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Plastic strain-induced rafting of γ' precipitates in Ni superalloys: Elasticity analysis

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Abstract

Rafting in Ni-based superalloys is investigated by examining the dependence of elastic energy on the shape and orientation of γ' particles. The precipitation misfit strain and the plastic strain occurring in the matrix are taken into account. The elastic energies associated with spherical or disc-shaped particles with different orientations are evaluated for some combinations of transformation strain and matrix plastic strain. The anisotropy in elastic constants as well as the difference in elastic constant between the particles and matrix are taken into account. It is found that the elastic energy becomes minimum when γ' particles adopt a certain shape and direction with respect to the elongation axis $\langle 001 \rangle$. These results are in agreement with the rafted morphologies observed in crept superalloys. The onset of the shearing of rafted γ' particles, leading to accelerated creep of the alloy, is also discussed by examining the stress state of rafted γ' particles.

Keywords: Nickel superalloys; Rafting; Elasticity analysis; Particle interaction

1. Introduction

Ni-based superalloys are biphasic compounds, consisting of a face-centred cubic γ matrix and γ' precipitates. The γ' precipitates having the $L1_2$ structure are stronger than the γ matrix at high temperatures. Thus, the creep of γ–γ' alloys is retarded by the γ' precipitate particles. Rafting, which occurs during creep, also increases the creep resistance of the γ–γ' alloys. These factors give the γ–γ' alloys unique high-temperature properties.

The morphology of the γ' precipitates strongly depends on the thermomechanical history of an alloy. After a standard heat treatment (e.g. 1250 °C/3 h/water quenched +1100 °C/1 h/air cooling + 850 °C/24 h/air cooling for CMSX-4 alloy), the microstructure consists of cuboidal γ' particles almost periodically arranged along the $\langle 100 \rangle$ crystallographic directions [1]. During a creep test, the γ' particles coarsen along a preferential crystallographic direction [2]. The direction and shape of the precipitates depend, among other parameters, on both the signs of the misfit strain between the γ and γ' phases and the applied creep stress [3,4].

Several theories have been proposed to explain rafting or a shape change of particles occurring under an external applied stress [5–9]. However, the rafting of γ' particles can also occur under no external stress, if an alloy is prestrained and subsequently annealed [10,11]. This means that the rafting is primarily caused by the residual stress brought about by matrix plastic deformation, which should have a similar effect to that induced by the early stages of creep. The residual stress and its associated elastic energy can relax during further annealing at high temperature by a change in the morphology of the γ' particles. The present paper proposes that this relaxation of the residual stress is

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the origin of rafting. Several authors have already noticed a role of plastic strain in rafting [12,13]. In the following, we discuss the rafting phenomenon from this point of view, using the inclusion theory of anisotropic elasticity. The method employed is quite simple but quantitative and can predict the morphology change of γ' particles.

2. Elasticity analysis

We consider a single crystal having γ' particles with a volume fraction f, surrounded by the γ matrix. The misfit strain between γ and γ' phases due to precipitation is given by

$$\varepsilon_{ij}^{\mathrm{T}} = \varepsilon_0 \delta_{ij}, \tag{1}$$

where δ_{ij} is the Kronecker delta and

$$\varepsilon_0 = \frac{a - a_0}{a_0}. \tag{2}$$

Here, a_0 and a are the lattice parameters of the γ and γ' phases, respectively.

Next, we consider the role of plastic deformation in the matrix. We suppose that the matrix is uniaxially deformed plastically by ε_{P} along the tensile axis [001], as the γ' phase is harder than the γ matrix. This deformation is symmetric, i.e. the lateral directions undergo a plastic strain of $-\varepsilon_{\mathrm{P}}/2$. We can then define a plastic deformation-induced misfit strain given to the γ' particles as

$$\boldsymbol{\varepsilon}^{\mathrm{P}} = \begin{pmatrix} \varepsilon_{\mathrm{P}}/2 & 0 & 0 \\ 0 & \varepsilon_{\mathrm{P}}/2 & 0 \\ 0 & 0 & -\varepsilon_{\mathrm{P}} \end{pmatrix} \tag{3}$$

The total misfit strain (eigenstrain) $\boldsymbol{\varepsilon}^*$ is then given by

$$\boldsymbol{\varepsilon}^* = \boldsymbol{\varepsilon}^{\mathrm{T}} + \boldsymbol{\varepsilon}^{\mathrm{P}}. \tag{4}$$

The stiffnesses $\boldsymbol{C}$ and $\boldsymbol{C}^*$, of the γ and γ' phases, respectively, have cubic symmetry and are anisotropic ($C_{11} - C_{12} \neq 2C_{44}$). $\boldsymbol{C}$ is assumed to be that of pure nickel: C_{11} ($=C_{1111}$) = 246.4 GPa, C_{12} ($=C_{1122}$) = 152.5 GPa, C_{44} ($=C_{2323}$) = 122 GPa. $\boldsymbol{C}^*$ is assumed to be proportional to $\boldsymbol{C}$ ($\boldsymbol{C}^* = 1.15\boldsymbol{C}$) for simplicity.

The particles are cuboidal before the morphology change (rafting) and are equivalently approximated as spheres [6]. As shown later, the disc shape of the particles is good enough to see the tendency of the shape change. Thus, three types of Eshelby tensors $\boldsymbol{S}$ for sphere and discs normal to [001] and normal to [100] or [010] are used in the main analysis. By symmetry, the cases of disc-shaped particles normal to [100] and [010] are equivalent. These are for spheres

$$S_{1111} = 0.445, \quad S_{1122} = 0.091, \quad S_{1212} = 0.347. \tag{5}$$

These are obtained by numerical integration [14]. The other non-zero components of the tensor are obtained by suitable permutation. Similar to the isotropic case, the tensors with an odd number of the same index vanish.

For discs with the flat surface normal to [001]

$$S_{3333} = 1, \quad S_{3311} = S_{3322} = C_{12}/C_{11}, \text{ others } S_{ijkl} = 0. \tag{6}$$

The Eshelby tensors for discs normal to [100] and [010] are obtained by proper permutations.

We have also examined the elastic energy associated with a needle-shaped particle, using the method developed by Mura [14]. The Eshelby tensor for a needle along ⟨001⟩ can be analytically obtained. This is shown in Appendix A. However, it has been found that such a particle does not reduce the energy as much as a disc. Thus, the present paper does not describe the role of a needle in detail.

In order to discuss the change of the particle shape occurring under diffusion processes, we have also examined spheroidal inclusions, described by

$$\frac{x_1^2 + x_2^2}{a^2} + \frac{x_3^2}{c^2} \leqslant 1, \tag{7}$$

where the x_3-axis is parallel to [001]. The Eshelby tensor was calculated numerically using the method given in section 17 of Mura's book [14]. The aspect ratio $r = c/a$ was varied. The extreme cases of very small or large r are confirmed to coincide with the cases of a flat inclusion normal to [001] (disc) and a needle particle, respectively.

When the volume fraction f of misfitting particles is large as in industrial γ–γ' alloys, we have to take into account the interaction between the particles in order to evaluate the stress state. For this purpose we use the mean field method [15–17] together with the inclusion elasticity theory. In the mean field approach, the stress in a particle is given by

$$\begin{aligned} \boldsymbol{\sigma} &= \mathbf{C}^*\{\mathbf{S}\varepsilon^{**} - f(\mathbf{S} - \mathbf{I})\varepsilon^{**} - \boldsymbol{\varepsilon}^*\} \\ &= \mathbf{C}\{\mathbf{S}\boldsymbol{\varepsilon}^{**} - f(\mathbf{S} - \mathbf{I})\boldsymbol{\varepsilon}^{**} - \boldsymbol{\varepsilon}^{**}\}, \end{aligned} \tag{8}$$

where $\boldsymbol{\varepsilon}^{**}$ is the equivalent eigenstrain. First, Eq. (8) is solved to obtain $\boldsymbol{\varepsilon}^{**}$ as a linear combination of $\boldsymbol{\varepsilon}^*$. Then, by inserting $\boldsymbol{\varepsilon}^{**}$ back into Eq. (8), the stress in a particle is calculated. In the limit of $f \to 0$, the above equation reduces to a single-particle problem given as [14,18]

$$\boldsymbol{\sigma} = \mathbf{C}^*(\mathbf{S}\boldsymbol{\varepsilon}^{**} - \boldsymbol{\varepsilon}^*) = \mathbf{C}(\mathbf{S}\boldsymbol{\varepsilon}^{**} - \boldsymbol{\varepsilon}^{**}). \tag{9}$$

The elastic energy assigned to unit volume of a particle is given by [14,18]

$$W = -\frac{1}{2}\sigma_{ij} \cdot \varepsilon_{ij}^*. \tag{10}$$

Naturally, the shapes having the lowest elastic energy are realized, if the contribution of the interfacial energy is ignored.

3. Results

In Fig. 1, W is plotted against matrix plastic strain when the precipitation misfit is $\varepsilon_0 = -0.2\%$ and $f = 0.7$. When the plastic strain is positive (tensile case), the disc-shaped particles normal to [001] show the lowest elastic energy. The difference in the elastic energy between the considered