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Effect of Mo on the thermal stability of γ′ precipitate in Inconel 740 alloy

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ABSTRACT

The effect of Mo on gamma prime (γ′) coarsening kinetics of Ni–25Cr–20Co–1.8Ti–0.9Al–2Nb–0.03C–xMo (x = 0.5, 3, 6 wt.%) alloys was investigated with respect to the activation energy for γ′ precipitate coarsening. The coarsening rates were measured at temperatures of 760 °C, 780 °C, and 810 °C up to 500 h. Coarsening rate decreased with increasing Mo, and the activation energies for coarsening were determined to be 245 kJ/mol, 261 kJ/mol, and 278 kJ/mol for 0.5 wt.% Mo, 3 wt.% Mo, and 6 wt.% Mo, respectively.

1. Introduction

Nickel-based superalloys are widely studied as a candidate material within coal-fired power plants due to their high creep strength and excellent corrosion and oxidation resistance at high temperatures. Among the nickel-based superalloys, Inconel 740 was developed for steam boiler tubing in advanced ultra-supercritical fossil power plants [1].

The high temperature properties of Inconel 740 are known to be the result of fine dispersions of the γ′ precipitate. Hence, after exposure of this alloy to high temperatures, the mean radius of the γ′ precipitates increases due to coarsening, and this coarsening may result in degradation of the thermal stability. To achieve high thermal stability, it is necessary to study the kinetics of γ′-precipitate coarsening behavior. In previous investigations, the coarsening rate was controlled by volume diffusion [2,3]. For that reason, numerous studies have examined the influence of alloying elements affecting the diffusivity of solute atoms so that the coarsening rate can be reduced [4–6].

In previous investigations, Fährmann et al. [7] observed that the coarsening rate decreased and the activation energy for coarsening increased with increasing Mo content in the Ni–Al–Mo system. It was also reported that the solute controlling the coarsening rate was Al in the Mo concentration range from 8 wt.% to 13 wt.% and Mo in the Mo concentration of 20 wt.%. Namely, the solute controlling the coarsening rate changed to Mo with increasing Mo content. As a consequence of this, it was reported that the activation energy for coarsening increased and the coarsening rate decreased. Thus, the Mo played a role in the higher thermal stability. Hence, it was considered that Inconel 740 with added Mo increased the thermal stability. However, it was confirmed that the solute controlling the coarsening rate for Inconel 740 was Al or Ti [8]. Therefore, the effect of the Mo content on the coarsening rate, the activation energy for coarsening and partition coefficient of Ni–25Cr–20Co–1.8Ti–0.9Al–2Nb–0.03C–xMo (x = 0.5, 3, 6 wt.%) alloys were investigated in this study over a temperature range of 760 °C to 810 °C.

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2. Experimental Procedure

Ni–25Cr–20Co–1.8Ti–0.9Al–2Nb–0.03C–xMo (x = 0.5, 3, 6 wt.%) alloys were arc melted under an argon atmosphere using a water-cooled copper crucible and a non-consumable tungsten electrode. Each alloy was inverted and remelted at least 10 times to ensure homogeneity. The chemical composition of alloys was analyzed using an optical emission spectrometer, and the results are summarized in Table 1.

Specimens were solution-annealed at 1200 °C for 1 h and water quenched. Then, solutions were aged at 800 °C for 16 h and cooled in air. In this study, specimens were aged at 760 °C, 780 °C, and 810 °C for 50, 100, 150, 200, and 500 h to examine the effect of aging temperature and time on the coarsening of γ′ precipitates.

The morphological evolution was observed using field emission scanning electron microscopy (FE-SEM). Specimens were prepared for FE-SEM by mechanical grinding and polishing followed by electro-etching in a solution of 170 mL H_3PO_4 + 10 mL H_2SO_4 + 10 g CrO_3 at 3–4 V for 8–12 s at room temperature. The average precipitate size was measured via FE-SEM images using semi-automatic image analysis software. The radius of γ′ precipitate, r, was calculated from the traced areas using a circular-equivalence, i.e. $r = \sqrt{area/\pi}$, where the measurements were approximately equivalent to those determined from a planar section. Individual outlines of the precipitates' edges were labeled with a unique grayscale value employing a subroutine, BinaryLabel8, contained in a morphology collection plug-in developed for ImageJ [6]. To minimize the measurement error, more than 400 γ′ precipitates were measured in different areas of the samples.

Transmission electron microscopy (TEM) samples were fabricated by punching 3-mm diameter discs from 100- to 150-μm thick foils, which were produced by mechanical thinning. The 3-mm diameter discs were then jet electropolished employing a solution of 5 vol.% perchloric acid in methanol at −20 °C. Scanning transmission electron microscopy (STEM) and energy dispersive X-ray spectroscopy (EDS) were performed utilizing a JEOL 2100 operating at 200 kV. EDS was collected on 2048 channels and the acquired data was quantified using the Cliff–Lorimer approximations.

XRD was performed between 20° and 90° (2θ) at room temperature using a diffractometer with a Cu target and monochromator, a step size of 0.05°. A current of 50 mA and a voltage of 40 kV were employed. XRD pattern was shown Fig. 1. It was observed that there is no carbide.

3. Results and Discussion

3.1. Microstructural Characterization

The microstructures of alloys after aging are shown in Figs. 2–4. The γ′ precipitate shape for 3 Mo and 6 Mo alloys exhibited mainly a spherical morphology during aging. However, it was evident that the shape of γ′ precipitate consists of a cubic morphology over 200 h at 810 °C. For the 0.5 Mo alloy, the γ′ precipitate shape exhibited mainly a cubic shape during aging. This result implied that there was a transition

Table 1 – Chemical compositions of the specimens (wt.%).

Specimen	Mo	Co	Cr	Al	Ti	Nb	Si	Mn	C	Fe	Ni
0.5 Mo	0.4	19.8	24.9	0.9	1.8	2.1	0.5	0.3	0.02	0.7	Bal.
3 Mo	2.7	19.9	25.4	0.8	1.9	2.0	0.5	0.3	0.02	0.8	Bal.
6 Mo	5.8	20.7	26.4	0.9	1.8	2.0	0.5	0.2	0.03	0.5	Bal.

of precipitate shape from spherical to cubic. It was reported that the transition of γ′ precipitate shape depended on the total matrix/precipitate strain present due to the lattice mismatch [9]. The size of the γ′ precipitate became larger maintaining the spherical shape before the effects of strain were sufficient to influence the precipitate shape. Namely, it should be noted that for alloys of low misfit, the γ′ precipitate maintained the spherical shape for long. In our experiment, it was observed that the γ′ precipitate maintained for long with increasing Mo contents. This could suggest that the misfit decreased with increasing Mo contents, which is consistent with that of Wang et al. [10]. In addition, no coalescence behavior was evident in this work.

3.2. Coarsening Kinetics of the Precipitate

The sizes of the γ′ precipitates for the alloys aged at 760 °C, 780 °C, and 810 °C for different times are summarized in Table 2. At 760 °C, the mean size of the γ′ precipitates for the 0.5 Mo alloy grew from 19.1 nm after 50 h to 35.5 nm after 500 h. At the same temperature, the mean size of the γ′ precipitates for the 3 Mo alloy grew from 17.6 nm after 50 h to 27.8 nm after 500 h, and the mean size of the γ′ precipitates for the 6 Mo alloy grew from 17.1 nm after 50 h to 26.6 nm after 500 h. At 500 h, the mean size of the γ′ precipitates for the 0.5 Mo alloy grew from 35.5 nm at 760 °C to 54.0 nm at 810 °C. At same time, the mean size of the γ′ precipitates for the 3 Mo alloy grew from 27.8 nm at 760 °C to 41.9 nm at 810 °C, and the mean size of the γ′ precipitates for the 6 Mo alloy grew from 26.6 nm at 760 °C to 41.0 nm at 810 °C. It was observed that the growth of the γ′ precipitate increased as the temperature and time increased, but most notably when

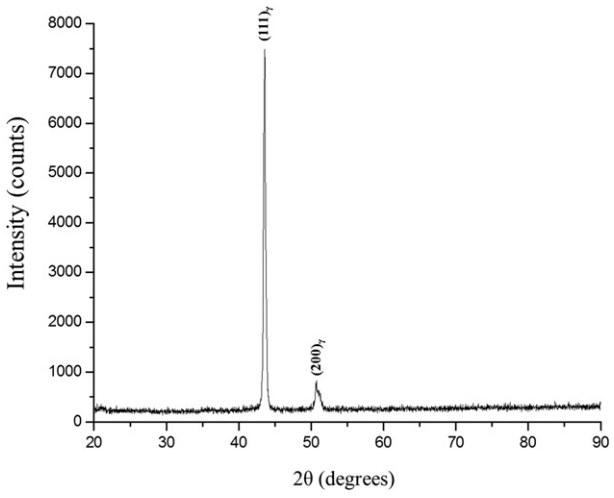

Fig. 1 – XRD pattern of the 6 Mo alloy.