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Thermo-mechanical fatigue damage behavior for Ni-based superalloy under axial-torsional loading

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ABSTRACT

The axial-torsional thermo-mechanical fatigue behavior for Ni-based superalloy GH4169 was investigated experimentally in the temperature interval from 360 °C to 650 °C. The experimental results showed that, in the same von Mises equivalent mechanical strain amplitude condition, the fatigue life can be seriously decreased when the axial mechanical strain and the temperature are in-phase, and the non-proportional loading of mechanical strains can result in the fatigue life to further decrease. The analysis results showed that the fatigue lives depend on the summation of fatigue, creep and oxidation damages. The interaction between dislocations and precipitations can induce the additional hardening under mechanical non-proportional loading, which can obviously increase the fatigue damage. The tensile mean stress and the non-proportional additional hardening can further increase the oxidation damage existed in all loading conditions, which result in the increase of inelastic strain at high temperature. Creep damage behavior on grain boundaries can be shown in the case of the high tensile stress and the high temperature acting simultaneously, and increased with shear stress at the same time. In addition, the tensile stress has an obvious effect on the nucleation of creep cavities contrasted to the shear stress at high temperature, and more creep damage can be caused by the non-proportional additional hardening.

1. Introduction

Most structural components of gas turbine engines are subjected to complicated multiaxial thermo-mechanical loading conditions. Therefore, the investigation on fatigue behavior of materials under such loading conditions is necessary to improve the accuracy of fatigue life prediction for the structural components. Axial-torsional thermo-mechanical fatigue (AT-TMF) tests can simulate the actual combined loading conditions underwent by the structural components of the gas turbine engines during start-up, shut-down and other control operations. The simultaneous change of mechanical loading and temperature may induce the fatigue, creep and oxidation damages at elevated temperature, but the dominant damage mechanism may vary with different materials and loading conditions.

The uniaxial TMF behavior is investigated frequently. The results showed that In-Phase (IP) TMF loading is more damage than Out-of-Phase (OP) loading for some superalloys [1–7]. The creep damage on grain boundaries causes the mainly intergranular fracture under IP loading, which induces the drastic decline of fatigue life [1–5]. The oxidation on grain boundaries also has significant effect on damage under IP loading [6]. Guth et al. [7] investigated the cracks nucleated at carbides and carbide/matrix interfaces during IP loading, and the results showed that the dwell time can increase damage at high temperature. The fatigue damage is dominant under OP loading [1], and it can be increased by high tensile stress at low temperature [2]. In addition, the heavy oxidation was observed in the notched specimens under OP loading [8]. However, for some other superalloys, the fatigue life reduces obviously under OP loading contrasted to that under IP loading [9–12]. Some investigations [10,11] showed that the oxidation damage at the crack tips is dominant under OP loading, and the tensile mean stress exacerbates the action of oxidation. Further, the high tensile stress at low temperature can accelerate the initiation of crack under OP loading.

Afterwards, lots of investigations about life estimation model under uniaxial TMF loading were reported [13–19], and some models which can consider the effect of damage mechanism can obtain satisfactory results [13,14]. The traditional life estimation models have been applied to the life prediction under uniaxial TMF loading, including Manson-Coffin criterion, Ostergren's frequency modified damage function, Smith-Watson-Topper criterion, etc [15,16].

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Until recently, the damage mechanism for the life prediction under multiaxial TMF loading has become the focus of research [20–27], and the von Mises criterion is applicable to the cyclic deformation analysis for some materials under multiaxial TMF loading [23,25]. It was found that the effect of thermal phase angle on fatigue behavior is obvious [21], while the damage mechanisms are uncertain in different multiaxial TMF loading conditions.

Ni-based superalloy is applied widely to the structural components of modern gas turbine engines due to its unique advantage of good mechanical properties, corrosion resistance, excellent weld ability and long-term thermal stability in a wide temperature range [28], so it is important to understand the multiaxial TMF behavior of Ni-based superalloy.

In this paper, the main aim is to identify the existed damage mechanism and the variation of fatigue lives for Ni-based superalloy GH4169 under different AT-TMF loadings. And the influence of involved fatigue, creep and oxidation damages on the lives under different AT-TMF loadings will also be specifically discussed.

2. Experimental details

2.1. Material

In this investigation, the thin-walled tubular specimen with the gauge section thickness of 1 mm of hot-rolled Ni-based superalloy GH4169 is shown in Fig. 1, and the chemical composition of the material is listed in Table 1. The material underwent a heat treatment condition from reference [28]: heating to 970 °C for 1 h, air cooling to 720 °C for 8 h, furnace cooling with cooling rate of 50 °C/h to 620 °C for 8 h, and air cooling to room temperature.

2.2. Axial-torsional thermo-mechanical fatigue testing

AT-TMF tests were carried out on a tension-torsion closed-loop servo hydraulic testing machine, as shown in Fig. 2. The machine utilizes radio-frequency induction heating unit and forced air cooling pipe around the specimen allowing rapid heating and cooling. Temperature was measured on the middle outer surface of the gauge section of thin-walled tubular specimen by a chromel-alumel (type K) thermocouple. Strain was measured by a high temperature tension-torsion extensometer with a gauge length of 25 mm.

In the strain controlled AT-TMF tests, the total axial strain was calculated by adding the thermal strain to the desired mechanical strain ($\varepsilon_t = \varepsilon_m + \varepsilon_{th}$) [21]. Since the shear strain is theoretically unaffected by the variation of temperature [29], the torsional thermal strain compensation is not required. Three loading waveforms, including the axial mechanical strain waveform, the engineering shear strain waveform and the temperature waveform, and two types of phase angle, including the thermal phase angle θ (between the axial mechanical strain and the temperature) and the mechanical phase angle φ (between the axial mechanical strain and the shear strain), need to be controlled. In this investigation, the thermal phase angle is specified as in-phase ($\theta = 0°$) or out-of-phase ($\theta = 180°$). Similarly, the mechanical phase angle is also specified as in-phase ($\varphi = 0°$, that is, proportional loading) or out-of-phase ($\varphi = 90°$, that is, non-proportional loading). Four types of loading condition are listed in Table 2, including mechanical phase angle in-phase and thermal phase angle in-phase (MIPTIP), mechanical phase angle in-phase and thermal phase angle out-of-phase (MIPTOP), mechanical phase angle out-of-phase and thermal phase angle in-phase (MOPTIP), and mechanical phase angle out-of-phase and thermal phase angle out-of-phase (MOPTOP).

The equivalent mechanical strain (ε_{eq}) and the equivalent stress (σ_{eq}) at time t are calculated by the von Mises criterion [30]:

$$\varepsilon_{eq}(t) = \sqrt{[\varepsilon_m(t)]^2 + [\gamma(t)]^2/3} \tag{1}$$

where the ε_m and γ are the axial mechanical strain and the engineering shear strain, respectively.

$$\sigma_{eq}(t) = \sqrt{[\sigma(t)]^2 + 3[\tau(t)]^2} \tag{2}$$

Table 1
Chemical composition of GH4169 superalloy (wt%).

C	Cr	Ni	Co	Mo	Al	Ti	Nb	B
0.07	20.00	53.00	0.70	3.00	0.50	1.00	5.10	0.01
Mg	Mn	Si	P	S	Cu	Ca	Pb	Fe
0.01	0.30	0.32	0.01	0.01	0.28	0.01	0.00	Balance

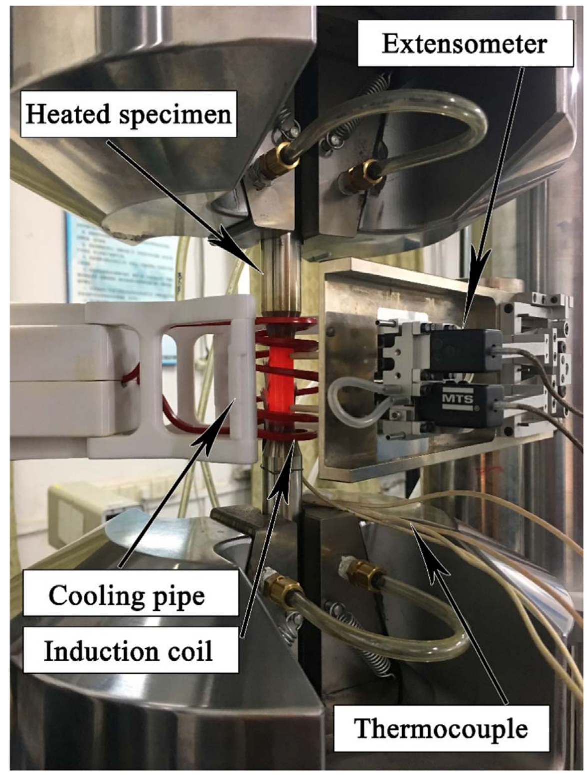

Fig. 2. Heated specimen, induction coil, cooling pipe, thermocouple and extensometer on the tension-torsion testing machine.

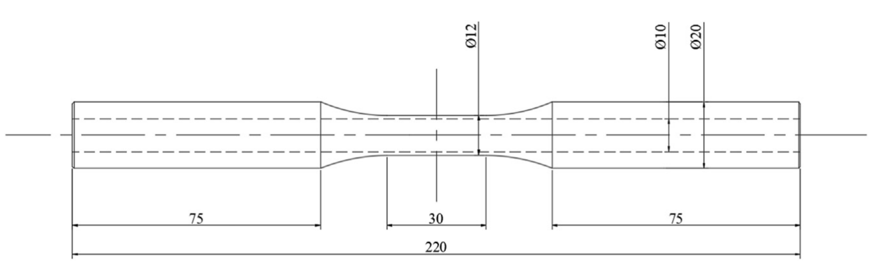

Fig. 1. Specimen geometry used in the AT-TMF tests.