Microstructure and dynamic mechanical properties of tungsten-based alloys in the form of extruded rods via microwave heating

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ABSTRACT

The dynamic mechanical properties of 93W–4.9Ni–2.1Fe alloys in the form of extruded rods sintered by microwave heating were investigated under dynamic compression using a split Hopkinson Pressure Bar. The microstructure and microhardness values of the sintered specimens after dynamic compression were analyzed and tested. The results show that the deformation amount and microhardness of specimens increase with increasing strain rate. When the strain rate is 3000 S^{-1}, the deformation amount is increased to the maximum value of 59.8%, and the microhardness values of the tungsten grains and the matrix phase are also promoted to the maximum values of 7.66 and 6.92 Gpa, respectively. The formation of cracks during compressive deformation initiates before the appearance of the adiabatic shear bands. As the strain rate increases, cracks initiating at the edge of specimens gradually propagate to the bulk alloy, and the adiabatic shear band is observed at about 45° to the loading direction under the strain rate of 3000 S^{-1}. These findings suggest that tungsten-based alloys extruded rods sintered by microwave heating would be an ideal material with excellent self-sharpening and penetration performance for penetrators.

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1. Introduction

Tungsten-based alloys, possessing a series of excellent physical and mechanical properties, have a wide range of applications in the field of ordnance, especially used as the basic materials for kinetic energy penetrators [1,2]. When penetrators collide with targets, work hardening will occur because of the high-speed stamping and impacting. Additionally, the high melting point of the tungsten-based alloy slows down the trend towards thermal softening, thus, the strain hardening and strain rate hardening will go on, which will result in mushroom-like head and less adiabatic shear bands, leading to the poorer penetration performances [3,4].

In order to promote the self-sharpening and penetration performances of tungsten-based alloys, researchers have undertaken considerable researches and found that refined grains could significantly optimize the microstructure of tungsten-based alloys so as to achieve the purpose of improving adiabatic shear sensitivity [5]. Microwave sintering, a kind of new sintering technology which can largely improve the mechanical properties of tungsten-based alloys, can effectively inhibit the growth of tungsten grains leading to a fine-grained microstructure during sintering [6,7]. Meanwhile, powder extrusion molding is a novel near-net molding technology, which developed on the basis of the metal slab and polymer processing. Due to the advantages of high efficiency, the unlimited length of product and the uniform longitudinal density, powder extrusion molding has obtained great importance and

has arrived to be a rapid development and application technology. But so far, the dynamic mechanical properties of the extruded tungsten-based alloy rods with large aspect ratio sintered by microwave have not been thoroughly investigated in the literature. Therefore, in this paper, the microstructure and dynamic mechanical properties of microwave sintered W–Ni–Fe alloy rods by extrusion will be investigated and corresponding self-sharpening potentiality will be discussed.

2. Experimental

Powder mixtures with a composition of 93W–4.9Ni–2.1Fe (wt.%) were first mixed in a cylinder mixer for 20 h, and then prepared for the extruding feed by adding an appropriate amount of binder. The characteristics of the tungsten, nickel and iron powders used in this study are summarized in Table 1. The extruded rods with a diameter of 24 mm were fabricated by a vacuum extruder (Dorst-V15, Germany). After solvent debinding and thermal debinding, the rods were sintered at 1550 °C for 30 min in a microwave furnace with a frequency of 2.45 GHz (HAMiLab-V6) in a flowing reducing atmosphere

Table 1
Characteristics of tungsten, nickel and iron powders.

Metal powders	Shape	Purity/wt.%	Average particle size/μm
Reduced tungsten powders	Irregular	99.9	2.0
Carbonyl nickel powders	Irregular	99.5	5–8
Carbonyl iron powders	Irregular	99.5	5–8

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Fig. 1. Photograph of cylindrical specimen.

(10 Vol.% H_2 and 90 Vol.% N_2). Temperature is monitored using an infrared pyrometer (Raytek MM2MH). The sintered rods were cut into cylindrical specimens (ϕ5 mm × 5 mm), as seen from Fig. 1. These cylindrical specimens were treated at 1200 °C for 120 min in a vacuum sintering furnace (R121600-1/UM) in order to remove internal stress. Uniaxial dynamic compression tests were carried out using a split Hopkinson Pressure Bar (Fig. 2) at the strain rate of 1000, 2000 and 3000 S^{-1}, respectively. Three specimens were evaluated per condition. The surface perpendicular to the loading direction and the sectioned surface along the loading direction of specimens were polished by automatic polishing machine and then etched. The microstructure was observed by scanning electron microscopy (SEM, JSM-6360LV). The microhardness of tungsten grains and the matrix of specimens were measured by an ultra nanoindentor (UNHT, Switzerland CSM).

3. Results and discussion

3.1. Deformation amount

Fig. 3 shows the photo of specimens after testing under the dynamic compression rate of 1000, 2000 and 3000 S^{-1} (from left to right, and original sample is in the leftmost). It can be seen from Fig. 3 that the deformation increases with the strain rate. In order to represent the degree of deformation, in this study, we introduce the formula of deformation amount, which can be expressed in the following:
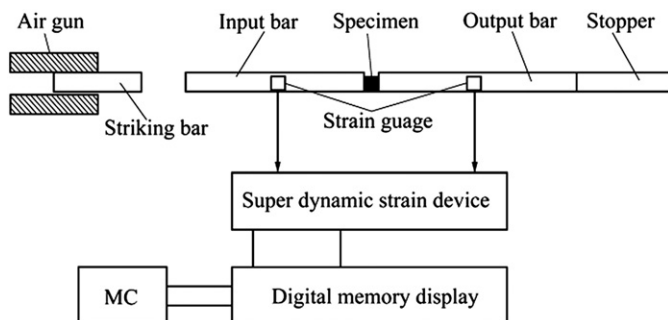
$$\varphi = \frac{S_1 - S_0}{S_0} \times 100\%$$

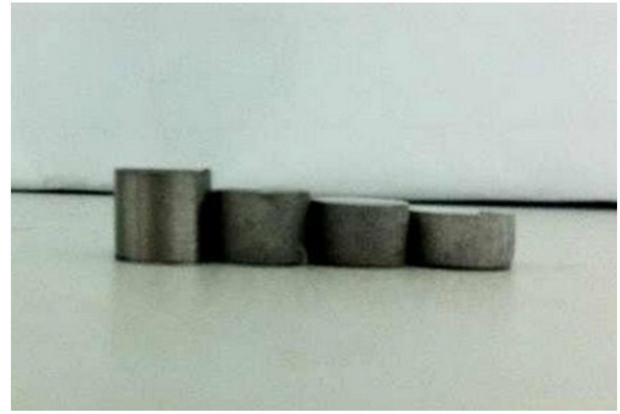Fig. 2. Hopkinson pressure bar device [8].

Fig. 3. Photos of specimens tested under the dynamic compression rate of 1000, 2000 and 3000 S^{-1} (from left to right, and original sample is in the leftmost).

where s_0 and s_1 are the areas of the surfaces perpendicular to the loading axial before and after dynamic compression, respectively. The deformation amount and strain rate of specimens are summarized in Table 2. It can be seen that the deformation amount increases with enhancing of strain rate, in particular, the deformation amount is increased to maximum value of 59.8% when the strain rate is 3000 S^{-1}. In spite of the substantial deformation, no macroscopic cracks and catastrophic fractures are clearly observed in Fig. 3, which suggests the excellent toughness of the extruded rods sintered by microwave.

3.2. Stress–strain curves

Fig. 4 shows the true stress–strain curves of specimens obtained by using different strain rates. It can be seen that elastic deformation occurs at the very early stage of dynamic compression, and the stress increases with increasing strain. After the stage of elastic deformation, the specimens will be plastically deformed. It is of interest to be observed that the greater the strain rate is, the more slowly the stress increases. Especially, when the strain rate is 3000 S^{-1}, the increasing tendency of stress is the slowest. Compared with the values of the stress increasing with increasing strain during elastic deformation, the three curves of dynamic compression generally show that the tendency is relatively slower during plastic deformation. The possible reason is the thermal softening effect. When the specimens are subjected to dynamic compression, the thermal softening effect is not obvious and the stress increasing is dominant with increasing strain during elastic deformation. However, during plastic deformation, the abrupt concentration of heat cannot be dissipated immediately, and thus the thermal softening effect is gradually becoming more dominant and leads to offset part of the strain hardening, which leads to the effect that the tendency of stress increasing becomes slower with increasing strain.

It can be seen from Fig. 4 that the maximum stress of the specimens under the strain rate of 1000, 2000 and 3000 S^{-1} is 2243 MPa, 2202 MPa and 2138 MPa, respectively, and during plastic deformation, the stress increasing tendency of the specimens under the strain rate of 1000 and 2000 S^{-1} is faster than that under the strain rate of 3000 S^{-1}. In the strain rate of 1000 or 2000 S^{-1}, the thermal softening effect of the specimens is not so obvious because of the relatively lower proportion

Table 2
Deformation amounts of specimens and corresponding strain rates.

Strain rate/ S^{-1}	Diameter before dynamic compression/mm	Diameter after dynamic compression/mm	Deformation amount/%
1000	5.00	5.51	21.4
2000	5.00	5.88	38.3
3000	5.00	6.32	59.8