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Cyclic deformation mechanisms of precipitation-hardened Inconel 718 superalloy

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Abstract

Cyclic deformation behavior of IN 718 fatigued at room temperature and 920 K was examined. A significant cyclic deformation softening was observed, and planar deformation bands were formed at both the temperatures. The coherent and ordered γ'' precipitates were observed to be sheared by dislocations moving on {1 1 1} slip planes. A model describing the formation of planar slip bands is given.

Keywords: Inconel 718 superalloy; Cyclic deformation; Microstructure; Precipitation-hardened alloy

1. Introduction

Inconel 718 (IN 718) superalloy belongs to a group of precipitation-hardened materials, where finely dispersed second-phase particles are predominantly responsible for its high strength. These precipitates have an ordered crystal structure and the alloy exhibits a planar slip character. However, conflicting observations on deformation mechanisms have been reported. Some investigators reported that planar deformation bands were produced by the microtwins [1]. Others observed that plastic deformation was proceeded via shearing of γ'' particles by the coupled motion of $a/2$<1 1 0> dislocation pairs [2]. Sundararaman et al. [3] reported that when the size of γ'' particles in IN 718 exceeded a critical value (~10 nm), plastic deformation was processed via shearing of γ'' precipitates by twinning, while, it was sheared by the movement of paired dislocations for the smaller precipitates. To date, there does not seem to be an agreement on the mechanism of precipitates shearing and the formation of planar slip bands in IN 718.

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2. Experimental

Wrought IN 718 was heat-treated using a commercial heat treatment schedule. It consisted of a solution treatment at 1227 K for 1 h, followed by aging at 990 K for 8 h, cooled to 895 K at a rate of 50 K/h, and held at 895 K for 8 h. Symmetrical pull-push LCF tests were carried out under total strain control mode at room temperature (RT) and 920 K, on a computerized INSTRON 8502 servohydraulic testing system. Fatigue substructures were observed using a JEOL-2000FX transmission electron microscope (TEM).

3. Results and discussion

3.1. Cyclic deformation behavior

The cyclic stress response curves as a function of number of cycles for IN 718 fatigued at RT and 920 K are shown in Fig. 1(a and b). It is seen that the material exhibited a relatively short period of cyclic hardening in the early stages, extending to a few cycles, at the higher cyclic strain amplitudes ($\Delta\varepsilon_t/2 \geq 0.8\%$) followed by a continuous cyclic softening to fracture at RT (Fig. 1a). However, the cyclic hardening was absent and continuous cyclic softening was observed as the cyclic strain amplitude decreased to $\Delta\varepsilon_t/2 = 0.6\%$. A nearly stable peak stress amplitude was observed at $\Delta\varepsilon_t/2 = 0.4\%$. This indicated that cyclic saturation stage was reached. The initial

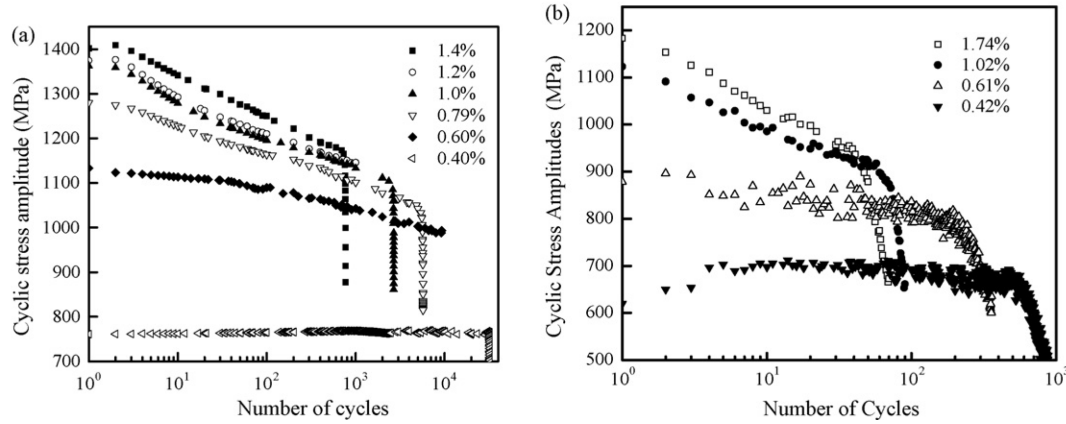

Fig. 1. Typical cyclic stress response curves as a function of number of cycles of IN 718 at: (a) RT and (b) 920 K.

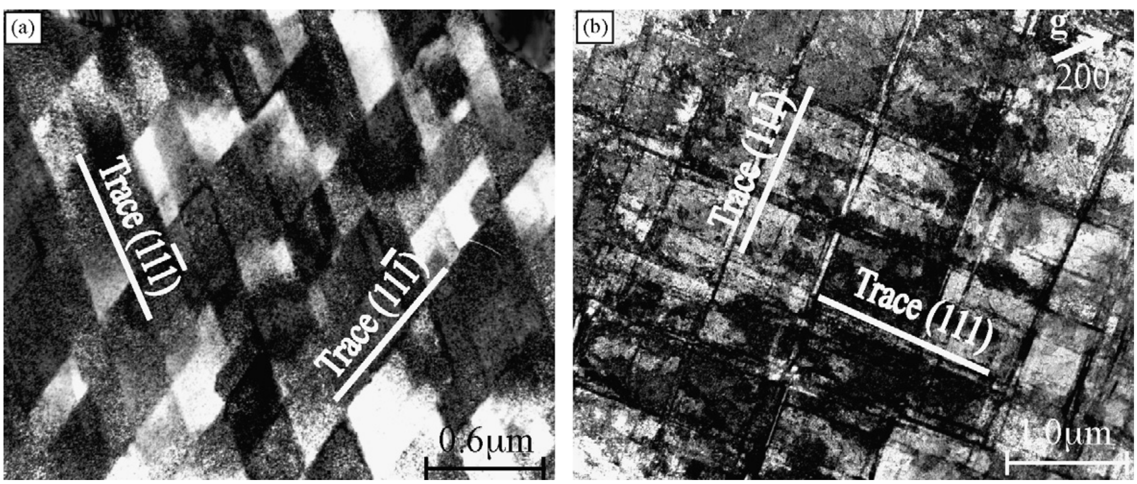

Fig. 2. Groups of planar slip bands observed in a specimen deformed at $\Delta\varepsilon_p/2 = 0.13\%$ at: (a) RT and (b) 920 K.

cyclic stress response value increased as the cyclic strain amplitude increased, and the difference in cyclic stress amplitudes at different cyclic strain amplitudes was reduced as the cyclic deformation progressed (Fig. 1a). However, an almost constant cyclic stress amplitude was achieved after an initial hardening in the early stages (3–5 cycles) at low cyclic strain amplitude at 920 K (Fig. 1b). With increasing cyclic strain amplitude, the initial hardening was reduced and finally disappeared, but the value of the first cyclic stress amplitude increased. At the high cyclic strain amplitudes the cyclic stress amplitude decreased continuously, i.e., as the cyclic deformation continued, only softening occurred until the fracture of the specimen. The difference between the saturation cyclic stress amplitude (evaluated at the half-lifetime) and the first cyclic stress amplitude increased as the applied cyclic strain amplitude increased. However, the difference in cyclic stress amplitudes between different cyclic strain amplitudes decreased as the cyclic deformation progressed (Fig. 1b).

3.2. Deformation structure

The deformation microstructures produced in the specimens fatigued at RT and 920 K were examined in the TEM. Regularly spaced arrays of planar deformation bands on {1 1 1} slip planes were observed, as shown in Fig. 2(a and b). They were characterized by the presence of two groups of planar deformation bands lying along the traces of intersection of

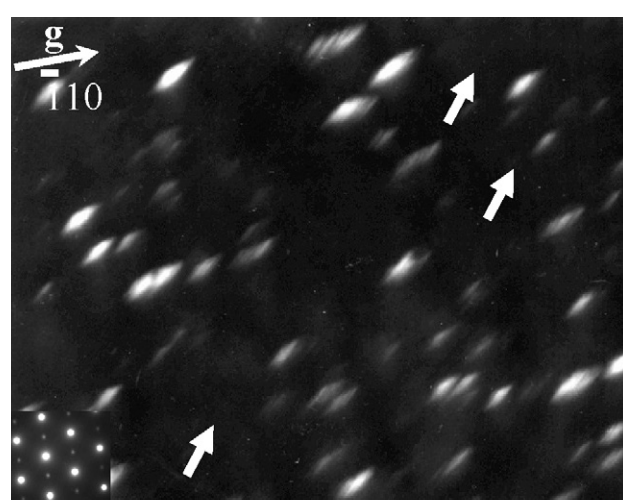

Fig. 3. Dark field micrograph with $\tilde{\mathbf{g}} = [\bar{1}\ 1\ 0]$ reflection and the foil in [1 1 0] orientation, showing sheared precipitates in a specimen deformed at $\Delta\varepsilon_p/2 = 0.6\%$ at 920 °C.

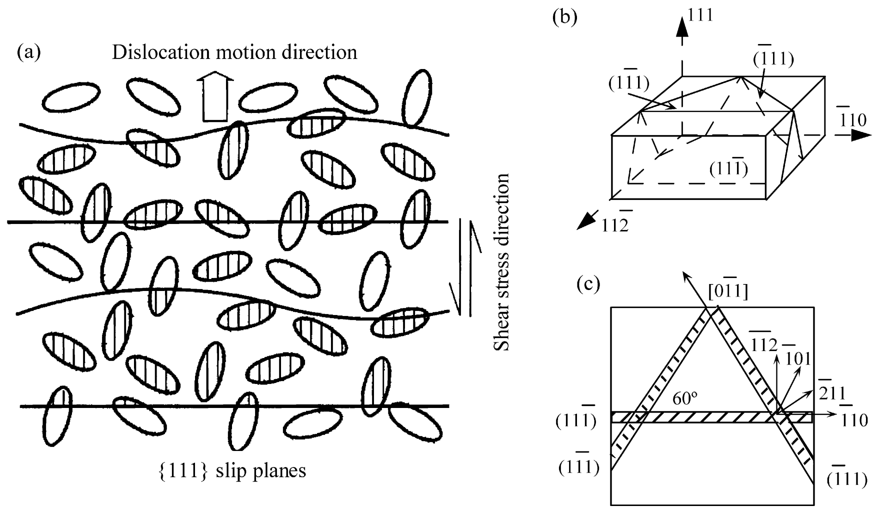

Fig. 4. A schematic illustrating the shear of γ'' precipitates and the formation of planar slip bands in IN 718 during cyclic deformation: (a) schematic representation of the shearing process of γ'' precipitates by dislocations, where cross-hatching of particles indicates the presence of antiphase boundary, (b) three-dimensional structure of $\{1\,1\,1\}$ slip planes in the $[1\,1\,\bar{2}]-[\bar{1}\,1\,0]-[1\,1\,1]$ space and (c) projections of $\{1\,1\,1\}$ planes on (1 1 1) plane, i.e., planar slip bands formed on (1 1 1) plane.

$(1\,1\,\bar{1})$ and $(1\,\bar{1}\,\bar{1})$ slip planes with the (1 1 1) thin foil surface, respectively (Fig. 2a). Trace analysis showed that $(1\,1\,\bar{1})$ and $(1\,\bar{1}\,\bar{1})$ slip systems were activated simultaneously, giving rise to the saturated diamond-shaped deformation structure in the fatigued specimens at RT (Fig. 2a). Fig. 2(b) shows the typical substructure formed in the specimen fatigued at 650 °C. It consists of two groups of slip bands lying along (1 1 1) and $(1\,\bar{1}\,1)$ plane, respectively, with the incident beam (B) parallel to (1 0 0) normal. This clearly demonstrates that both (1 1 1) and $(1\,\bar{1}\,1)$ slips were activated in the fatigued specimens.

A significant cyclic softening was observed at RT and 920 K in the IN 718 superalloys, except when the material was deformed at the lowest cyclic strain amplitude. As a precipitation-hardened nickel-base superalloy, IN 718 is strengthened primarily by the metastable γ'' phase precipitates of about 30 nm in diameter and 5 nm in thickness [4]. This phase is Ni_3Nb based and with an ordered body-centered tetragonal (DO_{22}) structure. The dark-field examination of γ'' precipitates in the fatigued specimens in the TEM revealed that they were sheared during cyclic deformation, both at RT and at 650 °C, as shown in Fig. 3. Under fully reversed fatigue condition, as the cyclic deformation proceeds, the strengthening precipitates, γ'', present in the slip bands are sheared by the leading dislocations [4,5]. After this initial cutting of γ'', the trailing dislocations in the same slip plane would shear the γ'' precipitates again. The process would be repeated during each cycle and reduce the size of γ'' particles to an extent that they offer very little or no resistance to the movement of dislocations. Thus, as the successive shearing of particles by dislocations continues, the stress required to shear the smaller particles is reduced. The preferential paths, which have a lower critical stress for the dislocation slip, would be established during the progressive deformation of the material. As a result, cyclic deformation softening was displayed and the precipitate-free planar slip bands would be produced [4].

Fig. 4 illustrates schematically the shearing process of γ'' precipitates by the coupled motion of $a/2\langle 1\,1\,0\rangle$ pairs on $\{1\,1\,1\}$ primary slip planes and the formation of planar slip bands in the IN 718 during cyclic deformation. Due to the order of γ'' particles, antiphase domain boundary (APB) is created in γ'' particles upon shearing by the first dislocation in the quadruplet (Fig. 4a). Order is then restored in one of the γ'' variants by passage of the secondary dislocation. The third dislocation reintroduces APB into these two, and, finally, the fourth dislocation restores order in all particles. Since cross-slip of the coupled dislocations is extremely difficult, slip continues to occur on the same slip plane during continued deformation, resulting in the formation of planar slip bands in the fatigued IN 718 specimens. Fig. 4(b) shows a three-dimensional structure of all the four $\{1\,1\,1\}$ slip planes in the $[1\,1\,\bar{2}]-[\bar{1}\,1\,0]-[1\,1\,1]$ space, and Fig. 4(c) displays projections of three $\{1\,1\,1\}$ planes, i.e., $(\bar{1}\,1\,1)$, $(1\,\bar{1}\,1)$) and $(1\,1\,\bar{1})$) planes on (1 1 1) plane, indicating the traces of planar slip bands on (1 1 1) planes.

4. Conclusions

Cyclic softening was displayed for IN 718 fatigued at RT and 920 K, and the typical deformation structure consisted of a regularly spaced array of planar deformation bands. TEM examination revealed that the γ'' precipitates in IN 718 were sheared by the slip of dislocations during cycling. The dislocations on the slip plane repeatedly sheared the γ'' precipitates and reduced their size. The preferential paths, which had fewer and smaller precipitates and lower critical stress for dislocation slip, were established. As a result, cyclic deformation softening occurred and planar slip bands formed.

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