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Effect of Annealing Temperature on Tensile Properties of Inconel 600

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ABSTRACT

Inconel 600 is a well-known material for high temperature application. Therefore, the study on the effect of annealing to the microstructure and material properties was very important. In this research, Inconel 600 was heat treated at various annealing time and temperature. The aim of the study is to investigate the behavior of Inconel 600 when subjected to annealing temperatures in the range of 600^oC-1100^oC for 1 and 2 hours. The samples were prepared for heat treatment and tensile testing. Appropriate metallographic techniques were introduced to study the variations in grain size and material behavior of Inconel 600. The results were compared with as-received material. The analysis correlates the grain growth with time and temperatures. The size of the grains increases dramatically in the temperatures ranging from 1000^oC-1100^oC. The relation between tensile strength and grain size is inversely proportional and the solvus temperature of Inconel 600 alloy was identified to be occurred in the range of 1000^oC-1100^oC.

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INTRODUCTION

Inconel 600 is Nickel-base alloys that contain major elements of Ni-Cr-Fe. This alloy has been widely used as corrosion-resistant materials and it has been widely applied in high-temperature application (Al-Rubaie, K.S., *et al.*, 2007). Inconel 600 is a solid solution strengthened alloy. The properties required for particular application can be controlled by heat treatment. The alloy has good mechanical properties with the combination of toughness and strength. High Ni content in Inconel 600 provides corrosion resistance to the alloy. Chromium (Cr) content increases corrosion resistance by forming passive oxide layer. The element also provides the resistance to various oxidizing environments and sulfur compounded (Al-Rubaie, K.S., *et al.*, 2007; Sato, Y.S., *et al.*, 2008).

Variations in grain size have a great influence to the property of polycrystalline material. The relation between yield strength of polycrystalline materials and grain size is according to Hall-Petch relationship

$$\sigma = \sigma_o + Kd^n \dots\dots\dots (1)$$

where σ is flow stress corresponding to grain size d , n is Hall-Petch exponent and σ_o and K is a constants at a given strain and temperature (Kashyap, B.P., K. Tangri, 1995; Sahay, S.S., *et al.*, 2003).

A number of studies have been done to investigate the heat treatment on fatigue crack growth rate in Inconel 600 (Al-Rubaie, K.S., *et al.*, 2007; Park, H.-B., *et al.*, 1996). However, the study on material behavior with increasing annealing time and temperature for particular Inconel 600 alloy is very limited. It is important to investigate the effect of annealing temperature and time on grain growth and mechanical properties of Inconel 600 alloy specifically for high temperature applications in order to ensure the creep resistance (Huda, Z., *et al.*, 2011). Grain size also influences the mechanical properties of a material. The effect of γ' precipitation in the matrix of Inconel 600 during thermo-mechanical process can retard the growth of the grain of Inconel 600. Hence, the grain growth in Inconel 600 alloy is limited (Song, K., M. Aindow, 2008). In this research, the authors aim to investigate the behavior of Inconel 600 by annealing the alloy at higher temperatures with variant time. For the particular application in gas pressure sensor, it is important to select and investigate the material behavior of Inconel 600 alloy since the joining of the alloy in the application such as brazing involves high temperature (in the range of 800^oC-1000^oC).

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Experimental Procedure:

Inconel 600 alloy is an austenitic type of nickel-based alloy (Ni-Cr-Fe) and it was acquired from Azbil-Yamatake Corporation, Japan. The alloy was cut into 9 pieces having the dimension of 10 x 10 x 4 mm. One sample was utilized for microstructural investigation for as-received condition. Eight (8) samples and 24 pieces of Inconel 600 were prepared for tensile test using EDM-wire cut. For one condition; one small dimension sample and 3 pieces of tensile samples was prepared. The samples were annealed in a muffle furnace (Elite Thermal Systems) at 600°C, 900°C, 1000°C and 1100°C for 1 and 2 hours. There was no intermediate investigation between annealing temperature of 600°C-900°C because no significant change in grain size and tensile strength data was observed.

Then, all the small samples were prepared for microstructural analysis. The samples were set up for metallographic grinding with an appropriate grit of SiC papers followed by polishing with alpha-alumina powder. The samples were etched by chemical solution of 50ml pure HCl + 5g of CrO₃ for microstructural observation under an optical microscope (model: Olympus) facilitated with getIT software analysis.

For a particular time and temperature, three (3) samples were used for tensile testing. Tensile test have been conducted using Universal Testing Machine with tensile rate of 0.5 mm/min. The sample has been prepared according to the standard of ASTM E8. The data obtained then was analyzed and discussed.

RESULTS AND DISCUSSION

Microstructural Analysis:

Figure 1(a) shows the grain size of as-received Inconel 600 alloy. The grain size was measured by getIT software analysis under optical microscope and the estimated average grain size was 19µm (±3µm). After annealing at 600°C for 1 hour, the grain size was increased to 32µm (±3µm). Further annealing at 900°C, the grain size was increased slightly. The variations of microstructure is shown in Figure 1(b and c). The growth of γ grains very slow [8] for the temperature ranging from 600°C-1000°C for both annealing times. However, the grains grow rapidly for the temperature ranging from 1000-1100°C for both annealing times.

The grain growth was controlled by primary γ' precipitates. The grain growth was restricted during heat treatment before the solvus temperature. After solvus temperature, γ' precipitates dissolve in γ matrix. This phenomenon allows the grains to grow larger (Tian, G., *et al.*, 2009). So, it can be concluded that solvus temperature of γ' precipitates for Inconel 600 is in the range of 1000°C-1100°C. The γ' solvus temperature found in this study is almost similar with Haynes®-718 superalloy (Ni base superalloy) investigated by Huda 2011. The investigated γ' solvus temperature is below 1050°C (Huda, Z., *et al.*, 2011).

The evolution of grain size can be clearly seen in the graphical plot as shown in Figure 2. The grain size is slightly increased with increasing time and temperature. This phenomenon was agreed with some literatures as discussed before (Huda, Z., 2007; Tian, G., *et al.*, 2009). From Figure 2, it is seen that the grain growth is slight rapid for the 2 hours annealing time compared with 1 hour annealing for annealing temperature ranging from 600°C-1000°C. This behavior indicates that the γ' need minimum time of 1 hour to dissolve in γ matrix and it occurred starting at 900°C while the grains are coarsen more rapidly for 2 hours starting at 600°C.

Tensile Strength Analysis:

The changes in grain size after annealing influence the mechanical behavior of Inconel 600 alloy. Tensile test was conducted to investigate the effect of annealing time and temperature on mechanical strength of the Inconel 600 alloy. Figure 3 shows that the tensile strength and elongation of Inconel 600 depend on annealing time and temperature. At first glance, the graphical plot in Figure 3 (a) shows the strength of Inconel 600 alloy drops with increasing annealing times and temperatures. The behavior is contradictory with increasing of grain size (in previous Figure 2). Small increment in tensile strength and elongation was seen for 2 hour annealing compared with 1 hour at the temperature range from 600°C-900°C.

Figure 3 also exhibited the tensile strength decrease with increasing elongation. The results indicates that the grains growth with increasing annealing time and temperature effects the mechanical behavior of Inconel 600 alloy. During rapid grain growth, deformation of high-angle boundary occurs and leaves a soften region with the reduction of dislocation density. The strength will suddenly decreases and the material become soften (Li, Y.J., *et al.*, 2004). This behavior can be seen clearly at temperature in the range of 1000°C-1100°C for both annealing times.

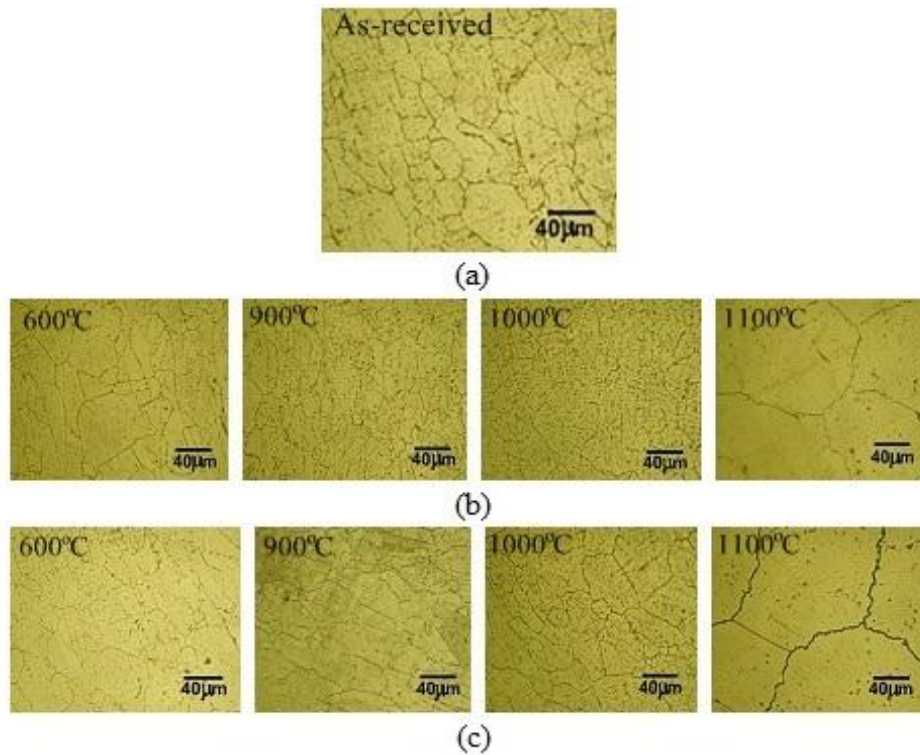


Fig. 1: Microstructures of Inconel 600 for: (a) as-received condition, (b) annealed for 1 hour, and (c) annealed for 2 hours at 600°C, 900°C, 1000°C and 1100°C.

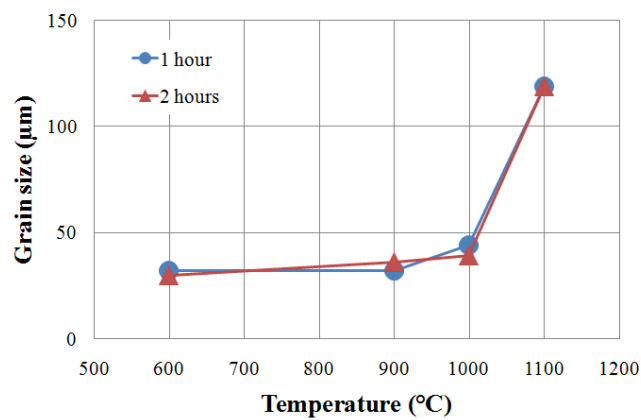


Fig. 2: Changes in grain size due to changes in Inconel 600 heat treatment conditions.

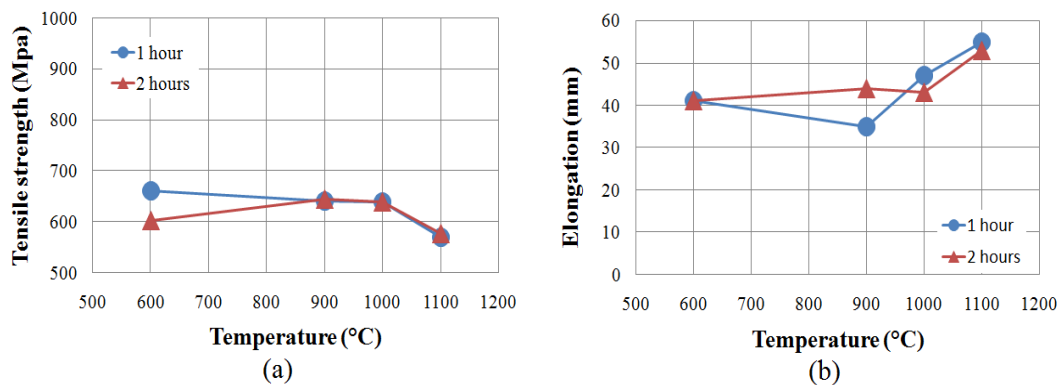


Fig. 3: Effect of heat treatment temperature on: (a) tensile strength and (b) elongation of Inconel 600.

The diffusion rate of grain boundary motion increases with rising temperature. The migration of grain boundary influences the tensile strength and elongation at elevated temperature. In Hall-Petch relationship, grain size is inversely proportional with tensile yield strength. Small grain size increases tensile strength since the material possesses many grain boundary that can inhibit dislocation gliding during tensile test (Wei, C.N., *et al.*, 2003).

Conclusion:

The study on material behavior of Inconel 600 after annealing at different temperature and time was successfully conducted. From the data analysis, it can be concluded that with increasing time and temperatures, the grain size of Inconel 600 also increases. After annealing at 1000°C, the grain size of Inconel 600 increases dramatically with time. The changes in grain size lowers the strength and increases the elongation of Inconel 600 with increasing annealing times and temperatures. After investigations, the solvus temperature of γ' precipitates for Inconel 600 is in the range of 1000°C-1100°C.

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