Dynamic mechanical behaviour and dislocation substructure evolution of Inconel 718 over wide temperature range

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\textbf{A B S T R A C T}

A compressive split-Hopkinson pressure bar and transmission electron microscope (TEM) are used to investigate the mechanical behaviour and microstructural evolution of Inconel 718 at strain rates ranging from 1000 to 5000 s\(^{-1}\) and temperatures between \(-150\) and \(550\) \(^\circ\)C. The results show that the flow stress increases with an increasing strain rate or a reducing temperature. The strain rate effect is particularly pronounced at strain rates greater than 3000 s\(^{-1}\) and a deformation temperature of \(-150\) \(^\circ\)C. A significant thermal softening effect occurs at temperatures between \(-150\) and \(25\) \(^\circ\)C. The microstructural observations reveal that the strengthening effect in deformed Inconel 718 alloy is a result primarily of dislocation multiplication. The dislocation density increases with increasing strain rate, but decreases with increasing temperature. By contrast, the dislocation cell size decreases with increasing strain rate, but increases with increasing temperature. It is shown that the correlation between the flow stress, the dislocation density and the dislocation cell size is well described by the Bailey–Hirsch constitutive equations.

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\textbf{1. Introduction}

Inconel 718 alloy is well suited to environments characterised by dynamic temperature change and corrosion, and is therefore widely used in such diverse applications as the International Space Station, cryogenic storage tanks, nuclear reactors, and pollution control equipment. The literature contains many investigations into the static properties of Inconel 718\textsuperscript{[1,2]}. However, the dynamic properties are also of important concern in many practical applications. Previous studies have shown that the dynamic behaviour of many engineering materials is significantly different from their static behaviour due to different deformation mechanisms\textsuperscript{[3]} or changes in the microstructural phase\textsuperscript{[4,5]}. Therefore, to ensure the mechanical integrity of Inconel 718 components in real-world applications, a detailed knowledge of the relationship between the mechanical behaviour and the microstructural evolution of Inconel 718 alloy under dynamic loading is required.

Generally speaking, the flow stress in engineering materials increases with increasing strain rate, but decreases with increasing temperature. However, the precise effects of changes in the strain rate or temperature depend on the particular material involved. Moreover, the combined effects of strain rate and temperature under dynamic loading are more complex than those under static loading\textsuperscript{[6–8]}. Previous research has shown that the rate of dislocation multiplication and the dislocation structures themselves are highly sensitive not only to the deformation temperature and strain rate, but also to the original crystal structure of the material\textsuperscript{[9–12]}. In general, the rate of dislocation multiplication increases with increasing strain rate or reducing temperature and leads to an improved material strength\textsuperscript{[13–15]}

The present study characterises the mechanical behaviour of Inconel 718 alloy during dynamic compression using a compressive split-Hopkinson pressure bar (SHPB) at temperatures ranging from \(-150\) to \(550\) \(^\circ\)C and strain rates in the range of 1000–5000 s\(^{-1}\). The microstructures of the impacted specimens are examined using transmission electron microscopy (TEM). The stress–strain relation and the evolution of the microstructure are discussed for each of the considered test conditions. Finally, the Bailey–Hirsch constitutive equations are used to describe the relationship between the flow stress, the dislocation density and the dislocation cell size.

\textbf{2. Experimental procedure}

Inconel 718 (AISI A2 Grade) bars with a composition of 18.29% Cr, 18.23% Fe, 4.8% Nb, 5.15% Mo, 0.97% Ti, 0.54% Al, 0.12% Co, 0.078%
Si, 0.065% Mn, 0.065% Cu, 0.051% C, 0.028% W, and a balance of Ni were purchased from Gloria Material Technology Corp. (Taiwan, R.O.C). The as-received bars were machined into cylindrical specimens with a length and diameter of 9.7 mm and the ends of each specimen were then carefully finished using a grinder to ensure a close contact with the incident and transmitter bars of the SHPB apparatus during the impact tests.

The specimens were deformed at temperatures of −150 °C, 25 °C, 300 °C and 550 °C under strain rates of 1000 s⁻¹, 3000 s⁻¹ and 5000 s⁻¹, respectively. The striker bar, incident bar and transmitter bar of the SHPB apparatus were made of DC53 die steel and had a diameter of 20 mm. The incident and transmitter pressure bars both had a length of 1 m, while the striker bar had a length of 317 mm. The low test temperature of −150 °C was obtained by fitting a refrigeration system filled with liquid nitrogen and oxygen around the specimen. Meanwhile, the elevated test temperatures of 300 °C and 550 °C were obtained by enclosing the specimens in a clamshell radiant-heating furnace with an internal diameter of 25 mm and a heating element of length 300 mm. (Note that the full details of the experimental procedure and analytical technique used to evaluate the dynamic mechanical response of the impacted specimens are presented in [16,17].)

Prior to each test, the specimen and the two ends of the pressure bars holding the specimen were maintained at the specified test temperature for approximately 10 min to ensure a uniform temperature distribution at the specimen/pressure bar interface. The
ture. From a microstructural viewpoint, the plastic deformation of Inconel 718 alloy is directly related to the motion of dislocations within the microstructure. The evolution of the dislocation structure depends on the applied strain rate and temperature. As shown in Table 2, the dislocation density increases with increasing strain rate, but decreases with increasing temperature. By contrast, the dislocation cell size decreases with increasing strain rate, but increases with increasing temperature. The results presented in Fig. 8 show that the higher dislocation density induced at higher strain rates prompts a reduction in the dislocation cell size. The presence of a small cell size leads to a thick cell wall, which acts as an obstacle to the motion of other dislocations, and therefore provides a hardening effect. Accordingly, the dependence of the flow stress and hardening behaviour on the dislocation cell size can be expressed as

$$\sigma - \sigma_0 = \frac{\sigma_0 G b}{d^m}$$

where $\sigma$ is the flow stress, $\sigma_0$ is the backstress; $G$ and $b$ are the shear modulus and Burgers vector, respectively; and $a_2$ and $m$ are material constants. By fitting the experimental data in Fig. 8, the values of $a_2$ and $m$ are found to be 3.85 and 1.03, respectively.

Overall, the results presented in Figs. 7 and 9 show that the mathematical models given in Eqs. (1) and (2) provide a good quantitative description of the correlation between the flow stress, the dislocation density and the dislocation cell size in Inconel 718 alloy.

4. Conclusions

This study has investigated the mechanical properties of Inconel 718 alloy at strain rates ranging from 1000 to 5000 s$^{-1}$ and temperatures of $-150$ to $550 \degree C$. The results have shown that the flow stress, yield strength and work hardening coefficient increase with increasing strain rate, but decrease with increasing temperature. Moreover, a large increase in the flow stress occurs at strain rates greater than 3000 s$^{-1}$, while a significant thermal softening effect occurs at temperatures ranging from $-150$ to $25 \degree C$. TEM observations have shown that the dislocation density increases with increasing strain rate, but decreases with increasing temperature. The high dislocation density and small dislocation cell size result in an increased flow stress. Finally, it has been shown that the Bailey–Hirsch models yield an accurate description of the dependence of the flow stress on the dislocation density and dislocation cell size, respectively.

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