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Effect of double aging treatment on structure in Inconel 718 alloy

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Inconel 718 alloy, a Nb-modified Fe-Cr-Ni-base superalloy, has been widely used in gas turbine and related applications due to its good mechanical properties and structural stability at elevated temperatures (∼650 °C). It is composed of γ matrix, NbC, γ', γ'' and δ phases, among which γ'' phase plays a main role in strengthening the alloy, and γ' phase, less than γ'' phase in contents, also strengthens the alloy to a certain extent, however, the existences of δ phases are disadvantageous to the mechanical properties of alloy. Y. Desvallees *et al.* [1] found that in Inconel 718 alloy the existences of δ phases reduce the quantity of γ' and γ'' phases, giving rise to low yield strength. Meanwhile, low-cycle fatigue and fatigue endurance can be diminished due to the fact that voids can form and grow easily in the position where δ phases precipitate. In addition, they also found that the ability of anti-crack extension of alloy can be improved and the growing tendency of grains can be controlled if the δ phases with disc shape precipitate along a certain direction, which is to say, the mechanical properties of this alloy depend significantly on the contents and shape of γ', γ'' and δ phases. It is clear that both the contents and shape of γ', γ'' and δ phases can change under different treatment techniques, leading to different mechanical properties of alloy. Krueger *et al.* [2] pointed out that there exist three kinds of thermomechanical treatment techniques according to the structure and properties of Inconel 718 alloy required in different service conditions: standard aging (STD), high strength aging (HS) and double aging (DA), among which DA is the most important technique. The components made by DA technique have fine and homogenous grains, very high strength, good ductility, low-cycle fatigue (LCF) and the ability of anti-crack extension.

Shuqi Li *et al.* [3] indicted that in Inconel 718 alloy the δ phases can precipitate along grain boundary through DA technique, which is beneficial to restrain the extension of cracks in grain. On the other hand, the contents of element-Nb can be consumed with the precipitating of δ phases, leading to the occurrence of depleted zone for γ' and γ'' phase around the precipitates of δ phases. Moreover, the stress concentration in the crack tip can be relieved in depleted zone if there exist the cracks in alloy, which restrain further the extension of cracks. In order to get enough strength, good ductility, the resistance to high temperature creep, and low-cycle fatigue corresponding to practical need or special use in Inconel 718 alloy, it is important to adjust grain size and the quantity of γ', γ'' and δ phases. In this letter, based on the study of the characteristic of phase transformation via XRD [4–6] and SEM in Inconel 718 alloy under three different double aging temperatures, we pointed out an optimized aging technique.

The chemical composition of Inconel 718 alloy used in this experiment is shown in Table I. The alloy rods in diameter of about 30 mm were heat treated at 980 °C for 1 h followed by cold rolling to plates in thickness of about 16 mm, and then quenched in water immediately. In order to study the effect of different aging techniques on the structure, three techniques are used:

(A) 750 °C, 8 h $\underline{55\,^\circ\mathrm{C/h}}$ 650 °C, 8 h
(B) 720 °C, 8 h $\underline{55\,^\circ\mathrm{C/h}}$ 620 °C, 8 h
(C) 690 °C, 8 h $\underline{55\,^\circ\mathrm{C/h}}$ 620 °C, 8 h

A KYKY2000 SEM was used to observe the structures of Inconel 718 alloy. The reagent solution for metallographic etching is a mixture of 100 ml ethanol, 100 ml hydrochloric acid and 5 gram $CuCl_2$ solution. The phase contents were measured via XRD [4]. The samples for XRD were prepared by mechanical polishing followed by chemical etching. The lattice constants of austenite were precisely measured with Nelson-Riley extrapolation method [6].

Fig. 1a shows the microstructure via DA at 750 °C/8 h + 650 °C/8 h. It is clear from Fig. 1a that most of δ phases precipitate along grain boundary either with particle shape or with discontinuous stick shape. Besides, some of δ phases with discontinuous stick shape can extend from grain boundary to in-grain and only a small amount of δ phases are precipitated in grain. Fig. 1b shows the microstructure via DA at 720 °C/8 h + 620 °C/8 h. As can be seen that both γ' and γ'' phases with disc shape distribute in the matrix, most of δ phases form discontinuous stick shape and only a small amount of granular δ phases precipitate along grain boundary. Fig. 1c shows the microstructure via DA at 690 °C/8 h + 620 °C/8 h. It is obviously that both γ' and γ'' phases form fine disc shape in alloy, and δ

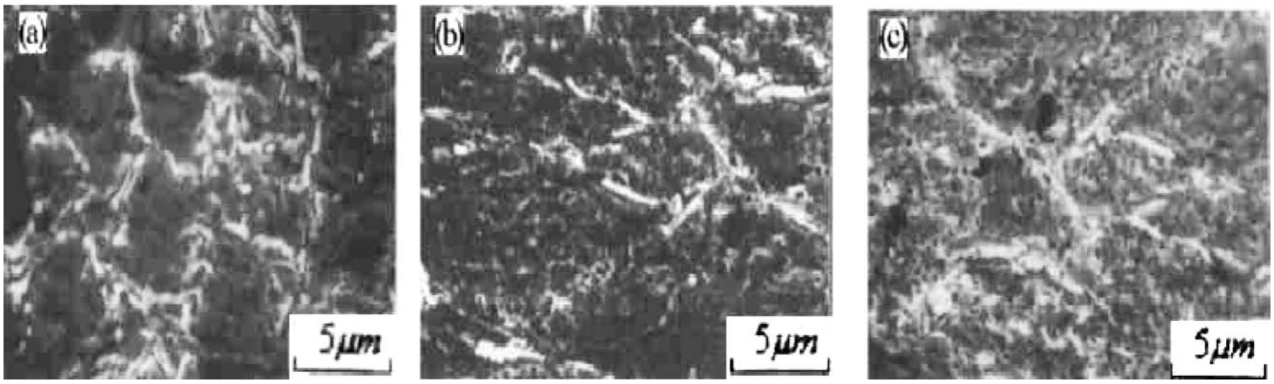

Figure 1 Micrograph of Inconel 718 alloy aged at (a) 750 °C/8 h + 650 °C/8 h, (b) 720 °C/8 h + 620 °C/8 h and (c) 690 °C/8 h + 620 °C/8 h, respectively.

phases with discontinuous stick shape distribute along grain boundary. Furthermore, from Fig. 1, it is clear that the grain size is very small since the temperature for solution treatment is low. According to the standards for evaluating the metallographic fineness of grain, we know that the fineness of grain is about grade 11 at 750 °C/8 h + 650 °C/8 h, about grade 13 at 720 °C/8 h + 620 °C/8 h, about grade 12 at 690 °C/8 h + 620 °C/8 h. Moreover, both γ' and γ'' phases with fine disc shape distribute in the matrix under three different double aging techniques. While for δ phases, with increasing aging temperature, they can change their shape from short discontinuous sticks shaped morphology to granule shaped morphology when they precipitate along grain boundary.

Fig. 2 shows the X-ray diffraction patterns of Inconel 718 alloy with different DA techniques. The presence of the NbC, δ and γ phases can be clearly identified from their diffraction peaks. However, the γ'' phases (112) diffraction peak is very close to the γ phase's diffraction peak. In addition, the γ' phase's diffraction peaks cannot be observed because of its crystal structure and its small amount. In order to get the contents of γ', γ'' and δ phases, the quantitative XRD analysis is used. The results are shown in Fig. 3. From Fig. 3, we can see that the contents of the γ', γ'' and δ phases by DA at 750 °C/8 h + 650 °C/8 h is the highest, while the contents of δ phase is the lowest by DA at 720 °C/8 h + 620 °C/8 h among three kinds of DA techniques. In addition, the weight percent of γ' and γ'' phase is almost equal under different DA techniques. Table II shows the lattice constant of austenite, which can be used in calculating the contents of the γ', γ'' and δ phases.

TABLE I Chemical compositions of Inconel 718 alloy used in this work (wt%)

Ni	Cr	Ti	C	Al	Nb	Mo	Mn	Si	P	Fe
52.4	18.87	0.98	0.041	0.54	5.26	2.95	0.1	0.11	0.006	bal.

TABLE II The lattice constant of austenite

750 °C + 650 °C	720 °C + 620 °C	690 °C + 620 °C
3.5975	3.5995	3.5992

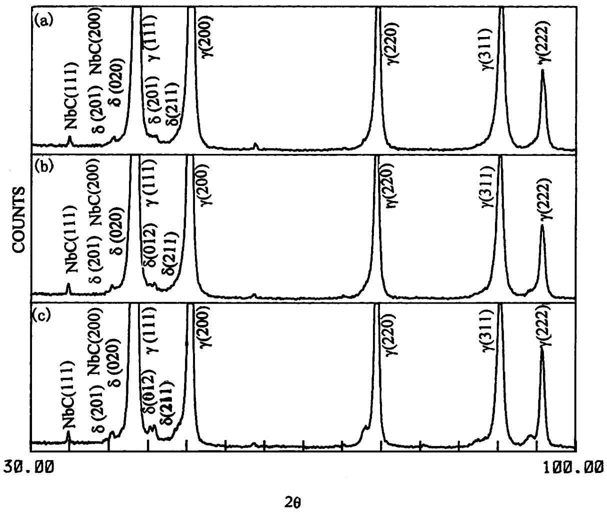

Figure 2 X-ray diffraction patterns of Inconel 718 alloy aged at (a) 750 °C/8 h + 650 °C/8 h, (b) 720 °C/8 h + 620 °C/8 h and (c) 690 °C/8 h + 620 °C/8 h, respectively.

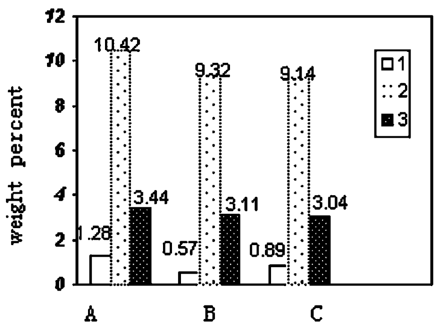

Figure 3 Relationship between the weight percentage of γ', γ'', δ phase and DA treatment states. 1-δ phase; 2-γ'' phase; 3-γ' phase.

By comparison of three kinds of DA techniques, the optimized technique of double aging under 720 °C/8 h + 620 °C/8 h is identified due to the fact that it can get higher contents of the γ' and γ'' phases, the lowest content of the δ phases and optimum structure in Inconel 718 alloy using this technique.

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