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The effects of inhomogeneous microstructure and loading waveform on creep-fatigue behaviour in a forged and precipitation hardened nickel-based superalloy

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ABSTRACT

The aim of the present paper is to identify the effects of sampling locations and loading waveforms on high-temperature low-cycle fatigue (HTLCF) and creep-fatigue life of a forged and precipitation hardened nickel-based GH4169 superalloy. Both the deformation and failure mechanisms are considered here. It has been revealed that HTLCF and creep-fatigue life of specimens were influenced by inhomogeneous microstructures at different locations. Compared with the HTLCF tests, the presence of dwell times in creep-fatigue tests tended to reduce number of cycles to failure. Intergranular damage was observed at both crack initiation and propagation stages. For the dwell times under tension, the intergranular damage was mainly associated with precipitate-assist voids. However, oxidation accounted for the presence of intergranular damage for the dwell times under compression.

1. Introduction

The nickel-based superalloy GH4169 has been found to exhibit good mechanical properties and corrosion resistance, excellent weld ability as well as long-term thermal stability [1]. Both the microstructures and mechanical properties of GH4169 are similar to those of Inconel 718 [1,2]. These two types of superalloys are widely used for rotating components such as discs and spacers of gas turbine engines [1,3]. Such components operate at high temperatures ranging from 300 °C up to 650 °C where fatigue, creep and oxidation processes limit their service lifetimes [3–5]. Depending on the specific service condition of the component, the failure mode may change drastically from transgranular to intergranular due to the cumulative effects of microstructures, creep and oxidation [3,6,7]. Previous studies [4,6,8–12] showed that the presence of creep dwells in creep-fatigue tests led to a reduced number of cycles to failure when compared with that of pure fatigue tests. In addition, oxidation effects need to be considered when interpreting some creep-fatigue test data, in particular for certain loading waveforms [7,13,14].

Material properties required to carry out the high temperature structural integrity assessment are derived from high-temperature low-cycle fatigue (HTLCF) and creep-fatigue tests [15]. The dwell periods of creep-fatigue tests under strain-controlled conditions are usually introduced at either the maximum tensile or compressive strain or both of them. Both the HTLCF and creep-fatigue lifetimes depend not only on temperatures but also on loading waveforms [8]. Brinkman et al. [16,17] reported that both the HTLCF and creep-fatigue lifetimes decreased with the increasing temperatures for Inconel 718 and several high temperature structural materials. Wei and Yang [4] carried out both the HTLCF and creep-fatigue tests on cast GH4169 superalloy at a temperature of 650 °C. It was found that the presence of dwell periods in creep-fatigue tests caused a reduction of up to 50% in fatigue lifetime and the reduced magnitudes varied with the total strain ranges. Typical loading waveform variables in a fully reversed test ($R_\varepsilon = -1$) are the total strain range, $\Delta\varepsilon_t$, the dwell time at the maximum tensile strain, t_d, and that at the maximum compressive strain, t_e. It has been found that the effect of creep dwells on fatigue lifetimes of high-temperature structural materials including GH4169 [4], Inconel 718 [16,17], M963 nickel-based superalloys [18], modified 9Cr-1Mo steel [17], 304 and 316 stainless steels [17], depended on those three loading waveform variables.

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Both the HTLCF and creep-fatigue behaviours of nickel-based superalloys could be affected by their microstructures [3,19,20]. Prasad et al. [19] carried out both the HTLCF and creep-fatigue tests at 650 °C on a forged disc of Inconel 718. Test specimens were extracted from three locations namely, rim, hub and bore regions of the disc. The bore accumulated less intergranular damage per cycle and thus had a higher number of cycles to failure when compared with those for the hub and rim [19]. This seems to be related with the different grain size and grain structure for the bore. Prasad et al. [19] reported that the average grain size for both the rim and hub was ~20 μm, but an intermixed grain structure was found for the bore with the grain size of ~10 μm for the finer grains and ~25 μm for the coarser grains. In addition, Khajaet al. [20] observed that room temperature tensile and cyclic behaviours of the forged and precipitation hardened Inconel 718 disc varied with the sampling location due to microstructural inhomogeneity. However, it is still not clear whether the HTLCF and creep-fatigue behaviours of the forged and precipitation hardened nickel-based superalloy are also sampling location dependent.

In the present paper, we report an experimental study of the effects of inhomogeneous microstructure and loading waveform on the HTLCF and creep-fatigue behaviours of a forged and precipitation hardened GH4169 superalloy at 650 °C. Measurements of grain size, micro-hardness, the numbers of intergranular δ phase and Σ3 coincident site lattice (CSL) boundaries were carried out on the specimens that had been extracted from different locations of the GH4169 disc. Various combinations of $\Delta\varepsilon_t$, t_d and t_e were selected to study the effect of the loading waveform. Finally, the deformation and damage mechanisms of GH4169 superalloy under HTLCF and creep-fatigue conditions were discussed with respect to the microstructure and fractography examinations.

2. Experimental

2.1. Material and heat treatment

The GH4169 superalloy, removed from a radial forging formed disc with a diameter of 180 mm, was provided by Fushun Special Steel Co., Ltd. The disc was manufactured by the following procedures: dual smelting, high temperature diffusion annealing, cogging, and then finished with radial forging process. Dual smelting included vacuum induction and the following vacuum self-consuming arc melting. High temperature diffusion annealing included following stages: first heating at 1160 °C for 24 h, second heating at 1190 °C for 72 h, and finally air cooling to room temperature. After ingoting scalping and confirming flawless surface, the final forging process was carried out by a hydraulic radial forging machine. Cylindrical bars with a diameter of 14 mm and a length of 100 mm were extracted by EDM wire-cut machine from three pre-defined locations of the forged disc: (a) outermost, (b) middle, and (c) innermost, as schematically shown in Fig. 1a. All three groups of cylindrical bars were then subjected to the same heat treatment that included the following steps: solid solution at 960 °C for 1 h, air cooling, first-stage aging at 720 °C for 8 h, cooling at 50 °C /h to 620 °C, second-stage aging at 620 °C for 8 h, and finally air cooling to the room temperature. This heat treatment procedure was selected to obtain the optimised precipitation hardened microstructure and the heat treatment parameters can be considered as the common industrial practice for GH4169 superalloy [21]. A similar heat treatment procedure had been applied previously to Inconel 718 superalloys to improve their creep-fatigue performance of [16,20,22]. The nominal chemical composition of GH4169 superalloy is given in Table 1, which is similar to that of Inconel 718 [16,20,22].

2.2. HTLCF and creep-fatigue testing

Uniaxial round bar test specimens with a gauge length of 8 mm and a gauge diameter of 6 mm were machined out of the heat treated cylindrical bars. Detailed dimensions of the test specimens are shown in Fig. 2. Finally, the gauge portion of each specimen was polished down to 1 μm diamond. Both the HTLCF and creep-fatigue tests were carried out on an Instron 8500 servo-hydraulic machine by using strain-controlled triangular and trapezoidal loading waveforms. All tests were conducted at a temperature of 650 °C ± 2 °C in air environment under fully reversed loading condition ($R_\varepsilon = -1$) with a constant strain rate of 0.4%/s. A high temperature extensometer, attached to the gauge-length area of the specimen, was used to monitor the axial strain during the strain-controlled tests. The end-of-test was defined to be the 40% decrease in the cyclic maximum tensile stress, conforming to ASTM E-2714-13 standard [23].

Table 2 summarises test parameters for each specimen and the characteristic locations of the disc where each specimen was extracted. Specimens F-1 to F-10 were subjected to HTLCF tests with $\Delta\varepsilon_t$ ranging from 1.0% to 2.0%, Table 2. Specimens F-1 to F-4 were extracted from the outermost location of the disc, specimens F-5 to F-8 were from the middle location, and specimens F-9 and F-10 were from the innermost location of the disc, Table 2. They were used to investigate the effects of both the total strain range and sampling location on high temperature low cycle fatigue (HTLCF) behaviour. Specimens CF-1 to CF-8 were extracted from the outermost location of the disc and then tested under creep-fatigue conditions, Table 2. These specimens were compared with pure fatigue loading specimens F-1 to F-4 to study the effects of creep dwells. Within this group, specimens CF-1, CF-3, CF-5 and CF-7 were tested with creep dwells at the maximum tensile strain ($t_d = 300$ s) and specimens CF-2, CF-4, CF-6 and CF-8 were tested with creep dwells at the maximum compressive strain ($t_e = 300$ s). Specimens CF-7 to CF-12 were creep-fatigue tested with $\Delta\varepsilon_t = 2.0\%$, Table 2, and they were used to examine the effect of sampling location on creep-fatigue behaviour of GH4169 superalloy. The following abbreviations are used throughout the paper: (i) 0–0 stands for HTLCF test without creep dwells, (ii) 300–0 stands for creep-fatigue test with the creep dwells applied at the maximum tensile strain, and (iii) 0–300 stands for creep-fatigue test with the creep dwells applied at the maximum compressive strain.

2.3. Microstructure evaluation techniques

Prior to the mechanical tests, three cubic shaped specimens (8 mm × 8 mm × 8 mm) were extracted from the characteristic locations (outermost, middle and innermost) of the forged and precipitation hardened GH4169 superalloy disc, Fig. 1a. These specimens were used to examine the microstructure inhomogeneity by using both optical and scanning electron microscopy (OM and SEM). Specimens were metallographically polished down to 1 μm diamond finish and then etched using the chemical solution that contained 50 ml HCl, 40 ml H_2O, 10 ml HNO_3 and 2.5 g $CuCl_2$ to reveal the microstructure features. Grain size measurements were carried out using the linear intercept method, conforming to ASTM E-112 standard [24]. Hitachi S-4800 SEM was used to examine the distributions of intergranular δ phase of the precipitation hardened GH4169 superalloy specimens. The area fraction of the intergranular δ phase was measured by Image-Pro Plus software on the SEM images with a total scanning area of 600 μm × 400 μm. This method was adopted by Li et al. [25] to quantify the distribution of intergranular δ phase. Micro-hardness measurements were made on each specimen that had been extracted from the outermost, middle and innermost locations of the disc. CamScan Apollo