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FATIGUE BEHAVIOUR OF A CAST NICKEL-BASED SUPERALLOY INCONEL 792-5A AT 700 °C

UTRUJANJE LITE NIKLJEVE SUPERZLITINE INCONEL 792-5A PRI 700 °C

Martin Petrenec, Karel Obrtlík, Jaroslav Polák, Tomáš Kruml

Institute of Physics of Materials, AS CR, Žižkova 22, 616 62 Brno, Czech Republic
petrenec@ipm.cz

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Cylindrical specimens of a cast polycrystalline superalloy, Inconel 792-5A, were cyclically strained under total strain control at 700 °C up to the point of fracture. Cyclic hardening curves, the cyclic stress-strain curve and the fatigue-life curve were recorded. The dislocation recorded structure was studied using the technique of oriented foils in a transmission electron microscope. Scanning electron microscopy was used to investigate the surface relief. High amplitude straining is characterized by initial hardening followed by the tendency to saturate. Low amplitude cycling results in the stabilized stress response. Surface slip markings and slip bands lying along {111} planes in the interior of the grains cut both channels and precipitates. Experimental results concerning the surface relief and the dislocation structure are used to discuss the stress-strain response.

Key words: high-temperature fatigue; superalloy, cyclic hardening curves, cyclic stress-strain curve, Manson-Coffin curve, slip markings, slip bands

Cilindrične preizkušance, izdelane iz lite polikristalinične superzlitine Inconel 792-5A, smo izmenično deformacijsko utrujali pri 700 °C do porušitve. Določili smo ciklične krivulje utrjevanja, ciklične napetostno-deformacijske krivulje in krivulje dobe trajanja. Razporeditev dislokacij v mikrostrukturi smo opazovali in študirali s tehniko orientiranih folij v presevnem elektronskem mikroskopu (TEM). Za opazovanje površinskega reliefa prelomnih površin smo uporabili vrstični elektronski mikroskop (SEM). Značilnost deformacijskega utrujanja z veliko amplitudo je začetno utrjevanje, kateremu sledi nasičenje. Rezultat utrujanja z majhno amplitudo pa je stabilen napetostni odziv. Površinske drsne linije in zdrsela področja ležijo vzdolž ravnin {111}, v notranjosti zrn pa sekajo oba kanala in izločke. Eksperimentalne rezultate, ki se nanašajo na površinski relief in strukturo dislokacij, smo uporabili za razlago napetostno-deformacijskega odziva materiala.

Ključne besede: visokotemperaturno utrujanje, superzlitina, krivulje cikličnega utrjevanja, napetostno-deformacijska ciklična krivulja, Manson-Coffinov diagram, zdrs, brazde, zdrsela področja

1 INTRODUCTION

The cast nickel-based superalloy Inconel 792-5A is used for the gas-turbine integral wheels of auxiliary power units in the aircraft industry [1]. Turbine wheels are subjected to repeated elastic-plastic straining as a result of heating and cooling during the start-up and shut-down periods. Consequently, low cycle fatigue is an important consideration in the design of the components, and the cyclic stress-strain and fatigue-life data are needed up to the working temperature of 900 °C. The fatigue behaviour of IN 792-5A has been reported only scarcely [2-4].

Strain localization is one of the most important stages during the fatigue damage of crystalline materials. It is closely connected to crack nucleation and manifests itself in specific changes to the internal structure and in the formation of a characteristic surface relief. Slip bands parallel to the active slip plane are formed and slip markings originate in the vicinity of the intersection of slip bands with the free surface [5]. Slip bands and slip markings have been reported for many materials, including nickel-based superalloy single crystals [6,7], and polycrystals [8–12]. The investigation of the dislocation structure in superalloy polycrystals at room and at high temperatures indicated planar slip bands parallel to {111} slip planes and cutting of the strengthening particles [7,9,12]. Surface slip markings were observed in Inconel 713 LC at room and at high temperature [11]. The effect of slip bands on the cyclic stress-strain response in polycrystalline superalloys has not been studied systematically. The fragmentation and shearing of γ' particles were considered to be the reason for the observed cyclic softening at room temperature [9-11].

The aim of the present work is to investigate the low-cycle fatigue characteristics of the cast nickel-based superalloy Inconel 792-5A in symmetrical total-strain amplitude cycling at the temperature of 700 °C. This contribution is part of a complex project aimed to investigate low-cycle fatigue and its relation to the internal structure in the range from 23 °C to 900 °C [3,4].

2 EXPERIMENTAL

The polycrystalline Inconel 792-5A alloy was provided by PBS Velká Bíteš a. s. as a conventionally cast rod. The chemical composition is 12.28 Cr, 8.87 Co, 3.98 Ti, 3.36 Al, 4.12 Ta, 4.1 W, 1.81 Mo, 0.1 Nb, 0.16 Fe, 0.031 Zr, 0.078 C, 0.015 B, the rest Ni (all in mass fractions, %). The macrostructure of the material revealed coarse grains with dendrites, carbides and

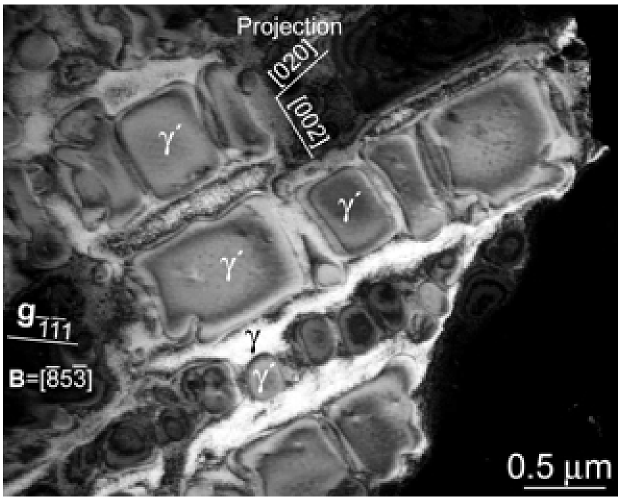

Figure 1: Microstructure of IN 792-5A as revealed by TEM micrograph (dark field)
Slika 1: Mikrostruktura superzlitine IN 792-5A, vidna v presevnem elektronskem mikroskopu (TEM; temno polje)

shrinkage pores up to 0.5 mm in diameter. Rugged grain boundaries due to the complex dendritic structure are apparent. The average grain size, assessed with the linear intercept method, was 3 mm. After heat treatment the microstructure consisted of γ' particles dispersed in a γ solid-solution matrix. The γ' phase has a bimodal distribution, with spherical precipitates of an average diameter of 190 nm and near-cuboid particles of an average edge-length of 630 nm (**Figure 1**) [3,4].

The low-cycle fatigue tests were performed on button-end specimens having gauge lengths and diameters of 15 mm and 6 mm, respectively [3]. The specimens were machined with the axis parallel to the rod axis and with the gauge lengths mechanically ground. The tests were performed with a computer-controlled electro-hydraulic MTS testing system using a total strain rate of $2 \cdot 10^{-3}$ s^{-1} with a fully reversed total strain cycle ($R_\varepsilon = -1$). The strain was measured and controlled with a sensitive extensometer with a 12 mm base. The tests were carried out at 700 °C in air. For the surface relief observations, some specimens were mechanically and electrolytically polished before cycling, then examined in a JEOL JSM6460 SEM. The internal dislocation structures were studied in a Philips CM-12 TEM operating at 120 kV with a double tilt holder using the technique of oriented foils. Specimens were sectioned in the gauge area parallel, or at an angle of 45°, to the loading axis using a spark-cutting machine. The oriented foils were prepared using the standard double-jet technique. Bright-field imaging conditions were mostly adopted and the diffraction patterns and Kikuchi lines were used to determine the grain orientation (stress axis **S.A.** and foil plane **F.P.**).

3 RESULTS

Figure 2 shows the stress amplitude, σ_a, against the number of cycles, N, for controlled total strain amplitudes, ε_a. The character of these hardening curves varies with the strain amplitude, ε_a, and in the domain of high ε_a an initial cyclic hardening followed by a phase of saturation was observed. In the domain of low ε_a the stabilized stress response was observed. The cyclic hardening behaviour at 700 °C is different from that at room temperature. At room temperature a pronounced initial hardening followed by long saturation period was observed across a wide range of cyclic strain amplitudes [3,4]. The cyclic stress-strain curve (CSSC) of the investigated alloy at a temperature of 700 °C is presented in **Figure 3** by plotting the stress amplitude, σ_a, versus the plastic strain amplitude ε_{ap} at half life. The experimental data of the stress amplitude versus the plastic strain amplitude were fitted using the power law

$$\lg \sigma_a = \lg K' + n' \lg \varepsilon_{ap}$$

The fatigue hardening coefficient $K' = 1950 \pm 240$ and the fatigue hardening exponent $n' = 0.129 \pm 0.013$ were evaluated using a regression analysis.

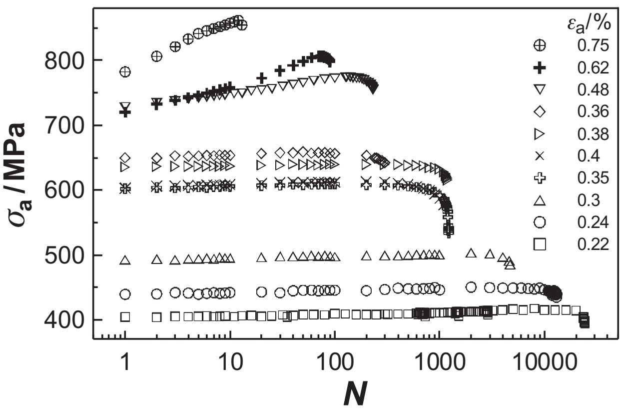

Figure 2: Cyclic hardening curves at 700 °C of IN 792-5A
Slika 2: Krivulje cikličnega utrjevanja zlitine IN 792-5A pri 700 °C

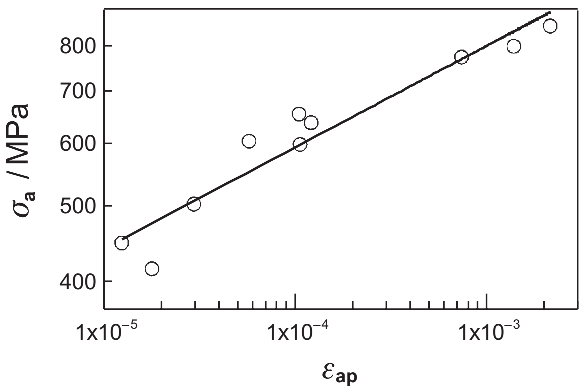

Figure 3: Cyclic stress-strain curve at 700 °C of IN792-5A
Slika 3: Ciklična napetostno-deformacijska krivulja zlitine IN 792-5A pri 700 °C

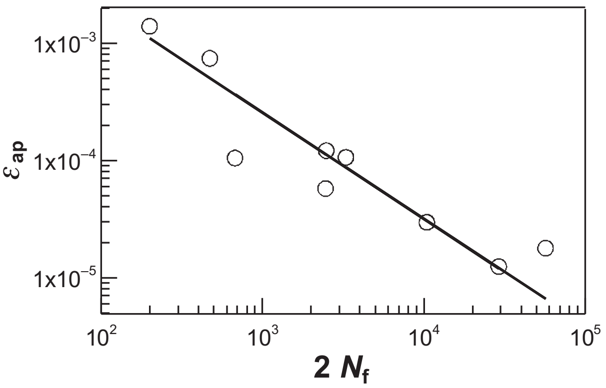

Figure 4: Manson-Coffin plot at 700 °C of IN 792-5A
Slika 4: Manson-Coffinov diagram zlitine IN 792-5A pri 700 °C

Figure 4 shows the fatigue-life curve plotting the plastic strain amplitude ε_{ap} at half-life versus the number of cycles to fracture, N_f, in the bilogarithmic representation. The Manson-Coffin law $\varepsilon_{ap} = \varepsilon'_f (2N_f)^c$ was fitted to the experimental data using the relation

$$\lg(2N_f) = (1/c)\lg\varepsilon_{ap} - (1/c)\lg\varepsilon'_f$$

The fatigue ductility coefficient $\varepsilon'_f = 0.133$ and the fatigue ductility exponent $c = -0.91$ were evaluated with a regression analysis. The absolute value of the Manson-Coffin exponent at 700 °C is considerably higher than that found during the room-temperature cycling ($c = -0.68$) [3,4].

Figure 5 shows an SEM micrograph of the surface relief of a specimen cycled up to fracture with the highest strain amplitude ($\varepsilon_a = 0.62$ %, $\varepsilon_{ap} = 0.139$ % at half life). Inhomogeneously distributed deformation, resulting in a high density of slip markings, is apparent. At low magnification (**Figure 5**) it can be seen that the slip markings follow one type of slip plane. Detailed observations show that the surface relief consists of wide slip markings passing through both the γ matrix and the γ' precipitates. The density of slip markings decreases with decreasing plastic strain amplitude, and the fatigue cracks nucleate along these slip markings.

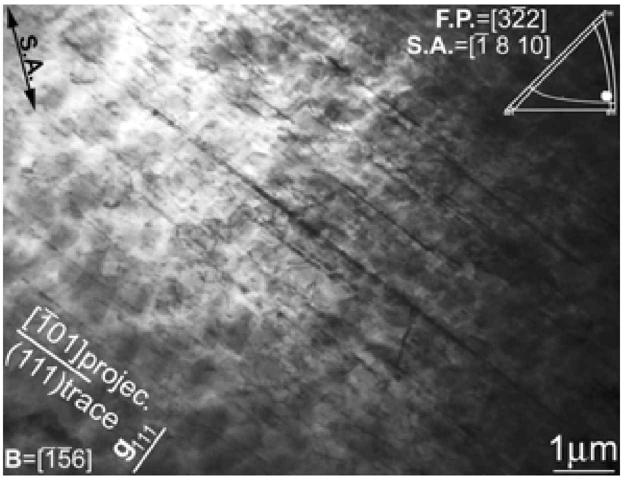

Figure 6: TEM micrograph of dislocation arrangement of specimens cycled to fracture at 700°C (ε_a = 0.75%, N_f =13)
Slika 6: TEM-posnetek razporeditve dislokacij v preizkušancu, ki je bil ciklično utrujan do porušitve pri 700 °C (ε_a = 0,75 %, N_f =13)

The internal dislocation structure was investigated with the aim of revealing an inhomogeneous microstructure related to the cyclic strain localization observed on the free surface. Typical TEM micrographs documenting the dislocation arrangement of a specimen cycled up to fracture ($\varepsilon_a = 0.75$ %, $\varepsilon_{ap} = 0.215$ % at half life) in a grain oriented for single slip are shown in **Figures 6 and 7**. The **S.A.** = [$\bar{1}$ 8 10] is denoted within the embedded standard stereographic triangle. Planar slip bands going parallel to the primary slip planes {111} were observed. The slip bands were present as thin slabs with a high dislocation density passing through both the γ' precipitates and the γ channels (detail is shown in Figure 7). The primary slip plane (111) forms an angle of 65° with the **F.P.** = (3$\bar{2}$2) and the Burger's vector

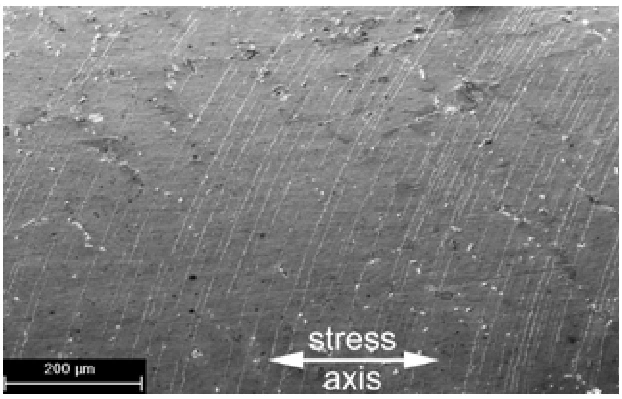

Figure 5: SEM micrograph of surface relief of specimens cycled to fracture at 700 °C (ε_a = 0.62 %, N_f = 100)
Slika 5: SEM-posnetek površinskega reliefa preizkušanca, ki je bil ciklično utrujan do porušitve pri 700 °C (ε_a = 0,62 %, N_f = 100)

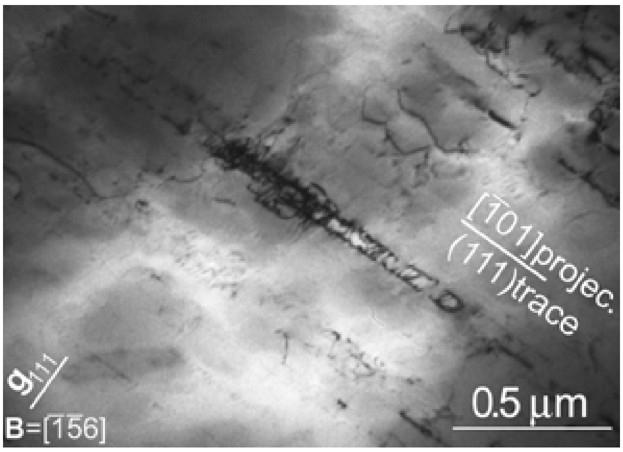

Figure 7: TEM micrograph – detail of slip band in the same specimens as **Figure 6**
Slika 7: TEM-posnetek – detajl s **slike 6**; zdrselo področje

[$\bar{1}$01] is almost parallel to the **F.P.** (deflection is only of 10°). Numerous very thin slip bands (thickness below 0.1 μm) run parallel to the primary slip plane. Bundles with a high dislocation density often form among closely spaced bands.

4 DISCUSSION

Inconel 792-5A is a natural composite consisting of γ' precipitates with an ordered structure coherently embedded in a γ solid solution (see **Figure 1**). This material is characterised by a very coarse grain size. Thus, only several grains are present in the volume of a specimen corresponding to the gauge length. This means that the measured elastic modulus of individual specimens differed appreciably (the measured values of the elastic modulus at 700 °C were in the interval of 110 GPa to 180 GPa). The difference in the elastic modulus of specimens strained with the same total strain amplitude resulted in a great difference of their stress response (**Figure 2**). A detailed study of the surface relief and the internal dislocation structure in the polycrystalline superalloy IN 792-5A, cyclically strained at 700 °C, revealed a pronounced plastic strain localization (**Figure 5**). This finding is in agreement with the results of previous works on the cyclic straining of different Ni-based superalloys [6-12]. Cyclic strain localization is manifested by the presence of sharp surface slip markings on the surface and by thin dislocation-rich slip bands in the bulk of the individual grains. These slip bands parallel to the {111} planes intersect both the γ channels and the γ' particles.

The cyclic stress-strain response of crystalline materials is closely related to the dislocation arrangement. Early in the fatigue life, the plastic strain starts to concentrate into thin slabs of material (see **Figures 6 and 7**) that could accommodate the cyclic plastic strain more effectively. High dislocation activity within the bands leads to the development of a typical surface relief. In spite of the high density of slip markings and slip bands, fatigue hardening (see **Figure 2**) occurs almost up to the specimen fracture. The reason why the presence of slip bands does not manifest itself in the change of the hardening behaviour must be sought in fact that they harden immediately after their formation and do not represent zones of higher persistent slip activity.

5 CONCLUSIONS

Experimental results of the fatigue behaviour in Inconel 792-5A polycrystals cycled with a constant total strain amplitude at 700 °C can be summarized as follows:

(i) High amplitude cycling is characterized by cyclic hardening followed by a phase of stabilized stress response. Low amplitude cycling results in a saturated cyclic stress-strain response.

(ii) The cyclic stress-strain curve can be fitted using the power law. The fatigue-life curve can be represented by the Manson-Coffin law.

(iii) Localization of the cyclic strain into slip bands results in the formation of slip markings on the free surface of the material. The cyclic plastic deformation is localized in the slip bands parallel to {111} planes and passing through both the γ channels and the ordered γ' precipitates.

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