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The effects of a second aging treatment on the yield strength of γ'-hardened NIMONIC PE16-polycrystals having γ'-precipitate free zones

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Abstract

The nickel-base alloy NIMONIC PE16 is strengthened by coherent spherical nano-scale precipitates of the $L1_2$-long range ordered γ'-phase. Along grain boundaries precipitate free zones (PFZs) may form, which lower the yield strength drastically. In this study it has been attempted to eliminate this softening effect by double aging treatments: the main γ'-precipitate dispersion is grown at 1079 K and subsequently finer γ'-particles are precipitated at 949 K – in between the larger 1079 K-γ'-precipitates and in the PFZs formed at 1079 K. Unfortunately softening by PFZs could not be suppressed by these procedures. In addition, multiple strengthening of finely grained, PFZ-free NIMONIC PE16-polycrystals by γ'-precipitates, by atoms dissolved in the matrix, and by grain boundaries has been modeled and computer simulated.

Keywords: Nickel alloy; Yield strength; Precipitate free zones; Transmission electron microscopy; Computer simulations

1. Introduction

In many polycrystalline precipitation strengthened materials precipitate free zones (PFZs) form along the grain boundaries (GBs). In general these PFZs are detrimental to the mechanical properties of the materials [1–6]. Krol et al. [6] found that PFZs reduce the yield strength σ_y of coarsely grained polycrystals of the commercial nickel-base alloy NIMONIC PE16 (Section 2) by up to 25%. This material is strengthened by coherent spherical nano-scale precipitates of the $L1_2$-long range ordered γ'-phase [7]. Their approximate composition is $Ni_3(Al,Ti)$ and their lattice mismatch is negligibly small.

The reason for the formation of PFZs varies from system to system; in NIMONIC PE16 it is as follows [8]. During the aging treatment the average radius r of the γ'-precipitates increases with time t as [9–12]

$$r^3 = kt + r_0^3, \tag{1}$$

where r_0 equals r at $t = 0$. The growth parameter k depends on the aging temperature and on the volume fraction f of the γ'-precipitates. During aging f stays virtually constant. Concurrently with the growth of the γ'-precipitates, two types of carbide particles form at GBs: Cr-rich $Cr_{23}C_6$ and Ti-rich $(Ti_{0.8}Mo_{0.2})C$. Since the chemical potential of Ti is lower in the

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$(Ti_{0.8}Mo_{0.2})C$-carbide particles than in the γ'-precipitates, the latter ones dissolve in zones along the GBs and their Ti-content is incorporated by the Ti-rich carbide particles. The width of the PFZs first increases in proportion to $t^{1/2}$ and finally saturates. Since in finely grained polycrystals the total amount of carbon contained in the specimen is distributed among many GBs, each of them receives only a little carbon and only very few $(Ti_{0.8}Mo_{0.2})C$-particles grow at each GB. Hence PFZs do not form in finely grained NIMONIC PE16-polycrystals, but only in coarsely grained ones [6].

On the basis of the Hall–Petch [13,14] equation

$$\sigma_y = \sigma_0 + k_{HP}/\sqrt{d}, \tag{2}$$

Krol et al. [6] developed a scheme to quantify the softening effects caused by PFZs in NIMONIC PE16. d is the grain size and $\sigma_0 = \sigma_y(d \to \infty)$ and k_{HP} are constants, which depend on the properties of the interior of the grains, for instance on the precipitate dispersion [5,6]. Twin boundaries are not counted as GBs because they are not strong obstacles to the propagation of slip [5]. Eq. (2) was fitted to experimental data $\sigma_y(d, f, r, \exp)$ taken for finely grained NIMONIC PE16-polycrystals, which are not softened by PFZs. Thus the function $\sigma_y(d, f, r, \mathrm{HP})$ was established, which one would measure if there were no softening due to PFZs at any grain size. "HP" indicates extrapolations on the basis of the "Hall-Petch" equation and "exp" refers to actual "experimental" data. PFZ-softening of coarsely grained polycrystals is given by the difference $\Delta\sigma_y(d, f, r)$:

$$\Delta\sigma_y(d, f, r) = \sigma_y(d, f, r, \mathrm{HP}) - \sigma_y(d, f, r, \exp). \tag{3}$$

$\Delta\sigma_y$ calculated for finely grained polycrystals vanishes, but σ_y of coarsely grained ones was found to amount to up to 25% of $\sigma_y(d, f, r, \mathrm{HP})$ [6]. $\sigma_y(d, f, r, \exp)$ of many coarsely grained specimens was even smaller than $\sigma_0 = \sigma_y(d \to \infty)$, that is there was GB-softening instead of GB-strengthening.

In under- and peak-aged NIMONIC PE16-specimens dislocations shear the γ'-precipitates [7,15,16]. Their $L1_2$-long range order causes two dislocations with identical Burgers vectors of the type $1/2\langle 1\,1\,0\rangle$ to form a pair and to glide together. In the PFZs, however, single $1/2\langle 1\,1\,0\rangle$-dislocations glide. Compatible deformation of neighboring grains requires multiple slip next to GBs. Hence cross slip and double cross slip are very frequent in the PFZs and lead to the creation and activation of many dislocation sources. The dislocations emitted by them glide easily through the PFZs, which are only solid solution strengthened, and pile up at the γ'-precipitates delimiting the PFZs. The stress exerted by the pile-ups helps their leading dislocations to enter the γ'-strengthened interior of the grains at relatively low external stresses. Upon entering this interior the $1/2\langle 1\,1\,0\rangle$-dislocations form pairs. The ease with which dislocations are created and the ensuing formation of very localized pile-ups in the PFZs facilitates the propagation of slip across GBs and thus softens the material. Baither et al. [16] stretched thin polycrystalline foils of NIMONIC PE16 inside a transmission electron microscope (TEM) and observed the described dislocation processes under full load. Krol et al. [6,16] found that for the described processes to operate, the width of the PFZs must exceed a certain minimum:

$$w' > 1.7(L_{\min} - r), \tag{4}$$

with w' = average width of the PFZs = average width of the γ'-free space between the carbide particles at the GBs and the γ'-precipitates delimiting the PFZs, $L_{\min} = 1/\sqrt{n_s}$, n_s = number of γ'-precipitates intersecting unit area of the glide plane, and r = their average radius. Often $L_{\min}$ is referred to as their square lattice spacing [15]. PFZs which do not fulfill condition (4) cause no softening.

It has been suggested that it may be possible to suppress the softening effects of PFZs by two stage aging treatments [6]. First the main γ'-precipitate dispersion is grown at temperature T_1. The resulting PFZ-width is w'_1. Subsequently the second treatment is executed at $T_2 < T_1$. Provided the solubility of the γ'-phase forming elements is markedly lower at T_2 than at T_1, a second γ'-dispersion precipitates in between the γ'-precipitates grown at T_1 and – hopefully – also in the PFZs created at T_1. The aging time at T_2 has to be chosen such that the square lattice spacing $L_{\min 2}$ of the second γ'-dispersion is markedly smaller than w'_1. The new γ'-particles which precipitate in the original PFZs, are expected to cause the $1/2\langle 1\,1\,0\rangle$-dislocations to form pairs even in these PFZs and thus to hinder multiple slip and the easy creation of dislocations in the PFZs, and hence to diminish their softening effects. It is, however, quite possible that these new γ'-particles enhance concentrated slip and thus the formation of very localized pile-ups because once several $1/2\langle 1\,1\,0\rangle$-dislocation pairs have cut through a γ'-particle, the effective area of its intersection with the glide plane is reduced. Compatible deformation of neighboring grains requires multiple slip in the original PFZs even if they contain small γ'-precipitates.

In this paper the effects of such two stage aging treatments on the yield strength of γ'-strengthened NIMONIC PE16-polycrystals are reported.

2. Experiments

The composition of NIMONIC PE16 is in at.%: Ni 41, Fe 34, Cr 17, Mo 2.0, Ti 1.5, Al 2.6, C 0.25. The preparation of the tensile specimens was essentially the same as in the previous investigation [6]. Cylindrical polycrystals with two different grain sizes d were produced by thermo-mechanical treatments. d was defined as the average spacing of GBs along straight lines; twin boundaries were