Research Article

Dynamic Shear Characteristic and Fracture Feature of Inconel 690 Alloy under Different High Strain Rates and Temperatures

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The high strain shear rate behaviour of Inconel 690 alloy was investigated by using the split Hopkinson torsional bar. The shear strain rates were tested at 900 s^{-1} , 1900 s^{-1} , and 2600 s^{-1} and at temperatures of -100°C , 25°C , and 300°C , respectively. It was found that the dynamic shear behaviour of Inconel 690 alloy was sensitive to strain rate and temperature. The fracture shear strain increased with increasing strain rate and temperature. In addition, the strain rate sensitivity was increased with increasing strain and strain rate but decreased with increasing temperature. Finally, the fracture surfaces were found to contain dimple-like features, and the dimple density increased with increasing strain rate and temperature.

1. Introduction

The Inconel 690 alloy is well used in gas turbines, nuclear reactors, spacecraft, and liquid rocket engine. The literature contains many investigations into the static properties of Inconel 690 [1–6]. Moreover, the interactive effects of strain rate and temperature on the fundamental mechanical properties of metals and alloys under high strain rate loading are much stronger than those under static loading. Thus, while the static properties of Inconel 690 alloy are well understood [7–10], the dynamic properties of Inconel 690 under shear loading over a wide range of temperatures require further investigation. However, during the structural component fabrication or subsequent service lives, Inconel 690 alloys are commonly subjected to high strain rate loading. Furthermore, such components are deployed under a wide range of temperature conditions. In order to investigate the ability of Inconel 690 alloy components to withstand the temperature and strain rate condition they are likely to experience in an actual fabrication and service environment, it is necessary to obtain detailed insights into the strain rate properties and failure characteristics of Inconel 690 alloy under different temperature conditions [11].

In this study, the dynamic shear deformation behaviour of Inconel 690 alloy is investigated using a torsional SHPB

system at shear strain rates of 900 s^{-1} , 1900 s^{-1} , and 2600 s^{-1} and temperatures of -100°C , 25°C , and 300°C , respectively. The fracture surfaces are examined via scanning electron microscopy (SEM). The correlation between the dynamic shear response of the Inconel 690 specimens and the fracture features is systematically analysed and discussed.

2. Experimental Procedure

Inconel 690 alloy with a composition of 29.3% Cr, 10.05% Fe, 0.3% Ti, 0.2% Al, 0.15% Cu, 0.03% Co, 0.03% Mo, 0.03% W, and 0.01% C and a balance of Ni (mass) was purchased from Gloria Material Technology Corp., Taiwan. Twin-flanged thin-walled tubular specimens with an outer diameter (OD) of 12 mm and a length of 11.5 mm were then machined from the bars. Figure 1 presents a schematic illustration of the final tubular specimen with an inner diameter of 5 mm and a wall thickness of 0.3 mm in the central gauge section.

Dynamic shear tests were performed at strain rates of 900 s^{-1} , 1900 s^{-1} , and 2600 s^{-1} , at temperatures of -100°C , 25°C , and 300°C , respectively, by using a split Hopkinson torsional bar system. In performing the tests, the specimen was mounted between the incident bar and the transmitted bar of the torsional SHPB system. Moreover, the test

FIGURE 1: Schematic of shearing test specimens.

temperature of -100°C was tested by using a refrigeration system positioned around the specimen and filled with liquid nitrogen and alcohol. The test temperature of 300°C was monitored using a K-type thermocouple with an accuracy of $\pm 2^{\circ}\text{C}$ attached directly to the specimen. The two bars had a diameter of 12.7 mm and a length of 1000 mm and were both machined from 7075-T6 aluminum alloy.

The spit-Hopkinson torsional bar system experimental apparatus contained the incident bar and the transmitted bar, and the specimen was positioned between the two bars. During testing, the incident bar was held in place by a clamp while a torque was applied to its free end. Then, the clamp was quickly released causing an incident torsional strain pulse. At the interface between the incident bar and the specimen, it generated transmitted pulse and reflected pulse. The amplitudes of the incident, reflected, and transmitted pulses were measured using strain gauges mounted on the incident and transmitted bars, respectively [12, 13]. Note that the full details of the experimental procedure and analytical technique used to evaluate the dynamic mechanical response of the shear specimens are presented in the author's present study [12, 13] and are therefore omitted here. After dynamic shear testing, the deformed specimens were sectioned parallel to the longitudinal axis. The sections were ground and polished using conventional techniques and were then etched in an acidic solution of 3 mL HNO_3 , 2 mL HF , and 95 mL H_2O for approximately 5 s. Finally, the fracture surfaces were observed using an optical microscope. The detailed characteristics of the fracture surfaces were identified using a Hitachi filed emission scanning electron microscope (SEM) with an accelerating voltage of 15 kV, work distance of 32 mm, and SE signal.

3. Results and Discussion

3.1. Shear Stress-Strain Response. Figure 2 shows the shear stress-strain curves of the Inconel 690 specimens deformed at different strain rates and temperatures. It is seen that the flow stress increases with increasing strain rate but decreases with increasing temperature. Furthermore, the fracture strain varies as a function of both the strain rate. Table 1 shows the effects of the strain rate and temperature on the fracture strain of the Inconel 690 specimens. It can be observed that,

FIGURE 2: The shear stress-strain curves of Inconel 690 alloy deformed at different strain rates and temperatures.

TABLE 1: Variation of fracture shear stress with fracture shear strain as a function of strain rate and temperature.

Temperature	Shear strain rate (s^{-1})	Fracture strain (ϵ_f)
-100°C	900	0.24
	1900	0.25
	2600	0.27
25°C	900	0.29
	1900	0.31
	2600	0.35
300°C	900	0.32
	1900	0.36
	2600	0.38

for a constant temperature, the fracture shear strain increases with increasing strain rate. Meanwhile, for a constant strain rate, the fracture shear strain increases with increasing temperature. In other words, the ductility of Inconel 690 increases under high strain rate loading and high temperature tested conditions. It is thought that the ductility enhancement is the result of a deformation-induced temperature rise prompted by the interaction between the high strain rate and the high temperature.

3.2. Effects of Strain Rate. To realize the effect of the strain rate on the shear response of Inconel 690 alloy, Figure 3(a) plots the variation of the shear stress with the strain rate as a function of the temperature and shear strain. It is seen

FIGURE 3: (a) Variation of shear stress with logarithmic strain rate as a function of temperature for constant shear strains of 0.05 and 0.15. (b) Variation of strain rate sensitivity with shear strain as a function of temperature and strain rate.

FIGURE 4: Variation of shear stress with temperature as a function of strain rate and strain.

that the flow stress increases with increasing strain rate. The effect of the strain rate on the shear stress can be quantified

FIGURE 5: Micrographs (SEM) of specimens fractured at strain rate of $2600 s^{-1}$ and temperature of $25^\circ C$.

via the strain rate sensitivity parameter β (equivalent to the gradient of the τ versus $\log \dot{\gamma}$ plot [14]); that is,

$$\beta = \frac{(\tau_2 - \tau_1)}{\ln(\dot{\gamma}_2/\dot{\gamma}_1)}, \quad (1)$$

where the shear stresses τ_1 and τ_2 are obtained from shear tests conducted at average strain rates of $\dot{\gamma}_1$ and $\dot{\gamma}_2$, respectively, and are calculated at the same value of the shear strain. Figure 3(b) plots the strain rate sensitivity of the Inconel 690 specimens against the shear strain as a function of the strain rate and temperature. It can be seen that, for a given temperature, the strain rate sensitivity increases

FIGURE 6: SEM figure of fracture surfaces of specimens deformed at different temperatures and strain rates: (a) -100°C , 900 s^{-1} ; (b) -100°C , 2600 s^{-1} ; (c) 25°C , 900 s^{-1} ; (d) 25°C , 2600 s^{-1} ; (e) 300°C , 900 s^{-1} ; and (f) 300°C , 2600 s^{-1} .

with increasing strain rate. In addition, it is observed that the strain rate sensitivity increases relatively slowly with increasing shear strain at 300°C but increases more rapidly at -100°C .

3.3. Effects of Temperature. It can be observed from the shear stress-strain behaviour of Inconel 690 alloy that the flow stress is significantly dependent on the test temperature. In Figure 2, it can be seen that the higher the temperature,

the lower the shear stress. Therefore, Figure 4 illustrates the temperature dependence of the flow stress for specimens deformed at different strains and strain rates. For a given shear strain and strain rate, the flow stress decreases dramatically with increasing temperature. It also can be seen that the rate of the decrease in the flow stress with increasing temperature is more pronounced at higher strain rates and larger strains. This can be attributed to the temperature rise generated in the specimen as a result of deformation heating [15].

3.4. Fractographic Analysis and Fracture Surface Observation.

Fractographic analysis of the Inconel 690 deformed specimens reveals that the primary fracture mechanism is the intense localized shearing. Figure 5 presents low magnification SEM image of specimen deformed at strain rate of 2600 s^{-1} and temperature of 25°C . Moreover, the same fracture feature in the other testing strain rates and temperatures conditions can be observed. Variations in the strain rate and temperature affect not only the stress-strain response of the Inconel 690 alloy specimens but also the fracture behaviour of the Inconel 690 alloy. Figures 6(a) and 6(b) present SEM images of the fracture surfaces of the specimens deformed at a temperature of -100°C under strain rates of 900 s^{-1} and 2600 s^{-1} , respectively. It is seen that both fracture surfaces contain dimple-like features aligned along the shear direction, which suggests a ductile fracture mode. In addition, it is seen that the density of the dimple-like features increases as the strain rate is increased. Figures 6(c) and 6(d) show the fracture surfaces of the specimens deformed at a temperature of 25°C and strain rates of 900 s^{-1} and 2600 s^{-1} , respectively. Comparing the fracture surfaces shown in Figures 6(c) and 6(d) with those shown in Figures 6(a) and 6(b), respectively, it is seen that the density of the dimples increases with increasing temperature. In other words, the ductility of Inconel 690 alloy increases with an increasing deformation temperature. Figures 6(e) and 6(f) show the fracture surfaces of the specimens deformed at a temperature of 300°C under strain rates of 900 s^{-1} and 2600 s^{-1} , respectively. The same fracture feature can also be observed. Figures 6(a)–6(f) indicate that the nature of the dimple structure is significantly influenced by the strain rate and the temperature. The increase in dimple density observed with increasing strain rate and temperature leads to a greater amount of plastic deformation and hence enhances the ductile response of the material. In general, the variation in the fracture features is consistent with the tendencies of the stress-strain curves presented in Figure 2 and accounts for the higher fracture strain observed in the specimens tested at higher strain rates and temperatures.

4. Conclusions

This study has examined the dynamic shear deformation behaviour of Inconel 690 alloy at shear strain rates of 900 s^{-1} , 1900 s^{-1} , and 2600 s^{-1} and temperatures of -100°C , 25°C , and 300°C , respectively. The results have shown that the dynamic shear response of Inconel 690 alloy is significantly dependent on the strain rate and temperature. The shear stress increases with increasing strain rate but decreases with increasing temperature. Meanwhile, the fracture strain reduces with reducing temperature but increases with increasing strain rate. The strain rate sensitivity increases with increasing strain rate and decreasing temperature. Finally, the SEM observations have shown that the Inconel 690 samples fail in a predominantly ductile mode and exhibit a greater ductility under elevated strain rates.

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