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ScienceDirect

Scripta Materialia 61 (2009) 1105–1108

Scripta MATERIALIA

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Crack appearance of single-crystal nickel-base superalloys after thermomechanical fatigue failure

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Received 2 August 2009; revised 24 August 2009; accepted 26 August 2009
Available online 2 September 2009

Thermomechanical fatigue (TMF) testing was conducted on single-crystal nickel-base superalloys. Distinct cracking behaviors were found to occur under different cycling conditions. A crack generally initiates from the specimen surface. For the TMF cycling without a compressive hold time, the crack initially grows perpendicular to the stress axis and then propagates along a twin plate. For the TMF cycling with a compressive hold time, the main crack propagates directly along a twin plate until final failure.

Keywords: Nickel alloys; Fatigue; Scanning electron microscopy (SEM); Microstructure

Single-crystal nickel-base superalloys have been extensively used in high-temperature applications over the past three decades [1,2]. Since many components for high-temperature applications are subjected to alternate loading and unloading with cycling of temperature and stress, thermomechanical fatigue (TMF) of superalloys has attracted much attention [3–7]. As part of our work on the practical superalloys in the High Temperature Materials 21 Project at NIMS (National Institute for Materials Science, Japan) [8], we have studied the fatigue of several superalloys and its related mechanisms [3,4,9,10]. It has been pointed out that during TMF testing the hold time at the maximum compressive strain can cause a decrease in the fatigue life of superalloys [3,4]. So far, however, the effect of the TMF cycling conditions on the crack appearance of superalloys after failure has not been studied systematically. The present work focuses on the general description of the appearance of a distinct crack in superalloys after different TMF tests (with or without a compressive strain hold time).

Single-crystal nickel-base superalloys developed at NIMS were used for the thermomechanical fatigue tests (Table 1). Their composition and the related heat treatment have been described in our previous publications [3,4,9,10]. Solid cylindrical specimens 6 mm in diameter and 15 mm in length were used. The TMF tests were performed by induction heating in air on a fatigue testing machine with hydraulic servo system (MTS type 810). The temperatures were varied linearly between 400 and 900 °C, which corresponded to the points of the maximum tensile and compressive stresses, respectively (i.e. out-of-phase). For the TMF test without a hold time, a triangular waveform was adopted with a frequency of 6 min per cycle, as shown in Figure 1(a). The strain was varied linearly in a total range of $\varepsilon_t = 1.28\%$ ($\pm 0.64\%$), or slightly beyond this range. For the TMF test with a hold time, a trapezoidal wave was adopted, some details of which are given in Figure 1(b). Three hold times, i.e. $t_h = 10$ min, $t_h = 1$ h and $t_h = 10$ h, were adopted at the maximum testing temperature (900 °C) with a compressive strain. A schematic illustration of the stress–strain relationship is given in Figure 1(c) for the test without a compressive hold time and in Figure 1(d) for the test with a compressive hold time.

After TMF failure, most observations on the tested specimens were made using a JEOL JSM-6060 scanning electron microscope or analyzed by optical microscopy.

Figure 1(c) and (d) shows schematic illustrations of the stress–strain relationship during TMF cycling. The process is straightforward for the test without a hold time during compression (Fig. 1(c)). In contrast, the TMF cycling behavior is complicated for the test with

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1359-6462/$ - see front matter
doi:10.1016/j.scriptamat.2009.08.036

Table 1. TMF tests of several superalloys under different conditions.

Superalloys	TMF tests	Fractographs
TMS-82	$t_h = 0$, $\varepsilon_t = 1.01\%$, $N_f = 1994$	Figure 3(a)
TMS-82	$t_h = 0$, $\varepsilon_t = 1.28\%$, $N_f = 710$	Figure 3(a)
TMS-75	$t_h = 0$, $\varepsilon_t = 1.01\%$, $N_f = 985$	Figure 3(c)
TMS-6	$t_h = 1$ h, $\varepsilon_t = 1.28\%$, $N_f = 63$	Figure 3(b)
TMS-138++B	$t_h = 1$ h, $\varepsilon_t = 1.28\%$, $N_f = 86$	Figure 3(b)
TMS-186	$t_h = 1$ h, $\varepsilon_t = 1.28\%$, $N_f = 114$	Figure 3(b)
TMS-82	$t_h = 1$ h, $\varepsilon_t = 1.28\%$, $N_f = 70$	Figure 3(b)
TMS-82	$t_h = 10$ hs, $\varepsilon_t = 1.28\%$, $N_f = 29$	Figure 3(b)
TMS-113	$t_h = 10$ min, $\varepsilon_t = 1.28\%$, $N_f = 74$	Figure 3(d)
TMS-82	$t_h = 10$ min, $\varepsilon_t = 1.28\%$, $N_f = 308$	Figure 3(d)
TMS-75	$t_h = 10$ hs, $\varepsilon_t = 1.28\%$, $N_f = 22$	Figure 3(d)

t_h, compressive hold time; ε_t, total strain; N_f, number of TMF cycles to rupture.

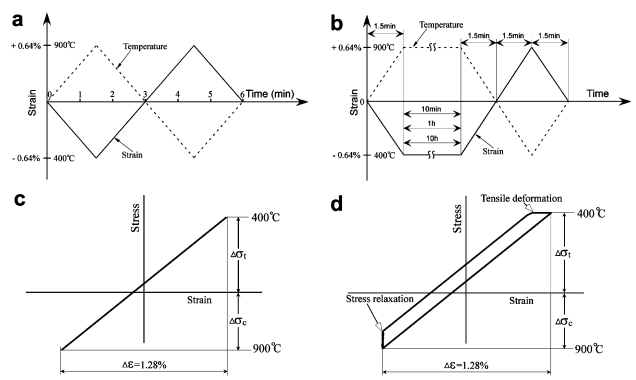

Figure 1. Schematic illustration of dependence of strain and temperature on time during TMF cycling. (a and c) Without a compressive hold time; (b and d) with a compressive hold time in the range of 10 min to 10 h.

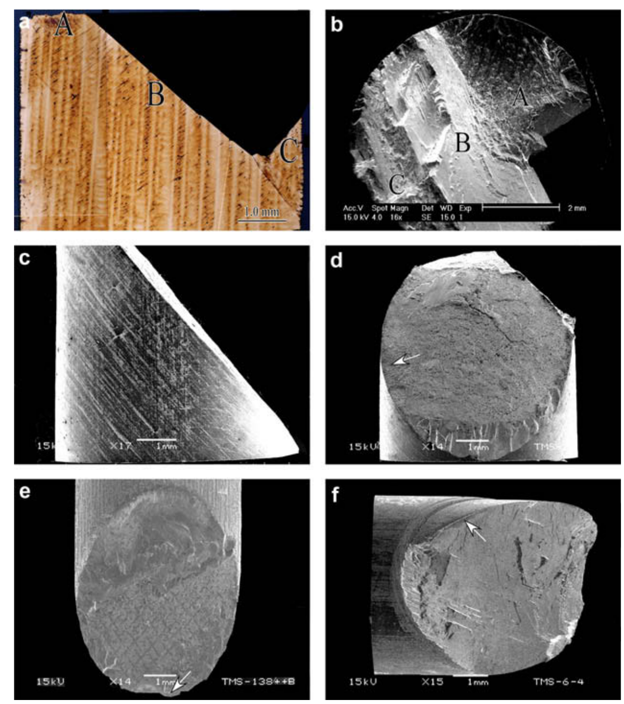

Figure 2. Crack appearance of several single-crystal nickel-base superalloys after thermomechanical fatigue tests. (a and b) TMS-75, $t_h = 0$; (c and d) TMS-82, $t_h = 1$ h; (e) TMS-138++B, $t_h = 1$ h; (f) TMS-6, $t_h = 1$ h.

a hold time during compression (Fig. 1(d)). During the period of compressive holding at 900 °C, there exists stress relaxation. At the top of the curve, there is tensile plastic deformation at 400 °C. The mechanism for the stress relaxation is quite complicated and the stress relaxation proceeds via different mechanisms at different cycling stages. The plastic deformation at the tensile stage is related to the generation of dislocations or deformation twins [10].

Figure 2 presents the crack morphologies of superalloys after TMF cycling failure. Though the fracture is complicated for every case, the crack morphologies simply show two distinct scenarios. Figure 2(a) and (b) shows fractographs of the TMS-75 superalloy after the TMF test without a compressive hold time. The main crack propagation process consists of three stages: (1) initial slow growth perpendicular to the stress axis with the aid of oxidation (marked "A" in Figure 2(a) and (b)); (2) accelerated propagation along a twin plate (marked "B" in the figure); and (3) the final break along a twin plate in another crystallographic plane (marked "C" in the figure). When a hold time exists during compression, the crack morphologies of superalloys show a different characteristic, as shown in Figure 2(c)–(f). The oxidation zone is small (marked by the arrows in Fig. 2(d)–(f)) and the fracture occurs more or less in one crystallographic plane. As reported previously [10], there are a lot of rings close to the fracture (Fig. 2(c)), which is due to the intersection of deformation twins with the surface. The fracture process is similar for the two testing conditions (with or without a compressive hold time). An initial slow propagation occurs with the aid of oxidation along the main crack and then the stress field around the crack tip accelerates its propagation along the twin plates.

Figure 3 gives a schematic illustration of the fractograph characteristic of superalloys after TMF tests. When the TMF test is carried out without a compressive hold time, the initial oxidation zone is large (marked "A" in Fig. 3(a)) and this zone is perpendicular to the axial stress. Subsequently an accelerated propagation of the main crack takes place along a twin plate (marked "B" in Fig. 3(a)). For the TMF test with a compressive