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Creep-fatigue behavior of turbine disc of superalloy GH720Li at 650 °C and probabilistic creep-fatigue modeling

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ABSTRACT

Creep-fatigue experiments have been conducted in nickel-based superalloy GH720Li at an elevated temperature of 650 °C with a stress ratio of 0.1, based on which, different dwell times at the maximum loading were applied to investigate the effect of dwell time on the creep-fatigue behaviors. The tested specimens were cut from the rim region of an actual turbine disc in the hoop direction. The grain size and precipitates of the GH720Li superalloy were examined through scanning electronic microscope (SEM) and energy-dispersive X-ray spectroscopy (EDS) analyses. Experimental data shows creep-fatigue lifetime decreases as the dwell time prolongs. Further, different scattering was observed in the creep-fatigue lifetime at different dwell times. Then a probabilistic model based on the applied mechanical work density (AMWD), with a linear heteroscedastic function that evaluates the non-constant deviation in the creep-fatigue lifetime, was formulated to describe the dependence of creep-fatigue lifetime on the dwell time. Finally, the possible microscopic mechanism of the creep-fatigue behavior has been discussed by SEM with EDS on the fracture surfaces.

1. Introduction

Turbine discs operating at elevated temperatures experience significant cyclic loading spectrum with a dwell time at the maximum load. As a consequence, creep-fatigue is the dominant damaging mode for a turbine disc, which is the life limiting damage to be considered in the design of a turbine disc [1–3]. GH720Li (in Chinese series, similar to Udimet 720Li in the series of U.S.A), a Ni based γ′ strengthened superalloy, is one of the most successful superalloys for turbine discs for a long-term employ at 650–750 °C due to its excellent creep, fatigue, oxidation and corrosion resistance at high temperatures [4,5]. Therefore, the creep-fatigue behavior of turbine discs of superalloy GH720Li is the focus of this investigation by performing creep-fatigue experiments with different dwell times at the maximum load.

Among the commonly used approaches in a creep-fatigue life prediction based on phenomenological framework, damage summation methods [1,6,7], strain range partitioning (SRP) [8], and recently developed energy-based models [9,10] are given preference in the present engineering applications. A general review on these works has been reported in Refs. [11–13]. Although the damage summation rule has been widely used in industry owing to its simplicity, it is somewhat inaccurate [14]. SRP model as one of the commonly used methodologies for creep-fatigue life prediction, however, is not favorable under finite test data and certain experimental conditions, especially under stress control loading [15]. As a consequence, an applied mechanical work density (AMWD) method based on work-energy principle, was recently proposed by Ji et al. [9], and has been utilized to predict the creep-fatigue lifetime of components at loading-controlled tests. In this context, the damage summation and AMWD methods are employed in the present study.

Studies on creep-fatigue properties of nickel-base superalloys reported that the dwell time at the maximum load has a significant influence on the creep-fatigue lifetime [16–18]. However, some issues concerning the creep-fatigue behavior have not been addressed yet. Firstly, the creep-fatigue property of the wrought nickel-base superalloy Udimet 720Li at 700 °C was only investigated under a short dwell time ranging from 1 to 50 s [17]. Nevertheless, the investigation of the effect of a long dwell time (for instance from several to dozens of minutes corresponding to the service dwell time of a turbine disc) on the creep-fatigue

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behavior of the turbine disc of superalloy GH720Li has not been performed. Secondly, some mechanical properties (fatigue crack growth and creep-fatigue) of the test pieces cut from the actual turbine disc are different from the plain specimens due to the different microstructure induced by the manufacturing process [19,20]. Consequently, creep-fatigue experimental data of the specimens from an actual turbine disc should be used to predict "turbine disc component" lifetime. Thirdly, the experimental data, especially the properties associated with mechanical cycling [21,22], such as lifetime, stress, and strain, always exhibit scattering for specimens of the same geometry under the same loading condition due to the random properties involving surface roughness, microscopic aspects etc. [23]. However, few studies have been conducted on the marked dispersion of the creep-fatigue lifetime of the turbine disc of superalloy GH720Li.

In this regard, the present study focuses on the creep-fatigue behaviors of a turbine disc of superalloy GH720Li under different dwell times with specimens from an actual turbine disc at 650 °C corresponding to the turbine disc's working temperature. This paper is constructed as follows: 1) Creep-fatigue experiments were performed to investigate the effect of dwell time at the maximum loading; 2) Fractographic analyses were conducted to survey the characteristics of the fracture surface and the mechanisms of creep-fatigue behaviors of turbine disc of superalloy GH720Li under different dwell times; and 3) Finally probabilistic models were established to describe the scattering in creep-fatigue lifetimes.

2. Experimental details

2.1. Material

The experimental material is from a forged turbine disc made of GH720Li superalloy. The chemical composition is listed in Table 1. To reveal the microstructure of the material from the turbine disc, polished specimens were etched with two etching methods. A reagent of 10 g $CuCl_2$, 100 ml HCl, and 100 ml C_2H_5OH was used for grain boundary observation (etching for 20–40 s). A solution containing 150 ml H_3PO_4, 10 ml H_2SO_4, 15 g Cr_2O_3 was used for electro-polishing to reveal second phases (holding for 3–5 s at 3–4 V). The microstructure of etched surfaces was examined by scanning electron microscope (Hitachi SU3500 SEM). As shown in Fig. 1, the alloy consists of rather uniform grains with an average size of around 12 μm; the coarse blocky primary gamma prime (γ') ranging from 1 to 4 μm in size distributed mainly on or near grain boundaries, while secondary γ' precipitates with a near spherical form and average diameter of about 0.5 μm largely and randomly distributed within the grain. Also, very fine spherical tertiary γ' precipitates with a size less than 50 nm are homogeneously distributed in the γ matrix.

2.2. Specimen geometry

The configuration of round specimen with 25 mm gauge in length and 5 mm in diameter for creep-fatigue test is illustrated in Fig. 2. All the test pieces were cut from the rim region of a turbine disc with an outer diameter of 280 mm and a wall thickness of 34 mm in the hoop direction, as shown in Fig. 3. The turbine disc was solution heat treated at a temperature of 1080–1110 °C, and held for 2–4 h, followed by an oil quenching. Following the solution heat treatment, the disc underwent a stabilization heat treatment at 650 °C for 24 h, followed by an air cool. Finally, the disc was heated to 760 °C for 16 h, followed by an air cool.

To relate the stress levels applied in creep-fatigue tests to the mechanical properties of GH720Li superalloy from the rim region of the turbine disc, the uniaxial tensile test prior to creep-fatigue tests was performed at 650 °C under constant strain rate $\dot{\varepsilon}=0.0001\ s^{-1}$. As shown in Fig. 4, the yield stress $\sigma_s=1162$ MPa, the ultimate stress $\sigma_b=1422$ MPa, and the elongation is 15.7%.

2.3. Procedures for creep-fatigue test

The creep-fatigue tests were conducted on an electric-actuator test machine with 50 kN load cell equipped with a three-zone resistance furnace with the temperature accuracy of ± 2 °C. The test temperature was set at 650 °C, equal to the maximum continuous working temperature for the rim region of the turbine disc. Before loading, the specimens were heated at 650 °C for 0.5 h to ensure the homogeneity of temperature. The temperature of the specimen was monitored by a K-type thermocouple placed in the center of each heating zone. Creep-fatigue tests were performed in stress control mode with the trapezoidal wave with 30 s rise and 30 s fall in laboratory air, as shown in Fig. 5. The stress ratio for the creep-fatigue loading was $R_\sigma=0.1$, i.e. the stress after unloading was maintained at $\sigma_{min}=\sigma_{max}/10$ ($\sigma_{max}=1000$ MPa) in all cases. During the tests different dwell periods Δt (in min) were introduced in order to assess the effect of dwell time on creep-fatigue behavior at the maximum loading, i.e. 3, 12, 30, 45, denoted by CF3, CF12, CF30, and CF45, respectively. In addition, multiple specimens were tested under every creep-fatigue loading level to investigate the scatter of creep-fatigue lifetime. All the experiments were conducted mainly in compliance with ASTM [24]. Meantime, a pure creep test (named CF∞) was conducted at 650 °C with $\sigma_{max}=1000$ MPa. An overview over all the tests is given in Table 2.

3. Results and discussions

3.1. Mechanical behavior

Fig. 6 shows the curve of strain history with different dwell times at 650 °C. As is defined in Ref. [1], the envelope strain is the maximum strain obtained at each cycle, and then the envelope curves of creep-fatigue with varying dwell times are shown in Fig. 7. The envelope curve for CF45 coincides with pure creep (CF∞) curve, which indicates that creep deformation is dominant under this loading. Meanwhile, an interesting finding is that the evolutions of the envelope strain reveal three different stages, similar to pure creep behavior; i.e. a decelerating stage (primary stage), a steady-state stage (secondary stage, described by the minimum envelope creep rate $\dot{\varepsilon}_{e,\min}$, equal to the minimum slope of the curve), and an accelerating stage (third stage).

Table 1
Chemical content of GH720Li (wt%).

Ni	C	Si	Mn	Cr	Co	Mo	Al
Balance	0.01–0.02	≤ 0.2	≤ 0.15	15.5–16.5	14–15.5	2.75–3.25	2.25–2.75
Fe	B	Zr	P	Cu	Ti	W	
≤ 0.05	0.01–0.02	0.025–0.05	≤ 0.015	≤ 0.01	4.75–5.25	1–1.5	