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MICROSTRUCTURE EVOLUTION DURING ISOTHERMAL AGING OF MULTIMODAL NICKEL-BASED SUPERALLOYS

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ABSTRACT

The morphological evolution of secondary γ′ precipitates under the coarsening process was investigated for commercial wrought Ni-based superalloys, which can be classified into two processes, i.e. "localization process" and "aggregation process". The localization process was defined as a phenomenon in which cuboidal γ′ precipitates were arranged in the <100> direction for superalloys. In contrast, the aggregation process was defined as a phenomenon in which neighboring spherical γ′ precipitates coarsen while overlapping their interfaces for superalloys. All the wrought Ni-based superalloys could be classified into the above two processes based on their volume fraction and lattice misfit. The coarsening of γ′ precipitates follow the aggregation process when the misfit is smaller than 0.05%, and it follows the localization process otherwise.

KEYWORDS:

nickel-based superalloys, gamma prime, lattice misfit, volume fraction, coarsening

INTRODUCTION

Ni-based superalloys are used for aerospace jet-engine components such as turbine blade and turbine disc due to superior mechanical properties[1]. These alloys owe their remarkable properties to the γ/γ′ two-phase microstructure. It is extremely important to properly control the precipitation microstructure of the γ′ precipitates. In this study, we focus on the wrought alloys, because the solution treatment can be carried out above the supersolvus temperature, to simplify the γ′ morphology as much as possible.

Precipitate coarsening causes a gradual loss of coherency between the γ matrix and γ′ precipitates, which can be detrimental to the mechanical performance of the superalloys. The thermodynamic driving force for microstructural coarsening is generally dominated by the reduction in free energy achievable by minimizing the system's interfacial energy[2]. In contrast, the elastic energy becomes the driving force for the superalloys with lattice misfit of coherent γ/γ′ interface. Besides, the γ′ volume fraction is also known to affect the coarsening[3].

The purpose of this study is to quantitatively evaluate the morphological change of γ′ precipitates during coarsening of the commercial wrought Ni-base superalloys and clarify the influence of γ′ volume fraction and lattice misfit on the coarsening. Then, based on the γ′ shape, the coarsening process is systematically classified.

EXPERIMENTAL

Test Alloy, Heat Treatment, and Microstructure Observation

Four kinds of wrought Ni-based superalloys are used in this study and their composition is shown in Table 1. Test alloys covers a wide range of γ′ fraction and γ/γ′ lattice misfit[4–10]. The alloys were solution-treated at supersolvus temperatures, followed by water quenching. The aging treatment was carried out at 1173 K, with an aging time ranging from 3.6×10^3 s (1 h) to 1.4×10^7 s (4000 h). Microstructure observation was conducted using field-emission scanning electron microscopy (FE-SEM).

Table 1: Chemical compositions for the wrought nickel-based superalloys used in this study, together with their volume fraction and lattice misfit at 1173 K.

	Composition (mass%)									Volume Fraction	Lattice Misfit
Alloy	Cr	Al	Ti	Fe	Nb	Co	Mo	W	Ni	f_v (%)	δ (%)
Inconel X-750[4,5]	14.9	0.79	2.49	6.58	1.00	–	–	–	Bal.	5	+0.5
Alloy 80A[6,7]	19.2	1.44	2.23	0.70	–	–	–	–	Bal.	8	+0.3
Udimet 520[8,9]	19.0	2.1	3.1	0.34	–	12.2	6.0	1.0	Bal.	22	+0.1
Udimet 720Li[8,10]	16.0	2.70	5.07	0.013	–	14.40	3.02	–	Bal.	40	+0.02

Quantitative Evaluation

For quantitatively evaluating the morphology of the γ′ precipitates in a γ/γ′ two-phase microstructure, a mathematical method based on the absolute moment invariants has been recently proposed by MacSleyne et al.[11], which reported that the application of second-order moment invariants is useful in quantitatively describing this morphology in the two-dimensional (2D) cross-sectional microstructure of γ/γ′ two-phase superalloys. Here, the absolute moment invariants ω_1 and ω_2 are defined as

$$\omega_1 = \frac{2A^2}{\bar{\mu}_{20} + \bar{\mu}_{02}} \quad (0 < \omega_1 \leq 4\pi) \tag{1}$$

And

$$\omega_1 = \frac{A^4}{\bar{\mu}_{20}\bar{\mu}_{02} - \bar{\mu}_{11}^2} \left(\omega_1^2 < \omega_2 \leq 16\pi^2\right) \tag{2}$$

In these equations, A is the cross-sectional area of the precipitates, and $\bar{\mu}_{pq}$ is the center moment taken from the mass center of the particle image defined by the following equation[12]:

$$\bar{\mu}_{pq} = \iint \left(x - \frac{\mu_{10}}{A}\right)^p \left(y - \frac{\mu_{01}}{A}\right)^q d^2\mathbf{r} \tag{3}$$

where (p, q) are arbitrary natural numbers that are set to (2, 0), (0, 2), and (1, 1) when considering a second-order moment.

This method can evaluate a variety of precipitated γ′ morphologies, such as cuboidal, spherical, and octodendritic shape. The absolute moment invariant ω_2 is able to evaluate the magnitude of cuboidal and octodendritic morphology[13]. By contrast, the absolute moment invariant ω_1 can evaluate aspect ratio.

Some of the γ′ particles interact and change morphology. Here, we use the term "group" to refer to a group of particles whose shape appears to be a result of particle interaction, such as, the particle that we refer to as, being aligned or arrayed. The fraction of interacting particles is quantified as follows[5]:

$$v = \frac{N^*}{N} \tag{4}$$

where N and N^* are the normal and group particle density and v is the dispersion parameter, respectively. The group of interacting particles is defined as those satisfying three conditions; that is, first, they have flat γ/γ′ interfaces, second, they do not overlap with the particles existing in the depth direction, and third, their channel is sufficient to narrow.

RESULTS

Microstructure of Superalloys

Figure 1 compares the microstructure of each alloy after 10–4000 h of aging at 1173 K. In the large misfit alloys, i.e. Inconel X-750 and Alloy 80A, the morphology of γ′ particles exhibits cuboidal for 10–100 h. The morphology evolves from cuboidal to irregular after 1000 h. In terms of the dispersion, for the 10–1000 h aged specimen the distribution of γ′ particles are heterogeneous; some particles are localized each other. In Udimet 520 with low misfit, the morphology of γ′ particles changed from spherical to cuboidal, and the dispersion exhibited localizing as described above. In Udimet 720Li with near zero misfit, the spherical morphology of γ′ particles remains unchanged throughout the aging. It is suggested that the microstructure evolution of the wrought Ni-based superalloys under the coarsening can classify the γ′ morphology into two types of coarsening processes, which are separated into depending on whether the shape of γ′ particles is spherical or not, and each coarsening process is defined as "localization process" and "aggregation process". Here, Inconel X-750, Alloy 80A and Udimet 520 are classified to "localization process", and Udimet 720Li to "aggregation process", respectively. As described above, the difference observed in the microstructure when the superalloys were aged at 1173 K, was most pronounced in the size, morphology and dispersion of γ′ particles. Therefore, in the following sections, these three parameters are quantified and evaluated from the misfit value.

Microstructure Quantification

Figure 2 shows the plots of the diameter of the secondary γ′ particles vs. aging time. In the all alloys, d linearly increased when increasing the aging time above 1 h, and the gradient was 0.33, which suggests that it increased along the Ostwald ripening during the aging treatment. It was found that the kinetics of particle coarsening during the coarsening process is the same regardless of the lattice misfit and γ′ volume fraction. However, for extremely long aging time, in the plots of Inconel X-750, Alloy 80A and Udimet 520, which are classified into the localization process, are located below the straight line with a slope of 0.33.

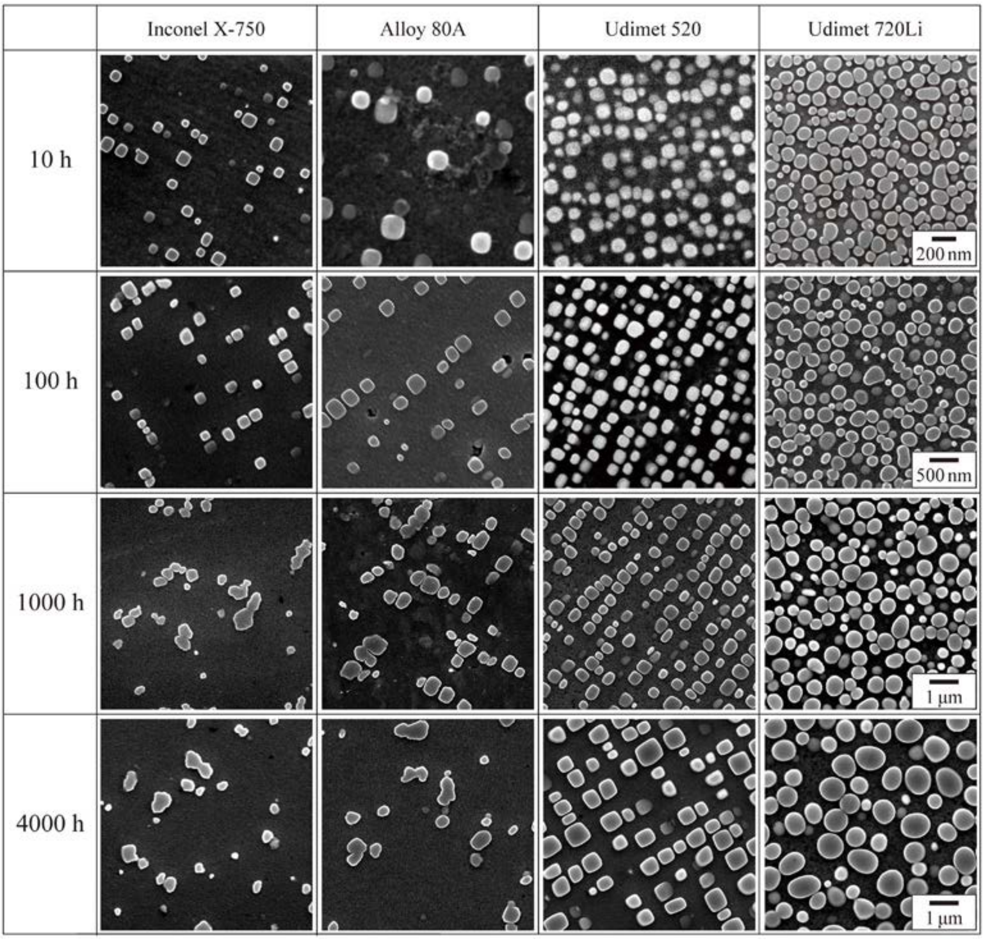

Figure 1: FE-SEM images of Inconel X-750, Alloy 80A, Udimet 520, and Udimet 720Li solution-treated at supersolvus temperatures, followed by the aging treatment at 1173 K.

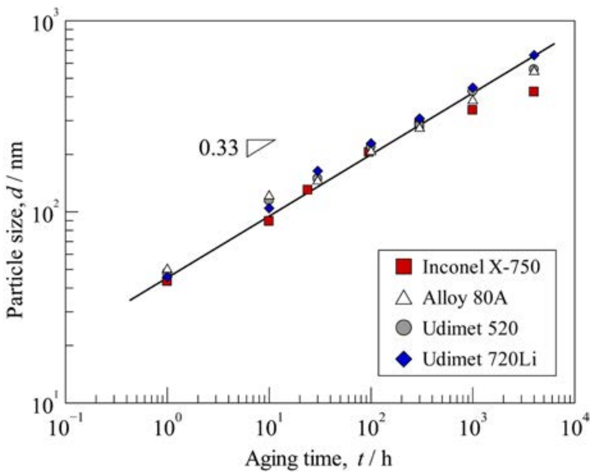

Figure 2: Plots of particle size vs. aging time at 1173 K for the wrought nickel-based superalloys.

Based on the SEM observation in the previous section, the morphological changes were quantified using absolute moment invariants. The median obtained from each (ω_1, ω_2) plots. The median of (ω_1, ω_2) for the aged specimens indicates a summary on a single plot in Fig. 3, where the former can be taken within the area surrounded by a dashed line having (4π, $16\pi^2$) as the maximum value. When the precipitate morphology is perfectly spherical, the ω_1 and ω_2 values are 4π and $16\pi^2$, respectively, corresponding to the domain maxima. As the square degree increases, the position of the (ω_1, ω_2) plot moves to the left and down on the parabola at the right end of the domain. When the morphology is perfectly cuboidal, ω_1 and ω_2 become 12.0 and 144, respectively.

In the plots of Inconel X-750, which are classified into the localization process, at 1 h, the median values of moment invariants are (ω_1, ω_2) = (12.5, 157.5), which is corresponding to the spherical shape. The values of (ω_1, ω_2) decrease with increasing aging time. After reaching the minimum value of (ω_1, ω_2) = (11.9, 152.5) at 300 h, the value increases with increasing aging time again. The change of value is corresponding to the morphological change from a spherical to a cuboidal and, to a spherical again (a). In contrast, for Udimet 720Li with zero misfits, the values of (ω_1, ω_2) increase with the aging, and the plot at 4000 h is (ω_1, ω_2) = (12.5, 157.7), which is very close to the domain maxima (ω_1, ω_2) = (4π, $16\pi^2$), revealing a true circular shape (b).

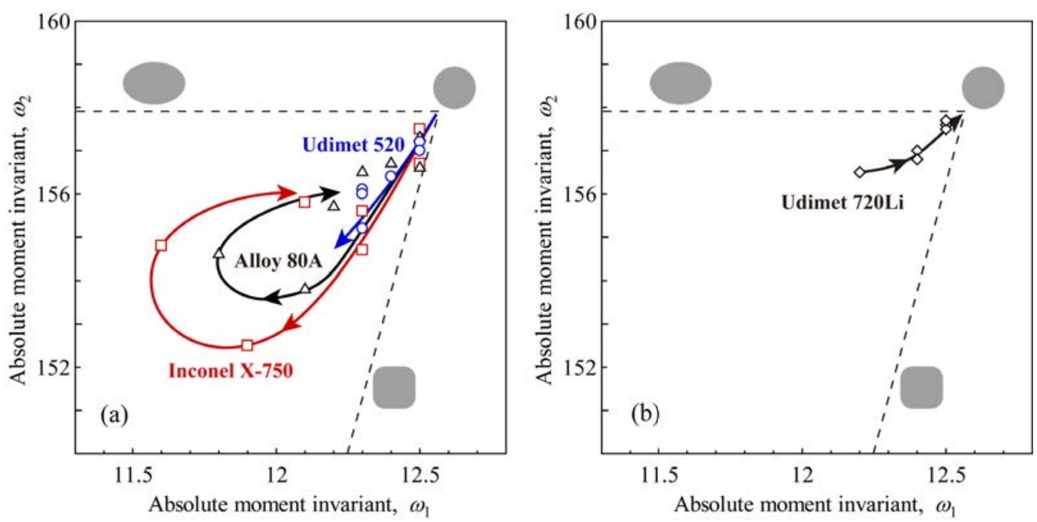

Figure 3: Changes of absolute moment invariant (ω_1, ω_2) plot with aging at 1173 K for Inconel X-750, Alloy 80A, Udimet 520 (a), and Udimet 720Li (b).

Figure 4 shows the change in dispersion parameter v with increasing aging time for the alloys of "localization process". This parameter is defined by Formula 1. In the plots of Inconel X-750, the parameter decreases at 1 h of aging and reaches a minimum of 0.7 at approximately 100 h. Then, it increases with aging and reaches a maximum value. The same tendency is shown for other superalloys. Here, the absolute value of misfit is [Inconel X-750] > [Alloy 80A] > [Udimet 520], and the order which these parameters start decreasing is [Inconel X-750] > [Alloy 80A] > [Udimet 520], too. Therefore, the parameter starts decreasing earlier as the absolute value of misfit is larger.

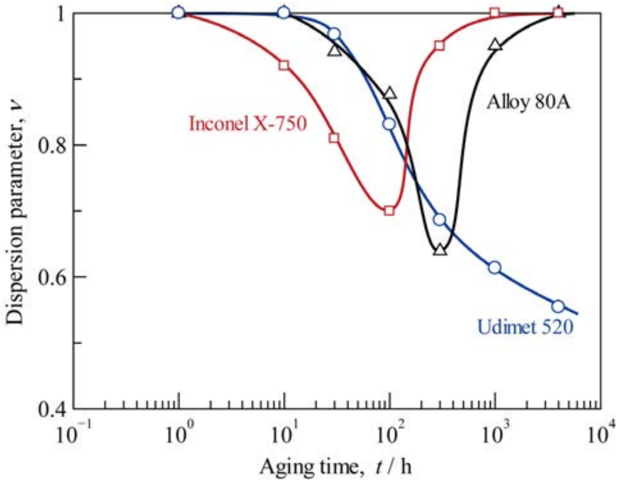

Figure 4: Plots of dispersion parameter vs. aging time at 1173 K for the wrought nickel-based superalloys.

DISCUSSION

Ni-based superalloys examined in this study possess diverse precipitate morphologies though coarsening process. As mentioned above, the coarsening process is divided generally into two processes, “localization process” and “aggregation process”. Their thermodynamic driving forces are considered to be as follows. “Localization process” is defined as the coarsening phenomenon where cubic particles are arranged in the <100> direction; which is driven by elastic energy due to lattice misfit. “Aggregation process” is defined as the phenomenon in which adjacent spherical particles coarsen while sharing their interfaces; which is driven by interfacial energy.

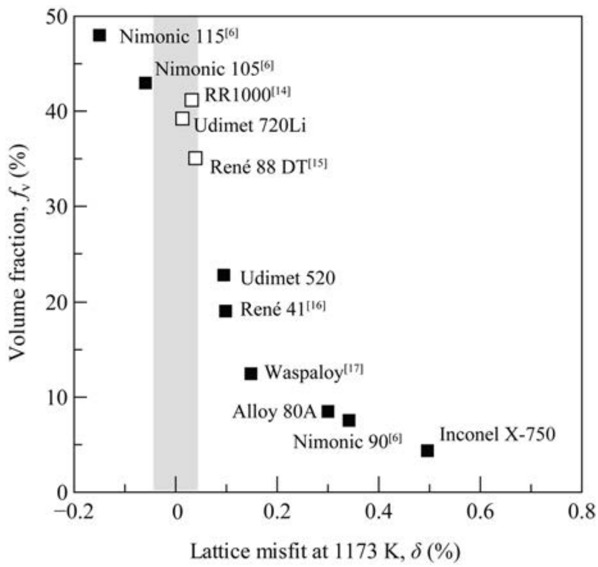

Figure 5: Classification of coarsening process for the wrought nickel-based superalloys. Solid squares mean the superalloys which show the localization process of γ′ precipitates, while open squares indicate that showing the aggregation process during coarsening.

Based on the SEM observation and microstructure quantification, the correlation between the coarsening process and microstructure parameter such as volume fraction and lattice misfit are summarized in Fig. 5, for popular wrought Ni-based superalloys. Except for the superalloys used in this study, we referred to the microstructure of previous studies[6,14–17]. The following two things can be understood from this conceptual diagram. First, the existing Ni-based superalloys can be divided into two major groups: low volume fraction, high misfit alloys and high volume fraction, low misfit alloys. Another, the coarsening process strongly depends on lattice misfit, not volume fraction; in case of the alloys with large misfit, it becomes "localization process", when not, it becomes "aggregation process".

CONCLUSIONS

Microstructure observations were performed for the four kinds of wrought Ni-based superalloys aged at 1173 K, and the effect of volume fraction and misfit on the coarsening process of the superalloys was also investigated. The results obtained in this study are summarized as follows.

(1) In the superalloys with large misfit such as Inconel X-750, Alloy 80A, and Udimet 520, the morphology of γ′ precipitates becomes cuboidal shape during the aging, and the γ′ precipitates are aligned in the <100> direction. This phenomenon is defined as localization process.
(2) In the superalloys with zero misfit, Udimet 720Li, the morphology of γ′ precipitates becomes spherical shape during the aging, and the γ′ precipitates coarsen while overlapping their interfaces. This phenomenon is defined as aggregation process.

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