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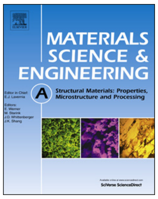

High temperature deformation behaviour of Haynes 188 alloy subjected to high strain rate loading

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ABSTRACT

The high temperature deformation behaviour of Haynes 188 alloy is investigated by means of a compressive split-Hopkinson pressure bar system at temperatures ranging from 25 to 800 °C and strain rates in the range of 1×10^3–$5\times10^3\ \mathrm{s}^{-1}$. It is found that the stress–strain curves obtained under high temperature conditions exhibit a flow softening effect. The maximum activation energy has a value of 51 kJ/mol and occurs at a temperature of 800 °C under a true strain of 0.3 and a strain rate of $1\times10^3\ \mathrm{s}^{-1}$. The Zerilli–Armstrong fcc model is shown to provide an adequate description of the stress–strain response of the Haynes 188 alloy specimens under the considered strains, strain rates and temperatures. An adiabatic shear band is formed in the specimen tested at room temperature under a strain rate of $5\times10^3\ \mathrm{s}^{-1}$. The dislocation density increases with an increasing strain rate or a decreasing temperature and leads to a greater flow stress. A linear correlation is observed between the square root of the dislocation density and the true stress. The dislocation hardening relation has the form $\sigma=\sigma_0+\alpha_1 Gb\sqrt{\rho}$, where α_1 has a value of 0.58 for the present Haynes 188 alloy specimens.

1. Introduction

Haynes 188 superalloy has many favourable properties, including good strength at high temperatures; excellent ductility, fabricability and weldability; and good resistance to hostile environments (e.g., corrosion, extreme heat, extreme cold, and so on). It is widely used for fabricating the combustor liners in aircraft turbine engines and is also used to produce the liquid oxygen posts in the main injectors of the space shuttle engines [1,2]. In such applications, the components are subjected to extremely high temperatures and strain rates. The literature contains many investigations into the low-cycle fatigue characteristics [3]; tensile-hold crack-growth behaviour [4]; axial and torsional fatigue behaviour [5]; and strengthening, oxidation and hot corrosion behaviour [6] of Haynes 188 alloy under high temperatures. However, the high temperature deformation behaviour and microstructure of Haynes 188 alloy impacted under high strain rates have attracted little attention thus far.

Previous studies have shown that the deformation behaviour of most metals and alloys is significantly dependent on the strain rate and temperature. Specifically, the flow stress increases rapidly with increasing strain rate or decreasing temperature [7–9]. Various mechanisms have been proposed to account for the change in mechanical properties prompted by high velocity deformation, including dislocation damping [10], thermal activation [11], and dislocation generation [12]. When plastic deformation occurs in a material, the microstructure changes accordingly and is characterised by the presence of dislocation structures. The dislocation density increases with increasing strain rate and leads to an increased flow stress [13]. However, a higher deformation temperature reduces the internal resistance to dislocation motion and results in plastic flow [14,15]. Thus, the actual dynamic mechanical behaviour of metals and alloys is determined by the results of a competition process between the work hardening effect caused by dislocation multiplication and the thermal softening effect caused by dislocation annihilation. Under high strain rate adiabatic loading conditions, the plastic deformation becomes unstable and adiabatic shear bands are formed due to a localisation of the plastic flow. The adiabatic shear bands act as preferential sites of crack initiation and are therefore a major cause of dynamic failure. As a result, the initiation and growth of adiabatic shear bands has been investigated for a wide range of metals and alloys [16–18].

The strain rate sensitivity, temperature sensitivity, thermal activation volume and activation energy of a material are all of crucial importance in engineering design problems. Critically, all of these properties are sensitive to the strain rate and temperature conditions. Moreover, to accurately predict the deformation of engineering materials over a wide range of strain rates and temperatures, a reliable constitutive description of the stress–strain behaviour is required. However, the literature contains little information regarding the properties of Haynes 188 alloy at high strain rates and temperatures,

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and no mention is made of an appropriate constitutive equation with which to model its dynamic behaviour. Therefore, the present study uses a split-Hopkinson pressure bar (SHPB) system to investigate the mechanical properties and deformation substructure of Haynes 188 superalloy at temperatures ranging from 25 to 800 °C and strain rates ranging from 1×10^3 to $5 \times 10^3\ s^{-1}$. The suitability of the Zerilli–Armstrong fcc model for describing the dynamic response of Haynes 188 alloy is investigated by comparing the predicted results for the stress–strain curves under the considered temperature and strain rate conditions with the experimental results. The microstructures of the deformed specimens are observed using transmission electron microscopy (TEM) and scanning electron microscopy (SEM). Finally, the correlation between the microstructural evolution of the impacted specimens and the mechanical response is systematically examined and discussed.

2. Experimental procedure

2.1. Material and specimen preparation

The Haynes 188 alloy used in the present tests was supplied by Aero Win Technology Corp. (Taiwan, R.O.C) in the form of a hot-rolled, solution-annealed bar with a diameter of 15 mm. (Note that solution annealing was performed at 1175 °C for 1 h followed by water quenching.) The alloy had a chemical composition (wt. pct) of 22.43 Ni, 21.84 Cr, 13.95 W, 1.24 Fe, 0.01C, 0.75 Mn, 0.40 Si, 0.012 P, 0.002 S, 0.034 La, 0.002 B, and a balance of Co. Fig. 1(a) presents an optical micrograph (OM) of the as-received alloy. It is seen that the microstructure consists of equiaxed grains with an average size of 42 μm. Moreover, it is observed that the grains contain a small number of annealing twins and M_6C carbide precipitates. Fig. 1(b) presents a TEM micrograph of the Haynes 188 alloy. The presence of a small number of dislocations is clearly observed.

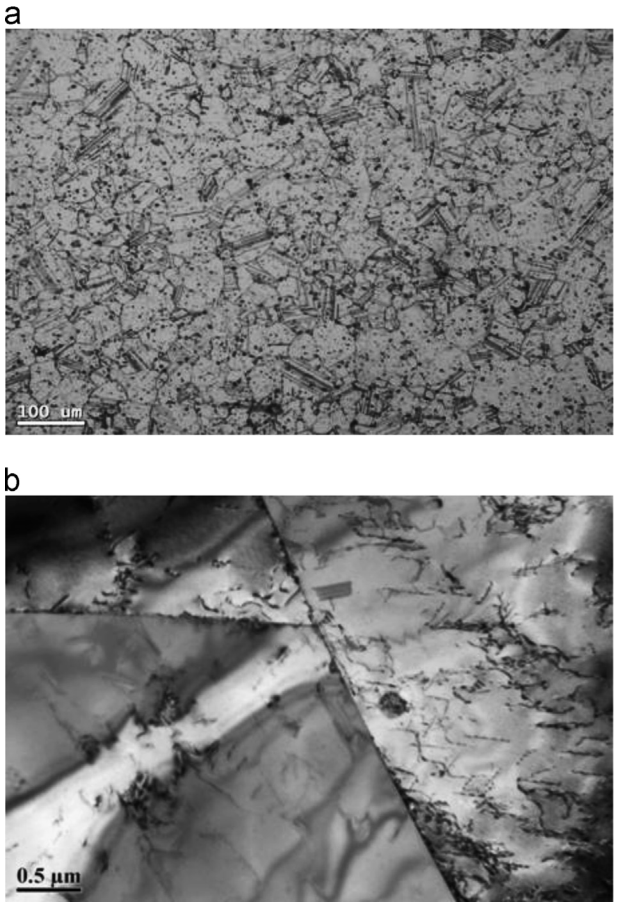

Fig. 1. Micrographs of as-received Haynes 188 alloy (undeformed): (a) OM and (b) TEM.

Cylindrical specimens with a length of 7 ± 0.1 mm and a diameter of 7.1 mm were machined from the as-received bar and finished to a final diameter of 7 ± 0.1 mm via a centre-grinding process. To ensure a uniaxial deformation state (i.e., frictionless conditions) during the impact tests, the end faces of the specimens tested at room temperature (25 °C) were lubricated with commercial molybdenum disulphide (Molykote), while the specimens tested at elevated temperatures were lubricated using a glass paste consisting of a powder of 80% P_bO and 20% B_2O_3 mixed with alcohol.

2.2. Mechanical testing

The specimens were deformed at temperatures of 25 °C, 400 °C and 800 °C and strain rates of $1 \times 10^3\ s^{-1}$, $3 \times 10^3\ s^{-1}$ and $5 \times 10^3\ s^{-1}$. In each test, the specimen was sandwiched between the incident bar and the transmitter bar of the SHPB system, and the incident bar was then impacted by a striker bar fired by a gas gun (see Fig. 2(a)). The striker bar, incident bar and transmitter bar were all made of DC53 die steel and had a diameter of 15 mm. The incident bar and transmitter bar each had a length of 1 m, while the striker bar had a length of 317 mm. The stress-strain curves of the impacted specimens were obtained by measuring the stress

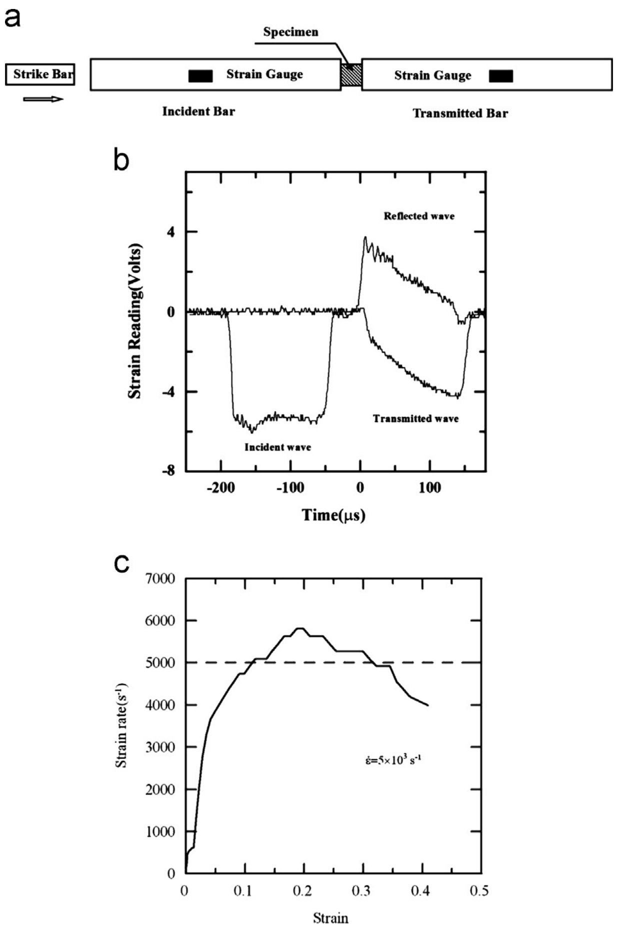

Fig. 2. (a) Schematic illustration of compressive split-Hopkinson pressure bar system. (b) Typical oscilloscope trace for Haynes 188 alloy specimen impacted at temperature of 25 °C and strain rate of $3 \times 10^3\ s^{-1}$. (c) Variation of strain rate with strain for specimen deformed at average strain rate of $5 \times 10^3\ s^{-1}$.