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Dynamic failure and adiabatic shearbands in fine-grain 93W–4.9Ni–2.1Fe alloy with Y_2O_3 addition under lower high-strain-rate (HSR) compression

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ABSTRACT

In this paper, Y_2O_3 dispersed 93W–4.9Ni–2.1Fe alloy with fine grains (FG) of about 3–5 μm has been fabricated by liquid-phase sintering of their respective nanocomposite powders. The dynamic properties of FG-WHA have been investigated under uniaxial dynamic compression using Split Hopkinson Pressure Bar. The results show that the FG-WHA exhibits an almost ideal elastic–plastic behavior with no work hardening and susceptibility of the adiabatic shear localization at lower strain rates than the traditional WHA. Two obvious adiabatic shearbands have been observed at the strain rate of 1900 s^{-1}. The adiabatic shearbands origins in the crack tip region in the surface area of the specimen, propagating deeply into the specimen along orientations at 45° to the impact direction. The bands have much narrower width of about 10–25 μm than that for traditional WHA (the width of bands is about 200 μm according to Kim et al. (1998a,b)). Within the center of the bands, the tungsten grains are severely elongated to be fibrous and orient along the propagation directions of the adiabatic shear bands, exhibiting plastic flow localized instability.

1. Introduction

W–Ni–Fe tungsten heavy alloys (WHA) are a kind of attractive candidate for kinetic energy penetrators because of their unique combination of high density, quasi-static strength and good ductility, equivalent to the depleted uranium (DU) alloys, as well as their environmental adaptability for the safety in comparison with the DU penetrators (Kim et al., 1998a,b; Yadav and Ramesh, 1995).

However, WHA penetrators have great difference from DU penetrators in sensitivity to dynamic failure. During high impact penetration, the deformation of DU penetrators quickly localizes into intense adiabatic shearbands (ASB), a phenomenon called "self-sharpening" effect. The good susceptibility to shear localization instability causes easy fracture at edges of the penetrator head and minimizes the size of the impacting face of the penetrator, exhibiting prominent self-sharpening effect under relatively lower high-strain-rate and showing excellent penetration performance (Andrew et al., 1991). While WHA penetrators exhibit much more strain-rate sensitivity compared to DU alloys and firstly form a stable mushroom-like-head during penetration, which has detrimental effect on the penetration efficiency. Landford et al. (1991) has demonstrated that tungsten heavy alloys have the potential for localized shear but it is extremely difficult even under very high-strain-rates. In their studies, a classic of 90W–7Ni–3Fe alloy specimen exhibits a number of 45° shear cracks nucleation within intense deformation bands under uniaxially compressed to 55% only at a strain rate of 5500 s^{-1}. Lee et al. (1998) reported that 92.5W–5.25Ni–2.25Fe alloy formed adiabatic shearbands at a strain rate of 4000 s^{-1} using Hopkinson Pressure Bar. So how to promote the "self-sharpening" effect of tungsten heavy alloys under lower strain rate has attracted considerable interests recently.

The possibility of forming localized adiabatic shearband is correlated to the microstructure. In the past, a large

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amount of work has been carried out to improve the susceptibility to shear localization in WHA by microstructure modification, such as cyclic heat treatment (Noh et al., 1994), deformation strengthening (Zhang and Wang, 2001) and refining grain size (Wei et al., 2006). Li et al. (2003) has reported that 93W–Ni–Fe alloy forged with 60% deformation was more likely to form adiabatic shearbands along the direction of forging. Among these methods, fine microstructure is prospective to reduce an abrupt plastic deformation and work favorably for localized deformation, which is directly related to the formation of adiabatic shearbands (Park et al., 2001).

In this study, we used nanocomposite powders with the addition of 0.03% Y_2O_3 to refine the microstructure of 93W–4.9Ni–2.1Fe alloy through liquid phase sintering. The nanocomposite powders were fabricated by sol-spray drying and subsequent hydrogen reduction process. The fine-grain (FG) spherical tungsten grains about 3–5 μm was obtained. The FG tungsten heavy alloy was tested under uniaxial compression using Split Hopkinson Pressure Bar (SHPB) to evaluate the dynamic failure. Localized adiabatic shearbands (ASB) were observed under a strain rate of 1900 s^{-1}.

2. Experimental procedure

The starting materials for the synthesis of W–Ni–Fe composite powders were ammonium metatungstate (AMT), $(NH_4)_6(H_2W_{12}O_{40})\cdot 4H_2O$, nickel nitrate hexahydrate, $Ni(NO_3)_2\cdot 6H_2O$, iron nitrate, $Fe(NO_3)_3\cdot 9H_2O$ and yttrium nitrate, $Y(NO_3)_3\cdot 6H_2O$.

An aqueous mixed solution containing W, Ni, Fe, Y salts was prepared by dissolving their own solid metal salts into the distilled water according to the final chemical composition of the alloy. The nanocomposite powders were then obtained by a multi-step process, consisting of sol-spray-drying of the solution at 250 °C–350 °C, calcining at 600 °C for 2 h and subsequent two-step reduction process (450 °C, 850 °C) in hydrogen atmosphere. The particle size of the nanocomposite powders was characterized as 200 nm by scanning electron microscope (SEM). Fig. 1 shows the SEM microphotograph of the nanocomposite powders. The nanocomposite powder was die-pressed and then sintered at 1410 °C for 60 min in hydrogen atmosphere. The sintered cylindrical specimens (φ10 × 10 mm) for dynamic test were obtained.

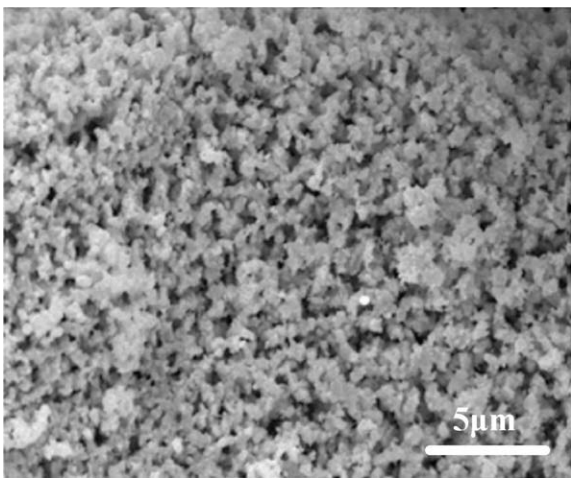

Fig. 1. SEM morphology of 93W–4.9Ni–2.1Fe composite powder containing 0.03%Y_2O_3

A Split Hopkinson Pressure Bar (SHPB) technique (shown in Fig. 2) given by Nemat-Nasser et al. (1991) was used to study the dynamic response of the alloy with strain rates of $1.2 \times 10^3\ s^{-1}$, $1.5 \times 10^3\ s^{-1}$ and $1.9 \times 10^3\ s^{-1}$. The original sintered cylindrical specimens were machined by linear cutting to a length of 7 mm and a diameter of 7 mm, and then they were sandwiched between two long elastic bars (called the input bar and output bar). One end of the input bar was impacted by a striker bar driven by air gun and the resulting compressive pulse propagated through the input bar and into the specimen. This loading pulse resulted in plastic deformation of the specimen. A fraction of the momentum generated by the pulse was transmitted through the sample into the output bar while a reflected pulse propagated back into the input bar from the specimen. These reflected pulses (strain rate) and transmitted pulses (stress) were measured using strain gages cemented on the input and output bar.

After the test, the recovered specimens were precisely cut in parallel to the impact direction; the section surface was polished and etched. The evolution of microstructure in the impacted specimens was observed using optical microscope to clarify whether and when the shearbands are developed.

3. Results and discussion

3.1. Microstructure of the FG 93W–4.9Ni–2.1Fe

Fig. 3 shows optical microstructure of FG 93W–4.9Ni–2.1Fe alloy with 0.03% Y_2O_3 before uniaxial dynamic compression test. It can be seen that fine spherical bcc tungsten grains of about 3–5 μm in diameter distribute homogeneously in the continuous distributed fcc Ni–Fe matrix phase. The maximum tensile strength and elongation of the alloy are 920 MPa and 15%, respectively. This good

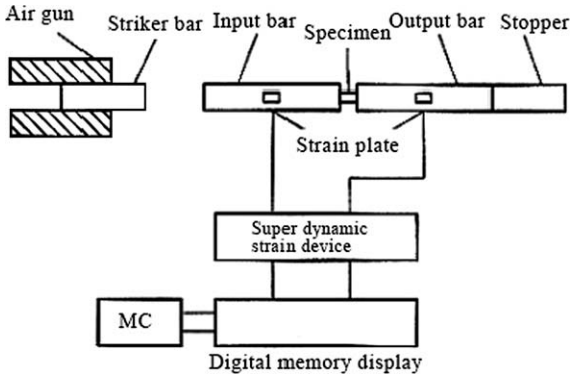

Fig. 2. Schematic of the Split Hopkinson Pressure Bar apparatus.