

Assessment of the stress-oriented precipitation hardening designed by interior residual stress during ageing in IN718 superalloy

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ABSTRACT

The following study presents a novel approach that utilizes residual stresses inside a component to produce stress-oriented precipitation and achieves texture strengthening during the ageing treatment. Refined investigations for the stress-oriented precipitation of γ'' were achieved via transmission electron microscopes (TEM) and neutron diffraction (ND). The results showed that all three variants of γ'' nucleated at short ageing times. The orienting effect of stress was appreciable only during the Ostwald ripening, due to the change of the γ''/γ lattice mismatch. The effect that the stress-oriented precipitation had on the mechanical properties was evaluated and analyzed via tensile tests.

1. Introduction

Precipitate hardening is a major strengthening mechanism that is used to control the mechanical properties of various alloys. The particles act as obstacles of dislocation motion and enhance the strength of alloys through precipitation reactions. The fundamentals of the various precipitation processes have been studied, showing that precipitation is typically composed of three stages: nucleation, growth, and coarsening of the precipitates [1]. Internal stress, which produces elastic strain in crystals, could directly affect the equilibrium conditions between the phases involved and inversely alter the driving force. Stress ageing is an efficient treatment for controlling the spatial arrangement of these coherent precipitate variants [2–5]. Stress-oriented precipitation could occur as a result of the preferential formation of particular nuclei or the growth of particular types of variants with the presence of an applied stress during ageing. For example, stress-oriented precipitations of the Au particles in the Fe–Mo–Au Alloy [6,7], the $\text{Ni}_3(\text{Al,Ti})$ in the Ni–base alloy [8,9], and the G.P. zones and the θ' in the Al–Cu alloys [4,5,10,11] were reported. It remains unclear if the stress-orienting process occurs primarily during nucleation or during variant growth and coarsening. D.Y. Li et al. [11] demonstrated that the stress orienting effect is more effective during the nucleation stage, which was substantiated with experimental observations. However, Sauthoff [6,7] and Gao et al. [12]

found that the stress orienting effect primarily occurs during the coarsening process.

Inconel 718 (or alloy 718) is a precipitation-strengthened Ni-based superalloy that has been widely used in aviation, space flight, energy, and chemical engineering industries [13,14]. The major precipitating phase in alloy 718 are the disk-shaped γ'' (Ni_3Nb , D0_{22} , tetragonal), as in the peak aged condition the volume fraction of the γ'' that is observed to be $\sim 15\%$, and γ' phase (L1_2 , cubic) is $\sim 4\%$ [15]. The γ'' displays a tetragonal structure and is coherently embedded in the cubic γ matrix with an orientation relationship of $\{100\}_{\gamma''} // \{100\}_{\gamma}$ and $[001]_{\gamma''} // [001]_{\gamma}$, where three possible variants with various $\{100\}$ habit planes appear. Oblak et al. [16] found that the precipitation of specific variants of γ'' are controlled by external loads during ageing in an [001] single crystal alloy 718. The research suggests that a lower free energy induced by the external load in a specific variant resulted in the presence of this specific variant and the absence of the others. Gao et al. [12] found that the preferential coarsening of the γ'' precipitates in a polycrystalline alloy 718 could be induced by creep. A systematic study on the stress-orienting process occurred primarily during the nucleation, growth or the coarsening has not been conducted.

The precipitation hardening typically results from the coherency strains that arise from the large lattice mismatch between the γ'' precipitates and the γ matrix in alloy 718 [17], which is sensitive to the

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size, the morphology, and the distribution of the γ'' precipitates. The yield strength of the alloy increased more than the stress-free samples because of the stress-oriented effect via ageing under a tensile load [16]. It is not feasible to apply external stresses on the full-sized superalloy workpieces (e.g. gas turbine discs). Residual stress that remains in a body that is stationary and at equilibrium with its surroundings [18] could be induced and designed to control the stress-oriented precipitation during ageing. A sequence of the thermo-mechanical processes during the manufacturing of these metallic components, such as forging, quenching, and welding, could produce uneven plastic deformation and result in a high level of residual stress. Residual stress in the superalloy components primarily occurs during the rapid post-solution cooling (e.g., quenching in water or oil) [19,20]. In order to achieve the specific requirements within the oilfield application, wrought alloy 718 is typically subjected to a solid solution treatment between 1021 °C and 1052 °C for 1–2.5 h, followed by water quenching. They are often compressed at the rim, but tensile in the center and the magnitude is around $-400 \sim 400$ MPa for alloy 718 [19,20]. The alloy is then typically subjected to a one-step ageing treatment between 774 °C and 802 °C for 6–8 h [21,22]. The quenching-induced residual stress could exist as a pre-condition of the γ'' precipitation. The distribution of the residual stress could be designed by controlling the boundary condition of the cooling [23,24].

In the present study, the stress orienting effect of the γ'' precipitates were initially identified in the samples that were aged under a tensile load with various ageing times. Factors that could affect the formation of the stress-oriented precipitation were discussed in a polycrystalline system. The stress-oriented precipitate hardening was evaluated by the tensile tests after they were aged for 8 h. A water-quenched cylindrical sample was manufactured to generate significant interior residual stress. The refined experiments on the preferential orientation of γ'' precipitates in alloy 718 were achieved via transmission electron microscope (TEM), field emission scanning electron microscopy (FE-SEM), and neutron diffraction (ND).

2. Experimental procedures

The alloy 718 was manufactured through the vacuum induction melting (VIM), the electro-slag remelting (ESR), and the vacuum arc remelting (VAR) processes. The ingot was subjected to high temperature diffusion with 1160 °C / 24 h + 1190 °C / 72 h + air-cooling, and was then radially forged into a round bar with a diameter of 220 mm. Table 1 shows the chemical composition (wt%) of alloy 718.

The material preparation methods and the experiments are described as follows. The rod specimens (12 × 67 mm) for the stress-free samples and the stress-aged samples were subjected to the following treatments: (i) solid solution treatment at 1030 °C for 1 h, (ii) air cooling (80 °C/min) from 1030 °C to 500 °C to minimize the residual stress and to avoid the precipitation of the γ'' phase [25], and (iii) ageing at 790 °C for 8 h under 0 MPa (stress-free), 300 MPa in tension, and -300 MPa in compression controlled with an electromechanical universal testing machine (Fig. 1). The polycrystalline microstructure image before ageing and the corresponding inverse pole figure Z (IPF-Z) are shown in Fig. 2. It primarily consisted of fcc- γ grain with an average grain size of approximately 150 μm . A small quantity of carbide was observed (white spots), and there was no visible delta phase precipitated at the grain boundary. The 300 MPa and -300 MPa stress represented the residual stress level in a turbine disk following quenching [19,20].

Table 1
Chemical composition of alloy 718 superalloy (in wt%).

C	Cr	Nb	Ti	Al	Mo	Fe	Ni
0.023	18.05	5.42	0.91	0.48	2.90	18	Balanced

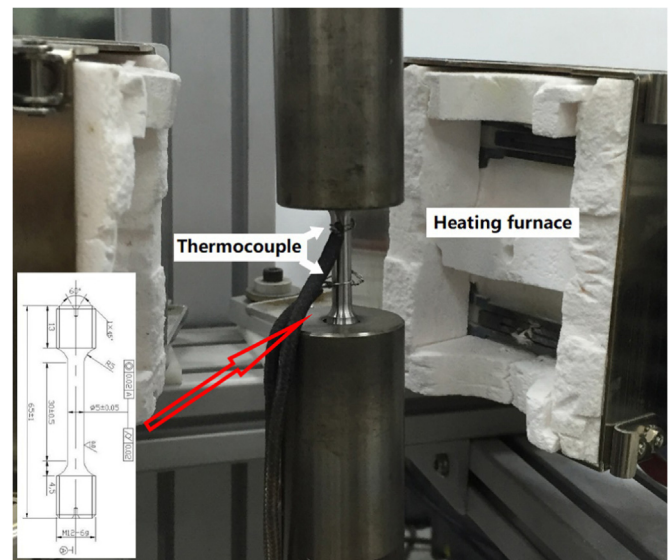


Fig. 1. A photograph showing the tensile test rig before stress ageing at 790 °C.

A relatively large specimen, containing residual stress, was also prepared in order to study the effect that the internal stress had on the stress-oriented precipitation. A cylindrical specimen (diameter and height of 40 mm) with a uniform microstructure was subjected to the following treatments (Fig. 3): (i) solid solution treatment at 1030 °C for 1 h, (ii) water cooling (over 200 °C/min from 1030 °C to 500 °C) to generate high-magnitude residual stresses and to avoid the formation of the γ'' precipitates, and then (iii) ageing at 790 °C for 8 h. A three-dimensional axisymmetric finite-element model of the quenching process was implemented with DEFORM software [20]. The model was based on a 30000-element mesh of the cylindrical geometry and incorporated a fully coupled thermal-mechanical analysis of the elastic-plastic deformation and the heat transfer.

The TEM specimens were prepared by performing electropolishing at about 20 V. The electrolyte contained 70% butanol, 20% ethanol, and 10% perchloric acid (volume fraction). TEM observations were performed on the FEI Tecnai G² F20 transmission electron microscope operated at 200 kV. The samples delegated to the FE-SEM observations were etched chemically with a mixed solution composited by 5 g CuCl_2 + 100 ml hydrochloric acid + 100 ml ethanol. The FE-SEM and the electron back scattered diffraction (EBSD) measurements were performed on a JSM-7800F (JEOL, Akishima, Japan) FE-SEM equipped with EBSD. The tensile tests were performed in accordance with the ISO 6892-1 2011 standard. In order to characterize the degree of anisotropy, small angle neutron scattering (SANS) experiments were performed via a V4 SANS instrument at Helmholtz Zentrum Berlin (HZB). The wavelength of the incident neutron was set at 0.60 nm, and the distance from the sample to detector was set at 8 m. Samples with a diameter of 6 mm and a thickness of 1 mm were used.

The residual stress fields in pieces of the quenched IN718 superalloy were characterized via neutron diffraction on the RSND diffractometer in the China Mianyang Research Reactor (China Academy of Engineering Physics, Mianyang, China). It was thought that the {311} reflection in the nickel-based alloys was unaffected by the intergranular microstrains [26], and the diffraction intensity and the noise-signal ratio were adequate for analyzing the stress data. The {311} peak was selected for the measurements. A monochromatic neutron beam with a nominal wave length of 1.593 Å was generated via a high-mosaicity germanium single crystal, which placed the {311} reflection from IN 718 at $\sim 94.5^\circ$ (Fig. 3).

Lattice spacing (d_{311}) were calculated using the Bragg's Law:

$$2d \cdot \sin \theta = \lambda \quad (1)$$

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