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Stress Relaxation Behavior of Heat Treated Inconel 718

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Abstract: The stress relaxation of heat treated nickel-based superalloy, Inconel 718 at 1% strain and high temperature was investigated. Solution treatment was applied on the as-received material at 980°C for 1 h before water quenched followed by double aging treatments at 720 and 621°C for 8 h, respectively and then cooled in air. There are basically, two stages involved in stress relaxation namely transformation-controlled at the beginning of test and creep-controlled at later stage. Different temperatures show that two stages are present. This study has found that recovery process at grain boundary decreased Vickers micro-hardness and dislocation density due to prolonged relaxation time and further decreasing by increasing temperature.

Key words: Heat treatment, stress relaxation, creep, microstructure, Inconel 718

INTRODUCTION

Nickel-based superalloy exhibits excellent mechanical strength and creep resistance at high temperatures, good surface stability, anti corrosion and oxidation resistance. Superalloy commonly used in gas turbine engines, space vehicles, submarines, nuclear reactors, chemical processing vessels and heat exchanger tubing (Loria, 1988; Hong *et al*., 2005; Smith and Hashemi, 2006). Examples of superalloys are Hastelloy, Inconel, Waspaloy, Rene alloys, Haynes alloys and Incoloy. The application of Inconel 718 as turbine disc of steam turbine power generation that operates at beyond half of melting point (T_m) can deteriorate its mechanical properties (Kim *et al*., 2008). To enhance their strength Inconel 718 has been heat treated using standard heat treatment process involving two processes namely solid solution strengthening and double aging precipitation strengthening (Ghosh *et al*., 2008; Liu *et al*., 2005; Xiao *et al*., 2008). Stress relaxation is a phenomenon when attaching a part of Inconel 718 into a component by mean of fitting, bolting or others. Blade-disc fixing in turbine engine are highly loaded connections that allow only micrometer size relative movement between blade and disc. Initially, stresses are intentionally introduced at a desired level to hold the blade firmly. However, at high temperature environment, relaxation of such stresses can results in losses of tension in fitting and cause undesirable vibration (Pan and Xiong, 2010). There is a research on stress relaxation of Inconel 718 at 500 and 550°C (Povolo and Reggiardo, 1988). Therefore, the aims of this study were to investigate the stress relaxation behaviour and mechanism of heat treated Inconel 718 in high temperature environments.

MATERIALS AND METHODS

The nickel-base superalloy used in this study was a 105 cm diameter round bar billet Inconel 718. The chemical composition of the material used is shown in Table 1. The specimens for stress relaxation tests were prepared according to the ASTM E8M-08 (2008). The specimen with the details of its geometry is presented in Fig. 1 with 3 mm thickness. To increase strength of Inconel 718 after sample preparation by EDM, the standard heat treatment process was introduced to the samples. Samples were annealed at 980°C for 1 h before quenched in water. Samples were then gone through double aging treatment process at 720 and 621°C for 8 h, respectively. Finally, the samples were cooled in air until reached room temperature. The schematic diagram of the standard heat treatment process is shown in Fig. 2.

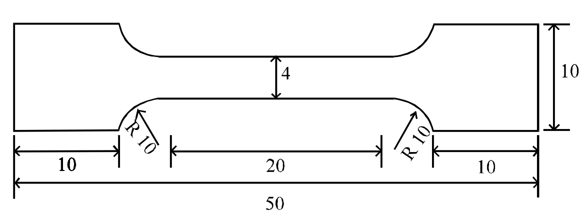

Fig. 1: Test specimen dimension (mm)

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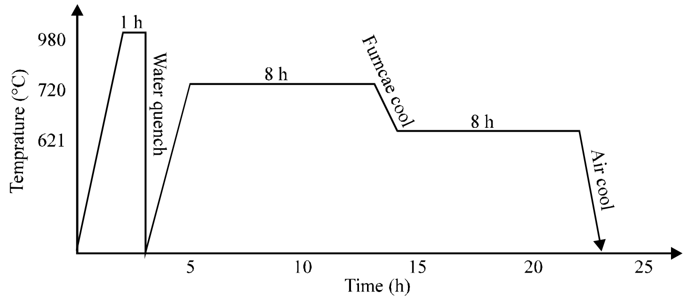

Fig. 2: Heat treatment scheme

Table 1: Composition of Inconel 718

Ni	C	Fe	Cr	Cu	Mo	Co	Mn	Al	Nb	Ti	Si
55.83	0.033	15.507	17.58	0.0293	3.522	0.238	0.005	1.032	5.189	1.1033	0.08

Stress relaxation testing was conducted at strain level 1% and test temperatures of 550, 650 and 750°C according to ASTM E8M-08 (2008). Specimens were attaching to testing machine by a special fixture in a furnace with a three thermocouples that were centre and mounted 100 mm apart from a middle furnace. The specimens will be allowed to reach desired temperatures and leave for thermal equilibrium for 30 min. Then strain at 1% applied to a specimen. The tests were carried out for 3, 48 and 72 h. Prior to the stress relaxation tests, tensile properties of heat treated Inconel 718 at elevated temperature of 550, 650 and 750°C were identified. All the mentioned tests were carried out using a computer-controlled universal testing machine Zwick/Roell Z030 (30 kN) equipped with a high-temperature furnace Maytec HTO-08/1 (1000°C) and a high-temperature extensometer Maytec LVDT.

Microstructure study was prepared for each temperatures mention above. There are nine specimens, each temperatures three specimen with the test done for 3, 48 and 72 h. Metallographic sections were prepared using standard mechanical polishing procedure. Samples were then etched using Kalling Reagent No. 2 with 5 g $CuCl_2$, 100 mL hydrochloric acid and 100 mL ethanol. The morphology characterization was studied by means of scanning electron microscopy.

The micro hardness of specimens was investigated using Vickers micro hardness test were made by using a machine Dynamic Ultra Micro Hardness Tester (DUH-W201S, Shimadzu) with 20 gram-force. Ten points were measured for each sample at centre of each grain boundary and the average was taken as the representative micro hardness of the material after relaxation tests.

The dislocation densities of specimens were evaluated by means of X-ray diffractometry with different technique by researchers (Griffiths *et al*., 2002; May *et al*., 2007). One of the techniques is from X-ray diffraction strain broadening analysis. From previous researcher, the peaks for measurement of the dislocation density were divided into $K\alpha_1$ and $K\alpha_2$ and the crystallite size; D and the local strain; ε were estimated as shown in Eq. 1.

$$\beta_t\left(\frac{\cos\theta}{\lambda}\right)=\frac{K}{D}+2\varepsilon\left(\frac{\sin\theta}{\lambda}\right) \quad (1)$$

where, K is the Scherrer constant; 0.89 and β_t is the Full Width at the maximum height; FWHM of $K\alpha_1$ lines. The FWHM value obtained from three planes 110, 211 and 220 of the Body Center Cubic (BCC) phase was used. The spread of the diffracted beams due to the instrument used was measured as the FWHM value; β_0 of $K\alpha_1$ lines of cold-rolled and annealed Inconel 718 samples as standard samples and then corrected from the FWHM value; β_m of $K\alpha_1$ lines of the tested heat treated Inconel 718 by using the following Eq. 2:

$$\beta_t^2=\beta_m^2-\beta_0^2 \quad (2)$$

Finally, the dislocation density; ρ calculated from strain broadening; ε is thus defined as shown in Eq. 3:

$$\rho=\frac{14.4\times\varepsilon^2}{b^2} \quad (3)$$

where, b is the Burgers vector; 0.25 nm as discussed by Syarif *et al*. (2007).

RESULTS AND DISCUSSION

Stress relaxation and tensile: Figure 3 shows the stress-strain curves of the heat treated Inconel 718 at different temperature levels, respectively. A tensile property at

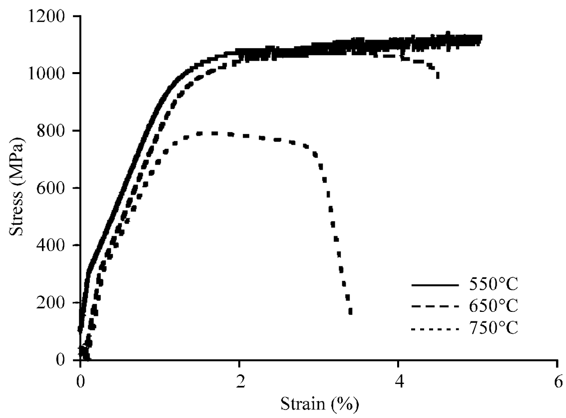

Fig. 3: Stress-strain curves of heat treated Inconel 718

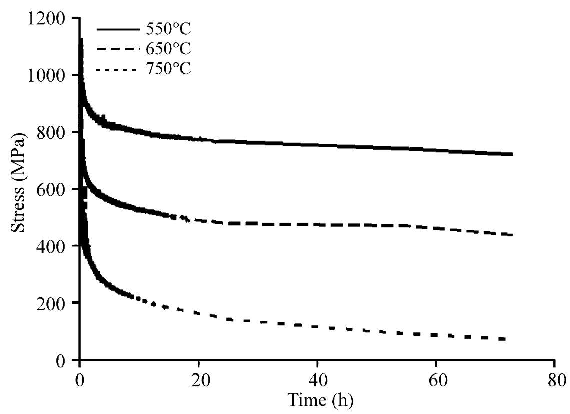

Fig. 4: Stress relaxation curves of various temp. Inconel 718

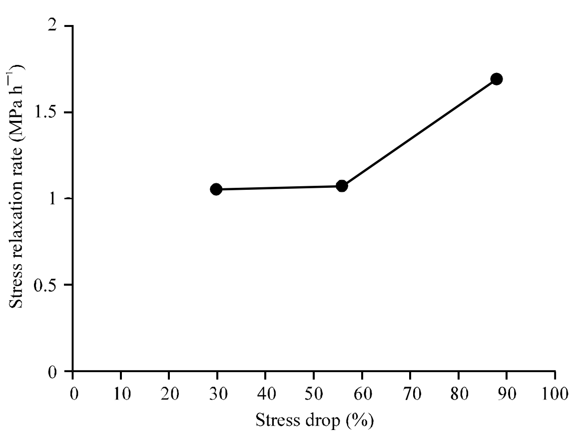

Fig. 5: Stress relaxation rate vs. stress drop, Inconel 718

different temperatures are summarized in Table 2. From Fig. 4 (stress relaxation curve), it show that pattern for three curve is about same but different in stress level depending on temperature. From Fig. 4, thermal applied stress or initial stress required to obtain strain 1% is 1050, 1000 and 583 MPa for temperature 550, 650 and 750°C, respectively. These values were lower compared to the ultimate tensile strength. As shown in Fig. 4, there are two distinguish regions of stress relaxation rate i.e., the accelerated region (transformation- controlled) for about 15 h and then reduced steadily and constantly (creep-controlled) until the tests end. Same results pattern have been discussed by Pan and Xiong (2010) by using different material. From Fig. 4 relaxation rate beyond 15 h can be calculated. After test end at 72 h, the internal stress or stress drop from initial stress to 730, 440 and 69 MPa for temperature 550, 650 and 750°C, respectively. These values were much lower compared to the yield stress of the same temperature conditions. This can be summarized in a Table 3 as thermal applied and internal stress. If compared drop percentage in thermal applied and internal stress is 30, 56 and 88% for temperature 550, 650 and 750°C, respectively. From Fig. 5, it was found that the stress drop (the difference between internal and thermal applied stresses) increased with increasing stress relaxation rate and testing temperature. This shows that increasing temperature can deteriorate Inconel 718 at much faster rate. There is optimum temperature which Inconel 718 can tolerate without fail.

Table 2: Mechanical properties of Inconel 718 at various temperatures

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

Table 3: Thermal effective and internal stress according to temperature

Temp. (°C)	Thermal applied stress (MPa)	Thermal effective stress (MPa)	Internal stress (MPa)
550	1050	320	730
650	1000	557	443
750	583	514	69

The stress changes during each test for certain temperature seem to reflect dimensional changes in that the initial stress rise results from the need to compensate for the shrinkage by increasing the elastic component of strain, thus keeping the overall displacement constant. Same observations have been found by Fahrmann *et al.* (1999).

Microstructures by scanning electron microscopy (SEM): The SEM for heat treated Inconel 718 after relaxation tests are shown in Fig. 6, 7 and 8. From Fig. 6, in the region of accelerated stage or transformation-controlled the grain boundary are intact and clearly seen. At this stage, very little deformation shows at

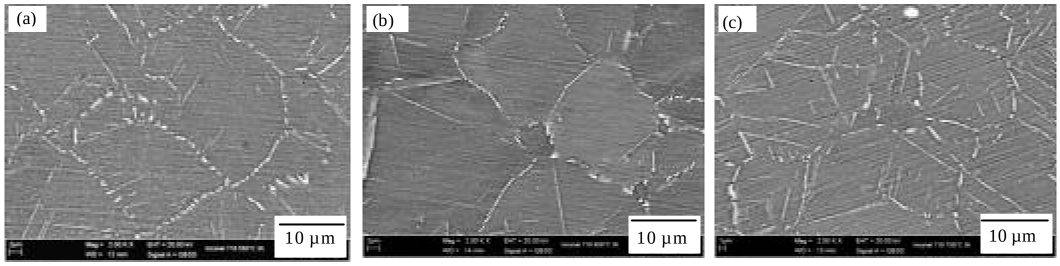

Fig. 6(a-c): SEM microstructure observed on heat treated Inconel 718 after relaxation test at 3 h, (a) 550°C, (b) 650°C and (c) 750°C

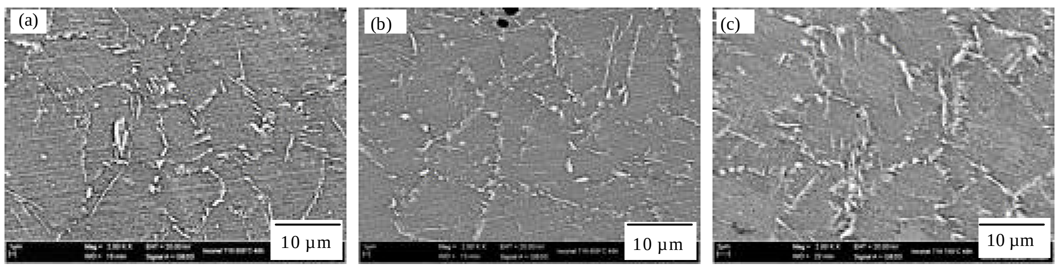

Fig. 7(a-c): SEM microstructure observed on heat treated Inconel 718 after relaxation test at 48 h, (a) 550°C, (b) 650°C and (c) 750°C

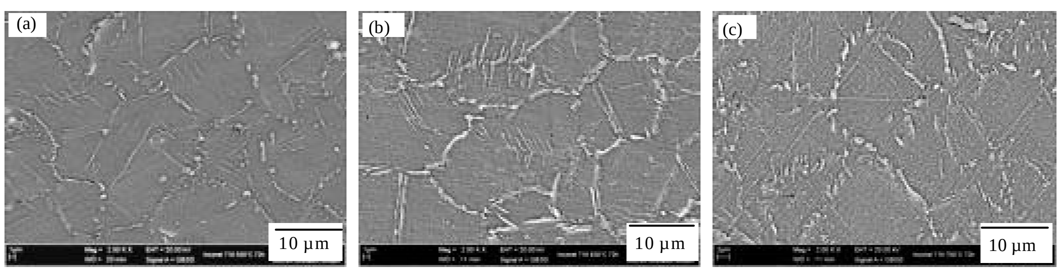

Fig. 8(a-c): SEM microstructure observed on heat treated Inconel 718 after relaxation test at 72 h, (a) 550°C, (b) 650°C and (c) 750°C

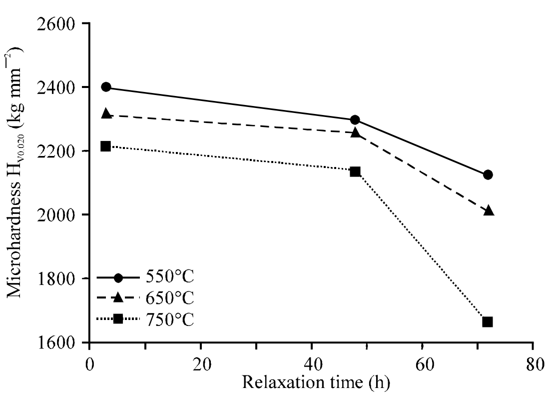

Fig. 9: Micro-hardness vs. time curves of heat treated Inconel 718

grain boundary. After prolonged relaxation test beyond 20 h, creep-controlled stage take place and then a recovery process begin to occur. There is a lot of sign of recovery at grain boundary after relaxation test beyond 48 h as shown in Fig. 7 and 8. This is due to prolonged relaxation time to test specimens at high temperatures. The most severe recovery process is at 48 h as shown in Fig. 7. The recovery processes become slow or saturated at 72 h relaxation test as in Fig. 8.

Micro-hardness: The average value of ten runs of Vickers micro-hardness (H_v) for heat treated Inconel 718 was decreased with increasing relaxation time as shown in Fig. 9 for different temperatures. This was believed due to the recovery at grain boundary. The increase in

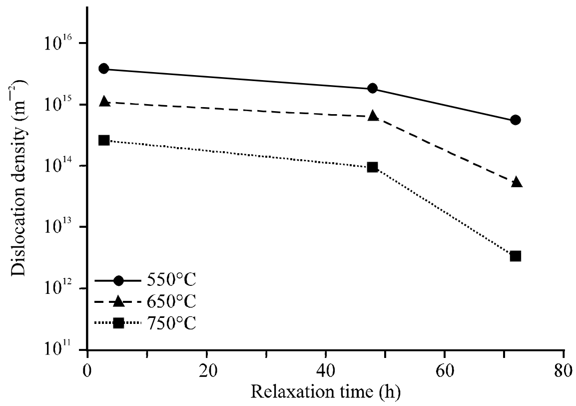

Fig. 10: Dislocation density vs. time curves of hard treated Inconel 718

Table 4: The Vickers micro-hardness

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

Table 5: The dislocation density

Time (h)	550°C	650°C	750°C
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 6: Recovery rate

	Time (h)	550°C	650°C	750°C
Recovery rate	3-48	4.38E+13	9.84E+12	3.56E+12
(m^{-2} h^{-1})	48-72	5.23E+13	2.39E+13	3.77E+12

relaxation time will decrease Vickers micro-hardness and increase in temperatures will further reduce the hardness. The hardness results are summarized in Table 4.

X-ray diffraction (XRD): Figure 10 shows the decrease of dislocation density with increasing relaxation time and further decreased by increasing temperature. Detail results are summarized in Table 5. From Fig. 10 the recovery rate for each temperature condition was calculated and tabulated in Table 6. From the results it is found that lower dislocation density gives lower Vickers micro-hardness and vice versa due to recovery process.

CONCLUSION

Based on the results, the following conclusions were made; stress relaxation rate of heat treated Inconel 718 at 1% strain is increased with increasing temperatures. The stress drop (the difference between internal and thermal dependent stresses) increased with increasing stress relaxation rate and testing temperature. 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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