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Grain Growth Behavior of Inconel 625 Superalloy

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Abstract: The grain growth (GG) behavior of Inconel 625 superalloy was studied in the temperature range of 900－1 250 ℃ and holding time range of 10－80 min. Microstructures of the alloy were characterized by optical metallography, scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Grains grew obviously with either increasing temperature or extending holding time at temperatures above 1 050 ℃. However, at temperatures lower than 1 050 ℃, the GG was sluggish due to the pinning effect of carbide particles on grain boundary (GB). Threshold temperature for transition from mixed grain structure to uniform one was considered to be around 1 100 ℃. Once the temperatures surpassed 1 200 ℃, an instant increase in the grain size occurred showing no dependence on holding time. TEM analysis showed that the dominant second phase formed heterogeneously on the GB was M_6C, which significantly impeded grain growth. On the basis of experimental data, the mathematical model of GG was established, which can describe GG behavior of Inconel 625 alloy during solution treatment (ST) at 1 100－1 250 ℃. The activation energy for GG of Inconel 625 alloy was 207.3 kJ, which suggested that the GG of Inconel 625 alloy was controlled by the process of GB diffusion.

Key words: Inconel 625 alloy; growth kinetics; solution treatment; precipitation

Nickel-based alloy Inconel 625 is a solid solution strengthening alloy with face-centered-cubic structure, which has high tensile, creep and rupture strength as well as outstanding fatigue and thermal fatigue strength, oxidation resistance, and excellent weldability[1,2]. The alloy has been widely used in aerospace, marine, chemical, petrochemical and nuclear industries[3]. High contents of molybdenum and niobium, which provide stiffening effect on nickel-chromium matrix, can promote the strength of Inconel 625 alloy significantly, and thus precipitation strengthening treatments are not required. This alloy is mainly supplied under solution-heat-treated condition, while mill annealing is less commonly used. The microstructures of solution-treated Inconel 625 alloy are generally composed of primary carbides dispersed in a single phase matrix, with essentially clean grain boundaries. This is usually the optimum condition for the best elevated temperature properties in service and room temperature fabricability. Inconel 625 components manufactured by hot forming techniques should generally be solution heat treated. This is because the alloy would subject to precipitation of secondary carbides (rich in chromium or molybdenum) on the grain boundary (GB) during air cooling. The formation of these carbides may result in the depletion of chromium or molybdenum near GB, which enhances the susceptibility to intergranular attack. However, grain growth (GG) inevitably occurs when the alloy is exposed to solution annealing temperatures[4]. It is well known that grain size has significant effect on mechanical properties. Fine grain can result in larger strength and toughness of the alloy, while coarse grain can produce better high temperature creep resistance[5]. Optimal grain size can be achieved if the solution treatment (ST) is performed under an appropriate combination of heating temperature and holding time. Thus, it is essential to understand and predict the behavior of GG under the condition of ST. In re-

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cent years, the corrosion resistance, hot workability and weldability of Inconel 625 alloy have been investigated extensively[6-10], while the available information on GG behavior of Inconel 625 is limited in pulished literatures.

The aim of the present study was to examine the behavior of GG with respect to the influence of heating temperature, holding time and precipitates on evolution of grain microstructure. The mathematical model which related grain size to temperature and time was proposed. Parameters involved in this model were determined by regression of experimental data.

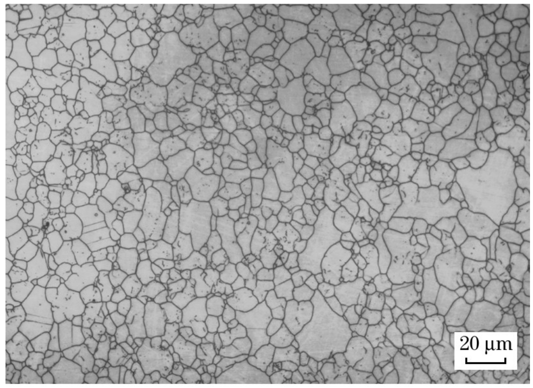

Fig. 1 Initial microstructure of Inconel 625 alloy

1 Experimental Procedures

Chemical composition (in mass%) of Inconel 625 alloy investigated is as follows: C 0.037, Si 0.02, Mn 0.01, Fe 0.11, Ti 0.32, Nb 3.68, Cr 20.51, Mo 9.65, Al 0.13, P 0.001, S 0.003, and Ni balance. The samples with size of 10 mm×15 mm×10 mm were machined from the hot-rolled plate of Inconel 625 alloy. The specimens were subsequently treated in the temperature range of 900−1250 ℃ for time ranging from 10 to 80 min in a muffle furnace, followed by water quenching. The polished specimens for optical metallography were etched in the potassium permanganate solution (1 g potassium permanganate and 10 mL concentrated sulfuric acid in 90 mL water) at 50 ℃ for 12 h. Average grain sizes of the alloy were measured by using the mean linear intercept method. The precipitate morphology was observed by scanning electron microscopy (SEM, S4300). Transmission electron microscopy (TEM, H-800) was used to characterize second phase in the selected samples, and the method to prepare thin foils for TEM examination was described in detail in previous work[11].

2 Results and Discussion

2.1 Effect of holding time on grain growth of Inconel 625 alloy

Optical image obtained from the specimen of hot-rolled plate of Inconel 625 alloy before ST is shown in Fig. 1. Microstructure observation revealed that the alloy underwent full recrystallization with final average grain size of 7 μm during hot rolling. Local mixed grains were observed, which might be associated with the secondary recrystallization.

The microstructures of the samples after thermal treatment at 1200 ℃ for various holding time are illustrated in Fig. 2, showing the evolution of grains with holding time. Comparing with Fig. 1, original regions of fine grain almost disappeared, and mixed grain microstructures were eliminated. It can be found that grain size increased significantly with holding time within 10 min, while GG became sluggish with further extending soaking time. Variations of grain size and rate of GG with time at various temperatures are plotted in Fig. 3. The curves showed that grain size increased with holding time (Fig. 3(a)), while GG rate declined with soaking time (Fig. 3(b)). In addition, it can be seen that the differences in grain size of the specimens exposed for 20−80 min were small, indicating that the effect of holding time on GG was weakened, which was consistent with the results of observation of grain microstructures. This result is similar to that of superaustenitic stainless steel 654SMO reported by Pu et al.[12]. As well documented, a reduction in GB energy is the driving force for the GG[13]. Theoretical analysis shows that the finer grain per unit of volume is, the larger total GB area is, and thus the total GB energy increases, which indicates that the GG is associated with a decrease in the GB area as a result of an increase in the average grain size. Therefore, since the alloy consists of a large number of fine grains at initial stage of heat preservation, which provides strong driving force for the GG, the grain evolves with a large growth rate. Subsequently, grain size increases as expense of fine grains with prolonging holding time, and the GG rate is reduced.

2.2 Effect of temperature on grain growth of Inconel 625 alloy

The microstructures of Inconel 625 alloy subjected to heat treatment at different temperatures for 20 min are illustrated in Fig. 4. It can be seen that both grain morphology and grain size of the alloy after thermal treatment at temperatures from 900 to