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Variations in overall- and phase-hardness of a new Ni-based superalloy during isothermal aging

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ABSTRACT

Influence of isothermal aging on the microstructures and hardness in Inconel 740, a relatively new Ni-based superalloy, was explored using the specimens aged at 810 °C for different times. As aging time increased, the size of gamma prime precipitates continuously increased while their fraction remained almost constant. Nanoindentation experiments revealed that the overall hardness increased till the aging time of 100 h and then decreased with the aging time. Estimation of phase hardness by applying a simple rule-of-mixture showed that, with aging time, the hardness of gamma matrix decreased whereas that of gamma prime precipitates increased. The aging-induced strength change is discussed in terms of the possible contributions of precipitation strengthening and solid solution strengthening.

1. Introduction

The Inconel 740, a relatively new member of Ni-based superalloy family, was developed for the applications to steam boiler tubing in 'Advanced Ultra-SuperCritical (A-USC)' fossil power plants [1–4]. Since the target steam condition of the new boiler system is above 375 bar and 700 °C, this alloy was designed to have excellent performances (such as good microstructure stability, high resistance to coal-ash-corrosion/oxidation, and high creep-rupture strength) at high temperature up to 770 °C [1–4].

Like many other Ni-based superalloys, Inconel 740 is primarily strengthened by the precipitation of very fine gamma prime (γ') (having an ordered face-centered cubic structure) in the disordered gamma (γ) matrix [1–4]. It is generally accepted that the precipitation strengthening in Ni-based superalloys is mainly controlled by cutting mechanism rather than bowing (or typically referred to as Orowan) mechanism [5]: while a pair of $a/2\langle 1\ \bar{1}\ 0\rangle\{1\,1\,1\}$ dislocations passes through the γ/γ' structure, the first dislocation enters the spherical γ' precipitates with the formation of an anti-phase boundary (APB) and the following dislocation removes it [6]. This type of cutting mechanism can be roughly subdivided into two groups; weakly coupled dislocations (WCD or weak pair-coupling) model [7] and strongly coupled dislocations (SCD or strong pair-coupling) model [8]. In superalloys, the former is typically applied to the case that the size and volume fraction of γ' are small [7], whereas the latter is known to be more appropriate for the case that the spacing of the dislocation pairs becomes comparable to the particle diameter [8].

Ni-based superalloys inevitably experience various microstructural changes during their high temperature service life, such as γ' coarsening, formation of topologically close-packed (TCP) phase, and increasing carbides contents (mostly $M_{23}C_6$) [9–12]. Thus, the influence of aging on the microstructure and mechanical properties of Ni-based superalloys have been studied extensively over the past decades [1,3,4,9–12]. However, limited efforts have been made on the topic for Inconel 740. In addition, to our best knowledge, there has been no attempt to analyze the role of each phase in the strength change in detail. With this in mind, in this study, we have explored how the overall hardness as well as phase hardness of Inconel 740 can be affected by the isothermal aging. Results are discussed in terms of aging-induced changes in the contributions of precipitation strengthening and solid solution strengthening in this new superalloy.

2. Experiments

Examined material is a commercial grade Inconel 740 (produced at Special Metals Corporation) whose nominal chemical composition (in wt.%) is 0.03C–25Cr–0.5Mo–20Co–0.9Al–1.8Ti–2Nb–0.3Mn–0.7Fe–0.5Si with the balance Ni. Since the dissolution temperature of γ' precipitates in this alloy is known to be 821 °C [1], samples were isothermally aged at 810 °C for different times (100, 200, 500 and 1000 h) and compared with as-received sample. The average grain

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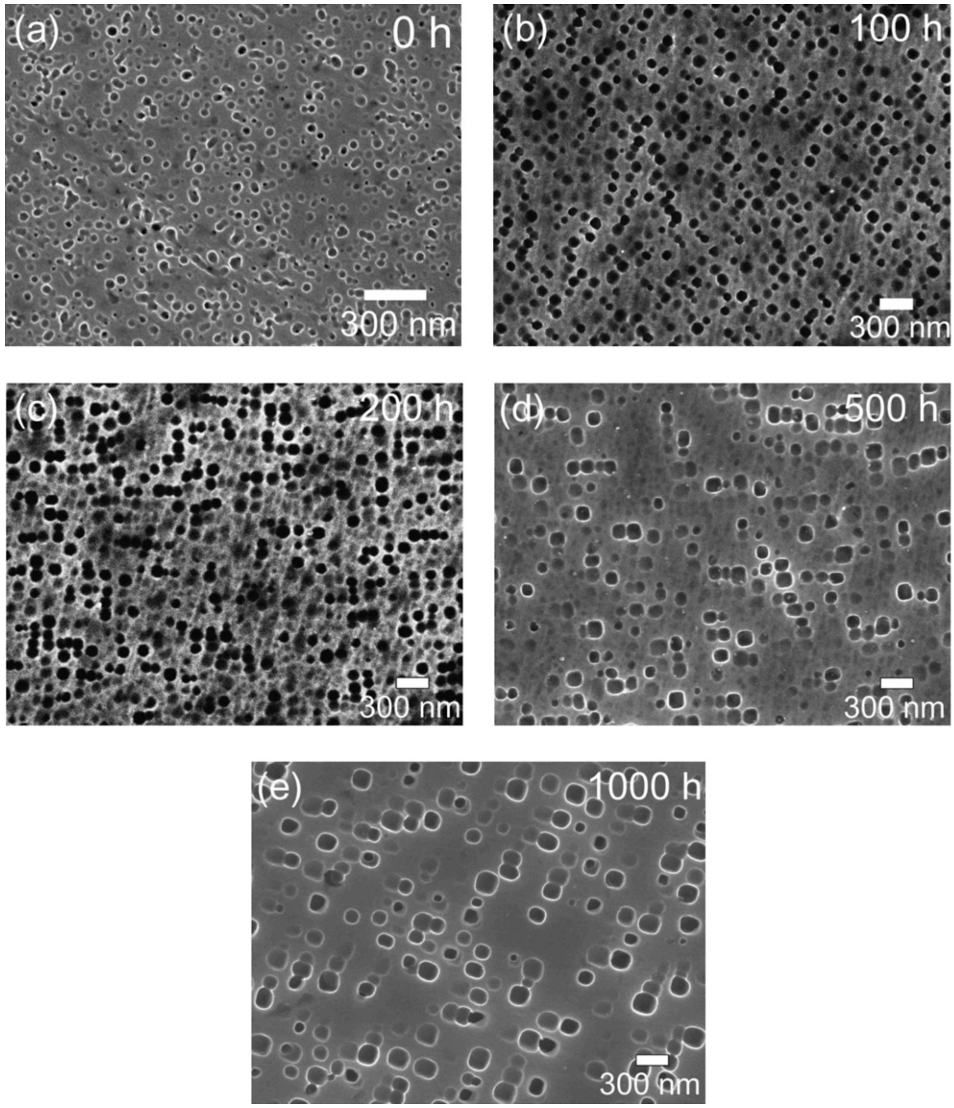

Fig. 1. SEM micrographs used for measuring the fraction of γ' precipitate (chemically etched samples) in the samples aged for (a) 0 h; (b) 100 h; (c) 200 h; (d) 500 h; (e) 1000 h.

size in the as-received sample was about 150 μm which is larger than nominal grain size in the literature [1].

Microstructural change due to aging was examined by using field emission scanning electron microscopy, FE-SEM (JSM-6340F, JEOL Ltd., Tokyo, Japan). With the SEM micrographs, the size and fraction of γ' were quantitatively measured using an image analyzer software (Image-pro, Media Cybernetics Inc., Bethesda, MD). An electrical etching (at 10 V for 90 s in a solution of 10 ml perchloric acid, 30 ml propionic acid and 40 ml ethanol) and a chemical etching (for 10 s in a solution of 33 ml nitric acid and 66 ml hydrochloric acid) were adopted for measuring the size and fraction of γ' respectively. Adoption of different methods was because the electrical etching (that selectively etches out the γ matrix having a large fraction) could induce an overestimation of γ' fraction, whereas the chemical etching (that selectively etches out the γ matrix) could result in an overestimation of γ' size.

The transmission electron microscopy (TEM) characterization was performed on selected samples with a CM-30 (Philips Electronic Corp., Mahwah, NJ) operating at 200 keV. Energy dispersive X-ray microanalysis was performed using a Link Pentafet energy-dispersive spectrometer (EDS) with an ultra thin window, controlled using the Link eXL system. To prepare TEM thin foils, thin sheet were cut out using a low-speed diamond saw and were mechanically thinned down to about 100 μm in thickness using a SiC paper of #1000. Discs having a diameter of 3 mm were punched out of the thin sheets and electropolished to perforation with an 800 ml methanol and 200 ml perchloric acid electrolyte at −50 °C and 20 V, using a double-jet electro polisher.

To investigate the aging-induced hardness change, nanoindentation experiments were carried out using a Nanoindenter-XP (MTS System Corp., Oak Ridge, TN) with a common Berkovich indenter. During the test, the sample was loaded up to the peak load (P_{max}) of 3 mN under a constant strain rate of 0.05 s^{-1}. The tip calibration and the hardness calculation were conducted in accordance with the Oliver–Pharr method [13]. The specimen surfaces were initially ground with fine SiC paper of #2000 and to avoid artifacts related to a hardened surface layer, indentation tests were made on electro-polished surface instead of mechanically polished one. Electrical polishing was conducted in a solution of 850 ml methanol and 150 ml hydrochloric acid at a room temperature and 40 V for 20 s.