specimens under the same loading conditions. Kupkovits and Neu [2], Fernandez-Zelaia and Neu [4] investigated the influence of notch severity on TMF for a Ni-base superalloy DS CM247LC. Both of the OP and In Phase (IP) loadings were considered. The OP TMF results revealed that fatigue life reduced with notch severity increasing when K_t was not more than 2. However, notched specimens with $K_t = 2$ and $K_t = 3$ followed the same life trend. This indicated that increasing the notch severity from $K_t = 2$ to $K_t = 3$ had no more detriments to OP TMF life. This was different from isothermal conditions [5]. A nonlocal invariant area-averaging method was found to correlate the life covering a wide range of stress concentration factors.

Current industry standards utilize life prediction methods based on either simple elastic analyses or simplified inelasticity models with commercial finite element analysis (FEA) software and thus lack fidelity in the service life predictions [6]. For the purpose of the high reliable application of engineering components, sophisticated stress analysis method as well as life methodology should be developed to consider the effect of stress gradient on TMF. Since the life time prediction of a real component is usually performed by post processing the stresses from a finite element analysis, a robust constitutive model as well as a

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Table 1
Chemical composition in weight percent ratio and heat treatment of DZ125.

C	Cr	Co	W	Mo	Al	Ti	Ta
0.07–0.12	8.4–9.4	9.5–10.5	6.5–7.5	1.5–2.5	4.8–5.4	0.7–1.2	3.5–4.1
B	Hf	Ni	Zr	Si	Fe	Mn	S
0.01–0.02	1.2–1.8	Balance	≤0.08	≤0.15	≤0.3	≤0.15	≤0.01
P	As	Sn	Sb	Pb	Ag	Bi	
≤0.01	≤0.001	≤0.001	≤0.001	≤0.0005	≤0.0005	≤0.00005	

Solution heat treatment: 1180 °C/2 h + 1230 °C/3 h air cooling + 1100 °C/4 h air cooling + 870 °C/20 h air cooling.

corresponding life model is necessary. However, very few researches considered complex loads for anisotropic metal structures. In order to develop the numerical method for gas turbine blades, it is an effective way to investigate the constitutive and life model applied for notch TMF. Thus, the present study will focus on the notch TMF of a DS Ni-based superalloy. The notch TMF experiments and results, fracture mechanism, the developed constitutive model and life prediction method are presented and discussed.

2. Material, specimen and experiment procedure

The nominal chemical composition of the tested DS superalloy, DZ125, in weight percent ratio and heat treatment of the alloy are given in Table 1. The microstructure of DZ125 DS superalloy mainly contains γ/γ' two phases. The size of γ' phase is between approximately 0.4–1.5 μm, and the average size of fine γ' phase in the dendrite regions is about 0.4 μm. The volume fraction of γ' phase is about 65%. The alloy was melted in vacuum induction furnace. Then, the alloy was cast into cylinder and manufactured to smooth specimens. Two notches (i.e. Kt = 1.5 and 2) were further machined according to the geometry profile shown in Fig. 1. The notch root and gage section area were polished to eliminate the machining defects. The direction of the columnar gains was parallel to the loading axis with the maximum angular deviation from the crystal direction limited within 5°.

The tests were carried out on an Instron TMF fatigue testing facility. The specimens were heated through a copper coil and cooled by the compressed air. Three thermocouples were welded on the surface of the specimens. One thermocouple welded on the middle of the gauge section was used to control the temperature. Two thermocouples used to monitor the temperature gradient along the gage of the test specimens were symmetrically welded approximately 10 mm away from the center of the specimen. The heating and cooling rates were 10 °C/s. The maximum temperature ($T_{\max}$) and minimum temperature ($T_{\min}$) were 500 °C and 1000 °C, respectively. The maximum stress ($\sigma_{\max}$), minimum stress ($\sigma_{\min}$) and stress amplitude (σ_a) were designed according to the industrial demands. The tests were conducted by load control. The nominal stress (σ_n) is defined by the average stress in the notch tip section. The fatigue life (N_f) was defined as the number of cycles to final fracture. The nominal stress and fatigue relationships for smooth and notch TMF test conditions were demonstrated in Fig. 2.

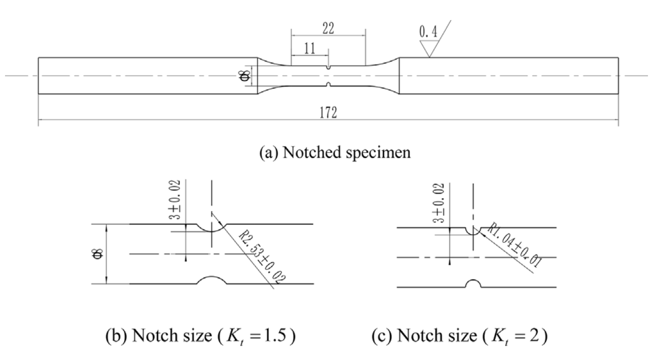

Fig. 1. Sizes of the tested specimens in mm.

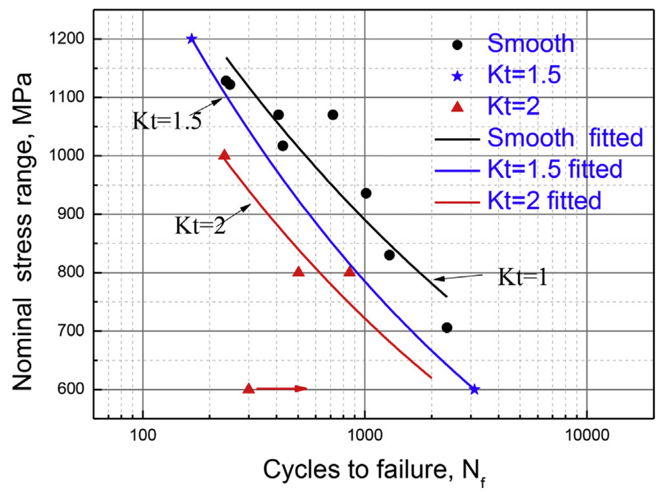

Fig. 2. TMF life results for notched and smooth specimens.

3. Fatigue life and fracture morphology

It is well known that the notch sensitivity of notch of the superalloy is highly dependent on the temperature dependent material properties. For the specimen subjected to TMF, the material properties will be changed with the temperature cycling. Thus, the notch sensitivity is difficult to determine according to the material properties under isothermal fatigue conditions. Fig. 2 showed the fatigue lives of the smooth and notched specimens. The results revealed that TMF lives decreased as the notch severity increases. This was due to a larger stress or strain cycling at the notch tip for specimens with $K_t = 2$. The results agreed with another DS superalloy CM247LC under a similar TMF condition investigated by Patxi and Neu [4]. As it can be seen in Fig. 2, it seems that the slops for notch condition are higher for long life conditions and lower for short life conditions. The effect of notch tends to be more serious in the long life region.

In order to identify the fracture mechanism of the tested specimens, the SEM was conducted on the fracture surfaces. Under smooth TMF loading, it was found that the failures can be due to different mechanism, such as fatigue dominated, fatigue creep dominated and fatigue oxidation dominated. Due to the hot spot in the real component, the OP TMF received more research attentions, and it was mainly a fatigue oxidation interaction procedure for superalloy when the temperature cycles through the brittle and ductile transition temperature for $\alpha - Al_2O_3$. Additionally, the stress concentration in the notches was another factor reducing the fatigue lives. Thus the combination of TMF and notch had a superposition decreasing effect on fatigue lives. Fig. 3