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Influence of dwell time on the creep–fatigue behavior of a directionally solidified Ni-based superalloy DZ445 at 850 °C

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ABSTRACT

Total strain-controlled creep-fatigue tests were performed for a directionally solidified Ni-based superalloy at 850 °C in air. Dwell times of 0, 1, 2, 3, 5, and 8 min were introduced at the tensile peak for each cycle. The results demonstrated that the fatigue life firstly decreased and then slightly increased with increasing dwell time. The fatigue life showed a minimum at a dwell time of 3 min. The initial softening rate was faster than the subsequent softening rate when dwell times of 1 and 2 min were used compared to the case with no dwell time. A compressive mean stress was produced by stress relaxation in the tensile dwell period. The reduction in the fatigue life was caused by a mixture of fatigue and creep deformation behaviors. However, the initial softening rate increased and a small amount of subsequent hardening occurred when 5 and 8 min of dwell times were applied. The higher compressive mean stress and a slight increase in the fatigue life for these samples of 5 and 8 min dwell times were attributed to a mixture of creep and plastic deformation. The change in the fatigue life with increasing dwell time was explained on the basis of the mechanical response, deformation mechanism, and fracture mechanism of the DZ445 superalloy.

1. Introduction

Nickel-based superalloys have been widely used in turbine blades and guide vanes of modern gas turbines, and need to withstand complex stress conditions, such as centrifugal, vibration, and thermal stresses during operation [1]. There exist many previous studies regarding pure low-cycle fatigue and pure creep deformation at elevated temperatures [2–7]. However, the turbine applications are subjected to the compound damage of fatigue, creep, and oxidation during start-up, operation, and shut-down processes. Therefore, the creep–fatigue behavior of superalloys has become a research hotspot in recent years [8–12].

Extensive studies of superalloys have been performed to investigate the influence of temperature [8,13], strain range [14,15], and waveform [16–18] on the creep–fatigue behavior. In general, the fatigue life is reduced with increasing temperature and strain range. However, to date, there is little research regarding the influence of dwell time on the creep–fatigue mechanical response, deformation mechanism, and fracture mechanism for directionally solidified Ni-based superalloy.

The superalloy DZ445 chosen for this study is a first-generation directionally solidified Ni-based superalloy used for new heavy-duty gas turbine blades [19,20]. In this investigation, tests were performed to study the influence of dwell time on the creep–fatigue behavior of this superalloy at 850 °C. Firstly, the influence of dwell time on the mechanical response was studied. This differed from the mechanical response of other superalloys. Secondly, the influences of dwell time on the stress relaxation behavior in the tensile dwell period and the mean stress with cycles were quantitatively analyzed, while previous papers only published qualitative results. Finally, we investigated the influence of dwell time on the deformation and fracture mechanism, which have not been systematically studied in the past. The change of fatigue life with dwell time was explained considering the above three factors.

2. Experimental

The nominal composition of the superalloy DZ445 (wt%) is as follows: 0.072 C, 13.10 Cr, 9.99 Co, 4.53 W, 1.75 Mo, 4.07 Al, 2.38 Ti, 4.80 Ta, 0.024 B, and the balance Ni. Master alloy ingots with a diameter in 80 mm were produced by vacuum-induction melting. This superalloy was directionally solidified into bars of Φ16 mm × 21 mm in size at a withdrawal speed of 7 mm/min. The bars were subjected to a heat treatment of 1210 ± 10 °C/2 h/AC + 1080 ± 10 °C/3 h/AC + 850 ± 10 °C/24 h/AC (AC: air cooling). The microstructure of such samples were shown in our previous paper [21]. The creep–fatigue specimens were machined to a gauge size of Φ8.5 mm × 26 mm, which

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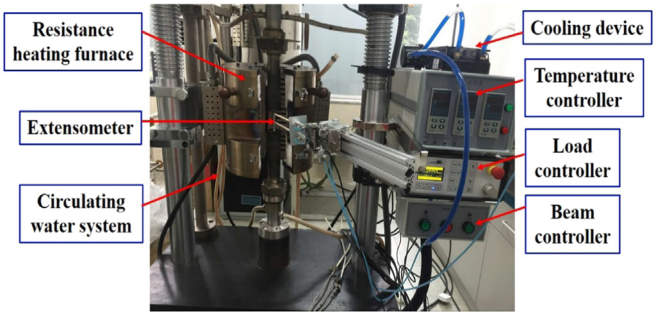

Fig. 1. Experimental setup for the creep-fatigue experiments.

was then polished using silicon carbide abrasive paper with mesh sizes of 400#, 600#, 800#, 1200#, 1500#, and 2000# to remove any surface-machining defects.

All fully reversed uniaxial strain-controlled low-cycle fatigue tests with and without a dwell time were conducted in air at 850 °C. The temperature along the gauge length was controlled with error of less than ± 2 °C. The experimental setup is shown in Fig. 1. The axial strain was measured with a rail-type extensometer with a gauge length of 25 mm directly attached to the gauge section. As shown in Fig. 2, a cyclic frequency of 0.08 Hz was used for the pure low-cycle fatigue, and dwell times of 1, 2, 3, 5, and 8 min were used at the maximum tensile strain of each cycle to form a trapezoidal waveform. The strain rate was 0.5%/s during the loading and unloading ramps. The strain ratio, R, was − 1($R = \varepsilon_{min}/\varepsilon_{max}$). Three specimens were prepared for each condition and all specimens were tested until failure (The definition of failure is as complete specimen separation).

The fracture surface and profile were observed by scanning electron microscopy (SEM) and optical microscopy (OM). Transmission electron microscopy (TEM) foils were cut from positions 3 mm away from the fracture surface. The polished foils were thinned using twin jet polishing with an electrolyte of 5 vol% perchloric acid and 95 vol% methanol at − 30 °C and 40 mA. Finally, bright field images using a JEM-2010F TEM were taken to observe the dislocation structures.

3. Results and discussion

3.1. Fatigue life

Previously, the fatigue life of the directionally solidified Ni-based superalloys MAR M002 and Rene 80 was shown to be reduced when a dwell time was applied during testing, which was attributed to accumulated inelastic strain energy [22,23]. Fig. 3 shows the relationship between the dwell time and fatigue life of DZ445 at 850 °C. The fatigue life initially decreased drastically with increasing dwell time, while the fatigue life increased slightly when the dwell time exceeded 3 min; the minimum occurred at a dwell time of 3 min. In order to quantify the

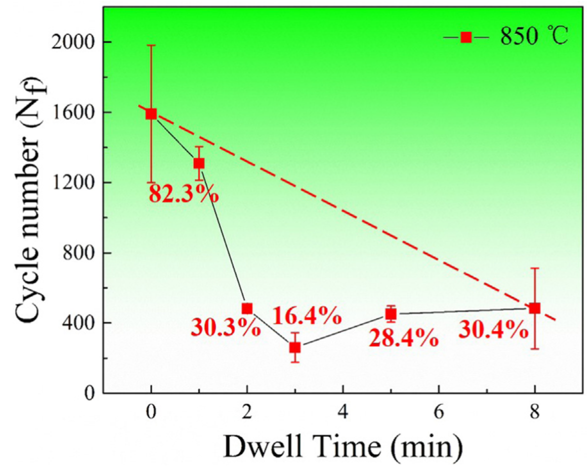

Fig. 3. Relationship between the dwell time and fatigue life (number of cycles to fracture) for the directionally solidified Ni-based superalloy DZ445 samples.

influence of dwell time on the fatigue life, the data were normalized to the value of the sample without a dwell time (shown by the red values in Fig. 3). The fatigue life values for 2 and 5 min dwell times were similar for GH4169 [15] at 650 °C and DZ125 [24] at 850 °C. This indicates that the fatigue life does not show a monotonically decreasing trend with increasing dwell time, where the fatigue life can even be extended for longer dwell times. The change in the fatigue life is closely related to the mechanical response, deformation mechanism, and fracture mechanism, which will be discussed in more detail in the following sections.

3.2. Mechanical response

3.2.1. Cyclic stress response

Fig. 4 shows the maximum tensile stress per cycle for samples with an applied dwell time. The cyclic softening/hardening properties of the superalloys are shown by variations in the maximum tensile stress as a function of cycle number. It can be seen that the initial softening rate was faster than the subsequent softening rate for 1 and 2 min dwell times compared to the case with no dwell time. For the 5 and 8 min dwell times, the initial softening rate increased and subsequently, slight hardening occurred. A large amount of subsequent hardening occurred after the initial softening for 3 min dwell times. The cyclic stress response of DZ445 differs from that of other alloys during creep–fatigue deformation. For example, 12Cr-ODS steels [25] and MAR-M247 superalloy [26] showed cyclic-hardening/softening and continuous softening, respectively. In general, the hardening behavior may be attributed to dislocation–dislocation and dislocation–precipitate interactions. High densities of dislocations and their interactions result in the formation of dislocation jogs and pileups, as well as dislocation tangles

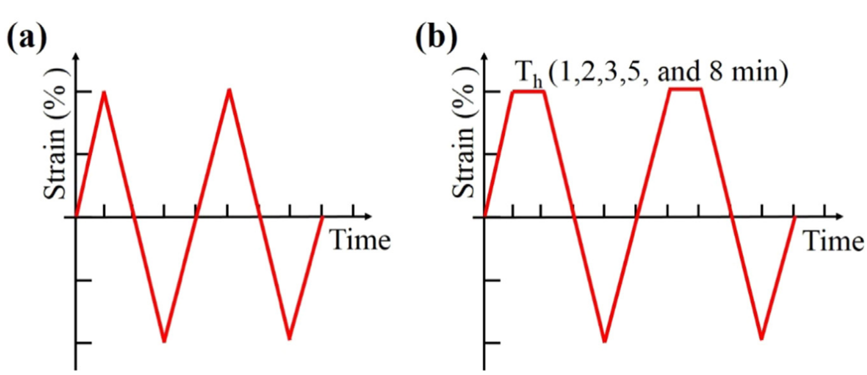

Fig. 2. Waveforms of the total strain-controlled creep–fatigue tests (a) without dwell time (b) with dwell time.