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STRESS RELAXATION BEHAVIOUR AND MECHANISM OF HEAT TREATED INCONEL 718 IN HIGH TEMPERATURE ENVIRONMENTS

RINGKASAN: *Kelakuan tegasan santaian bagi superaloi berasaskan nikel iaitu Inkonel 718 terawat haba telah dibuat kajian pada suhu tinggi. Rawatan larutan telah diperkenalkan kepada bahan diterima pada suhu 980 °C selama 1 jam sebelum dikenakan lindap-kejut dengan air, seterusnya bahan tersebut melalui proses penuaan berganda pada suhu 720 °C selama 8 jam dan pada suhu 621 °C selama 8 jam dan disejukkan dalam udara pada suhu bilik. Ujian tegasan santaian telah dilakukan dengan terikan 1 % pada suhu yang berbeza iaitu 550 °C, 650 °C dan 750 °C. Ujian dijalankan selama 72 jam. Ujian dihentikan pada 3 jam dan 48 jam bagi mengkaji evolusi mikrostruktur dan perubahan dalam sifat-sifat bahan melalui penggunaan Mikroskop Imbasan Elektron dan Pembiasaan Sinar-X. Keputusan menunjukkan tegasan bertambah tinggi dengan penurunan suhu. Sebaliknya, kadar tegasan santaian bertambah dengan pertambahan suhu. Pemerhatian mikrostruktur menunjukkan proses pemulihan berlaku. Ianya disokong oleh pengurangan ketumpatan kehelaan dengan pertambahan masa dan suhu, yang mana dipersetujui dengan keputusan kekuatan-mikro Vickers.*

ABSTRACT: The stress relaxation behaviour of heat treated nickel-base superalloy Inconel 718 at high temperature was investigated. Solution treatment was applied on the as-received material at 980 °C for 1 hour before water quenching followed by double aging treatments at 720 °C for 8 hours and 621 °C for 8 hours, then cooled in air. The stress relaxation test was conducted at 1 % strain at different test temperatures of 550 °C, 650 °C and 750 °C. The tests were carried out for a total of 72 hours. The tests were interrupted at 3 hours and 48 hours to investigate the evolution of microstructure and changes in material properties by using Scanning Electron Microscope (SEM) and X-Ray Diffractometer (XRD). The results showed that thermal dependent stress increased with decreasing temperature. In contrast, stress relaxation rate increased with increasing temperature. Microstructure observation by SEM showed that recovery process occurred. This was further supported by the decrease in dislocation density with increase in time and temperature, which is in-line with the Vickers micro-hardness results.

Keywords: Heat treatment, stress relaxation, recovery, microstructure, Inconel 718

INTRODUCTION

Inconel 718 is a nickel-based superalloy extensively used in fabrication of critical components for turbine because of its excellent mechanical properties at elevated temperatures and good corrosion resistance. Application of this alloy range from disc alloy in gas turbine engines to components used in nuclear and cryogenic structures, high-strength bolts and fasteners, and components in space craft, owing to its excellent fabricability and weldability (Kim *et al.*, 2008). In the turbine disc application, standard processing, high strength processing and direct age processing have been applied in order to achieve the desired properties (Nowotnik *et al*., 2008). Gas turbine blades are commonly made of Inconel 738LC alloy (Mazur *et al.*, 2005). Blade-disc fixing in turbine engine is highly loaded connections that allow only micrometer size relative movement between blade and disc. Initially, stresses were intentionally introduced at a desired level to hold the blade firmly. However, at high temperature environment, relaxation of such stresses can result in loss of tension in fitting and cause undesirable vibration (Pan and Xiong, 2010). Therefore, the aims of this study are to investigate the stress relaxation behaviour and mechanism of heat treated Inconel 718 in high temperature environments.

MATERIALS AND METHODS

The material used in this study was nickel-based superalloy Inconel 718. The chemical composition of the material used is as follows: Ni 55.83 %, C 0.033 %, Fe 15.51 %, Cr 17.58 %, Cu 0.0293 %, Mo 3.522 %, Co 0.238 %, Mn 0.005 %, Al 1.032 %, Nb 5.189 %, Ti 1.103 % and Si 0.08 %. The geometry of the specimens used is presented in Figure 1 with a thickness of 3 mm. To increase the strength of Inconel 718 after sample preparation by Electrical Discharge Machining (EDM), standard heat treatment process was introduced to the samples (Ghosh et *al.*, 2008; Liu *et al.*, 2005; Kuo *et al.*, 2009; Xiao *et al.*, 2008). Samples were annealed at 980°C for 1 hour before quenching in water. Samples then underwent double aging treatment process at 720 °C for 8 hours and 621 °C for 8 hours. Finally, the samples were cooled in air to room temperature.

Stress relaxation tests were conducted at three different test temperatures of 550 °C, 650 °C and 750 °C with the same strain level of 1 %. The tests were carried out for 3, 48 and 72 hours. Prior to the stress relaxation tests, tensile properties of heat treated Inconel 718 at elevated temperatures of 550 °C, 650 °C and 750 °C were identified.

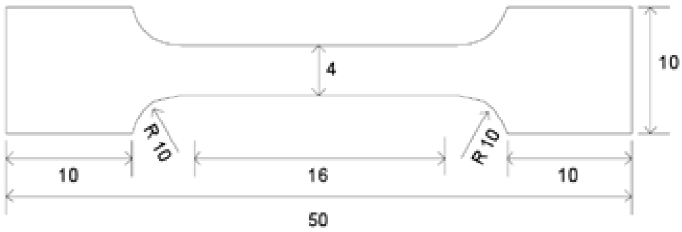


Figure 1. *Test specimen dimension (in mm).*

Metallographic sections were prepared using standard mechanical polishing procedure. Samples were then etched using Kalling Reagent No. 2 and studied by means of Scanning Electron Microscopy (SEM). The micro-hardness of specimens was investigated using Vickers micro-hardness tester by using a 20 gram force (Hv0.020) to all samples that underwent relaxation tests. The dislocation density of specimens was evaluated by XRD to provide the evidence of recovery. The dislocation density ρ is thus defined as:

$$\rho = (1.44 \times \varepsilon^2) / b^2$$

where b is the Burgers vector (0.25 nm) and ε is strain broadening (Syarif *et al.*, 2007).

RESULTS AND DISCUSSION

Figure 2(a) and Figure 2(b) show the stress-strain and stress-time (stress relaxation) curves of the heat treated Inconel 718 at different temperature levels, respectively. From Figure 2(a), the tensile properties at different temperatures are summarised in Table 1. Figure 2(b) showed that the thermal dependent stresses required to obtain 1 % strain were 1050, 1000 and 583 MPa at temperatures of 550 °C, 650 °C and 750 °C, respectively. These values were lower compared to the ultimate tensile strength. Figure 2(b) shows two distinguishable regions of stress relaxation rate; the accelerated region from the beginning up to 15 hours followed by the steadily and constantly reduced stress relaxation rate until the tests end. The slope of constantly reduced stress relaxation or calculated mean stress relaxation rates were 1.0531, 1.0713 and 1.6923 MPa/hour for 550 °C, 650 °C and 750 °C test conditions, respectively. After 72 hours, the measured internal stresses were 730, 443 and 69 MPa for 550 °C, 650 °C and 750 °C test conditions, respectively. These results are summarised in Table 2. These values were much lower compared to the

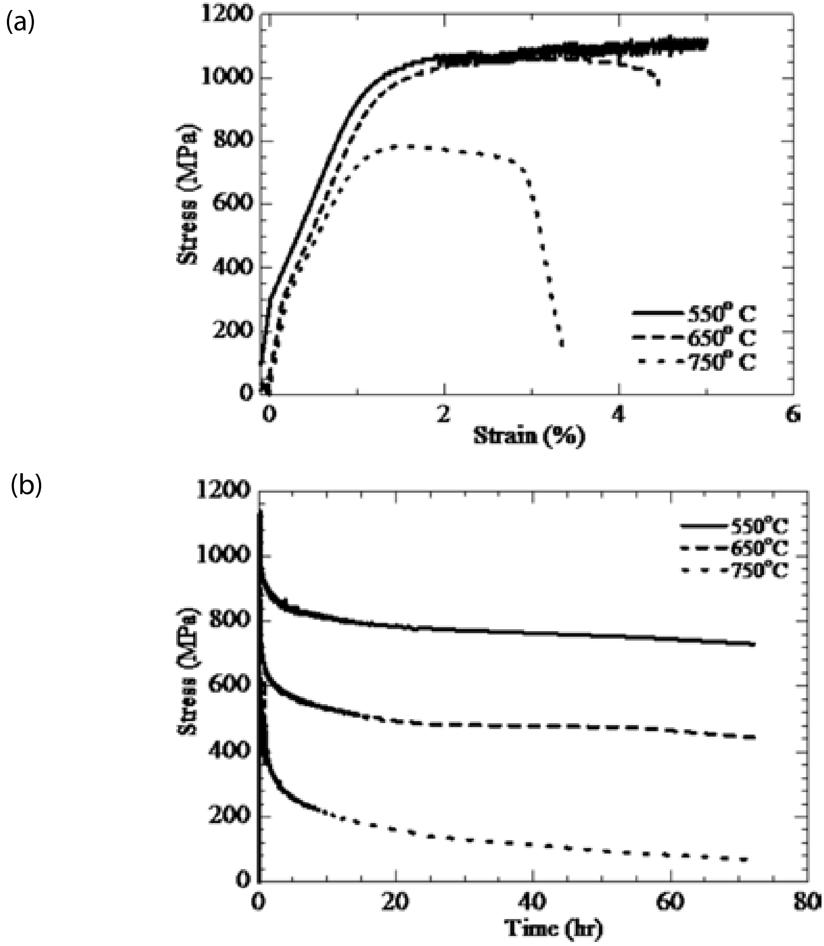


Figure 2. *(a) Stress-strain and (b) stress relaxation curves.*

yield stress under the same temperature conditions. It was found that the stress drop (the difference between internal and thermal dependent stresses) increased with increasing temperature.

The SEM micrographs for heat treated Inconel 718 tested at different temperatures are shown in Figure 3. After 3 hours of stress relaxation test, the grain boundaries were still intact and can be clearly seen with very little deformation at grain boundary. As shown in Figure 2(b), accelerated phase occurs at the beginning of the test. After prolonging the test beyond 20 hours, the creep-controlled mechanism started to dominate the behaviour where recovery process started to occur until the end of the stress relaxation test. These mechanisms of recovery are shown at 48 hours in the micrograph in Figure 3 where rearrangement of microstructure and grain boundary occur which give impact of blurring in micrograph. At 72 hours, where tests ended, grain boundaries are visible and clearly seen especially at lower temperature.

Table 1. Mechanical properties of Inconel 718 at various temperatures.

Temperature	$\sigma_{0.2}$	σ_{uts}	Elongation
(°C)	(MPa)	(MPa)	ε (%)
550	999	1140	5.1
650	970	1060	4.4
750	767	783	3.5

Table 2. Thermal dependent, internal and calculated mean stresses relaxation rate

Temperature (°C)	Thermal dependent (MPa)	Internal (MPa)	Stress drop (MPa)	Stress relaxation rate (MPa/hr)
550	1050	730	320	1.0531
650	1000	443	557	1.0713
750	583	69	514	1.6923

The average values of Vickers micro-hardness decreased with increasing relaxation time as shown in Figure 4 (a). This was believed to be due to the recovery at grain boundary. It was also observed that increase in temperature will further reduce the hardness. This phenomenon occurs because of rearrangement of microstructure and grain boundary which affects the hardness of the material. Higher temperature gives higher energy to the recovery process with more rearrangement of microstructure and grain boundary and reduced hardness of the materials. The hardness results are summarised in Table 3.

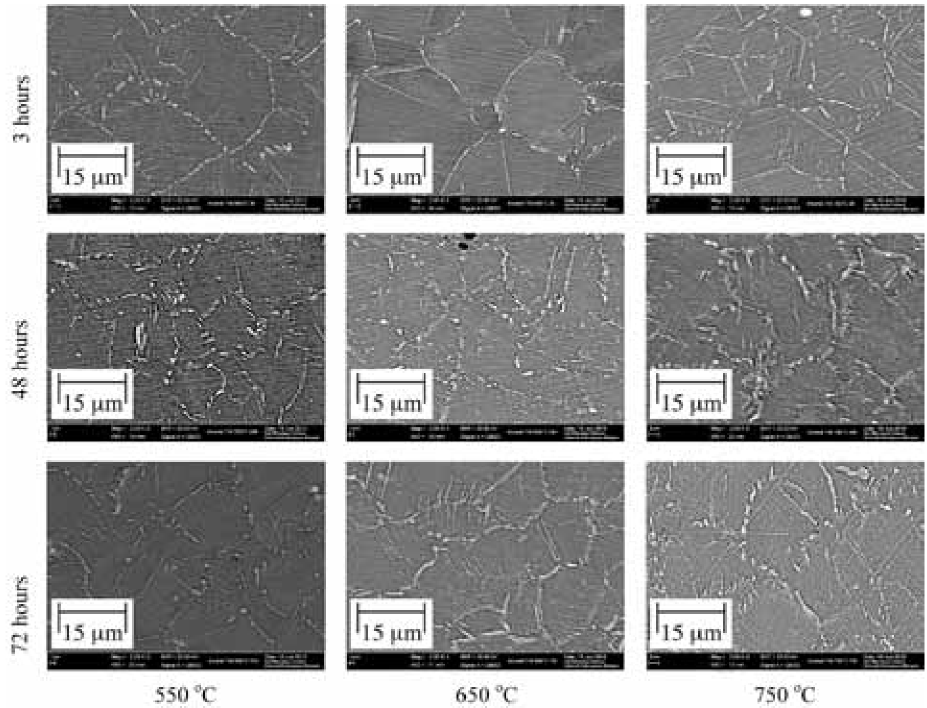
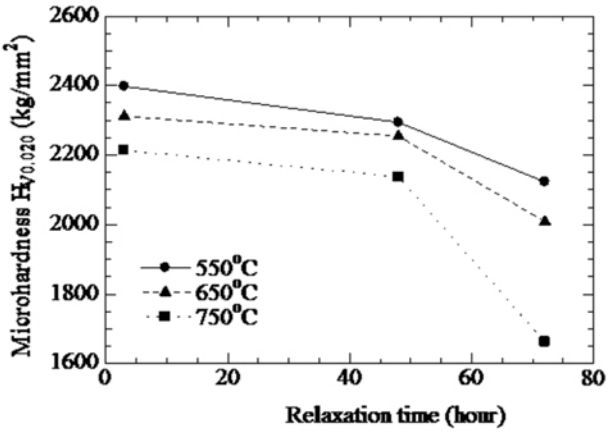
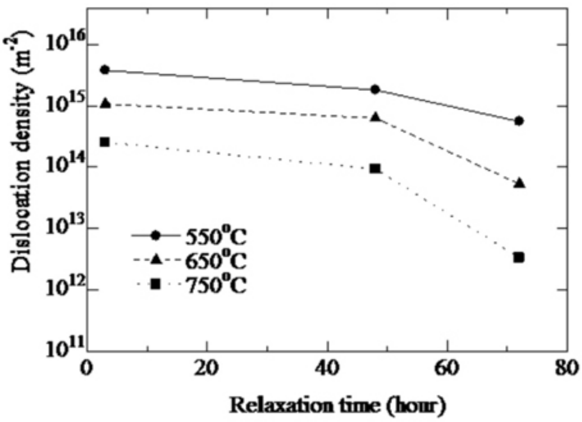


Figure 3. *SEM micrographs after relaxation test for 3, 48 and 72 hours.*

Figure 4 (b) shows the decrease of dislocation density with increasing relaxation time and further decrease by increasing temperature. Detail results are summarised in Table 4. From Figure 4 (b), the recovery rate for each temperature condition was calculated and tabulated in Table 5. It was found that lower dislocation density gives lower Vickers micro-hardness and vice versa due to recovery process.



(a)



(b)

Figure 4. *(a) Micro-hardness vs time and (b) dislocation density vs time.*

Table 3. Vickers micro-hardness at elevated temperature.

Time(hour)	Temperature(°C)		
	550	650	750
3	2398	2294	2123
48	2311	2254	2008
72	2213	2137	1662

Table 4. Dislocation density.

Time(hour)	Temperature(°C)		
	550	650	750
3	3.78E+15	1.07E+15	2.54E+14
48	1.81E+15	6.27E+14	9.73E+13
72	5.54E+14	5.31E+13	3.35E+12

Table 5. Recovery rate.

	Time(hour)	Temperature(°C)		
		550	650	750
Recovery rate (m-2/hr)	Mar-48	4.38E+13	9.84E+12	3.56E+12
	48-72	5.23E+13	2.39E+13	3.77E+12

CONCLUSION

In this study, stress relaxation behaviour of Inconel 718 has been studied at different temperatures. The difference in temperatures gives impact on stress relaxation rate, difference between internal and thermal dependent stresses, dislocation density and Vickers micro-hardness. Increasing the temperature will increase the stress relaxation rate of Inconel 718 at 1 % strain. Increasing temperature will also increase the differences between the internal and thermal dependent stresses. The dislocation density and Vickers micro-hardness decreased (evidence of recovery) with increasing relaxation time and further decreased by increasing temperatures.

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