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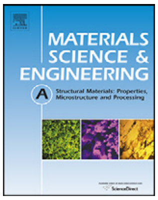

Microstructure and highly enhanced mechanical properties of fine-grained tungsten heavy alloy after one-pass rapid hot extrusion

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ABSTRACT

One-pass rapid hot extrusion of fine-grained 93W–4.9Ni–2.1Fe–0.03Y (wt.%) alloy with an average grain size of ~10 μm was performed at 1150 °C with an extrusion speed of ~100 mm/s and an extrusion ratio of ~3.33:1. Microstructure and mechanical properties of the as-extruded alloy were investigated. The results show that the tungsten particles of the as-extruded alloy are severely elongated along the extrusion direction and the aspect ratios of these elongated particles are 5–8. Three crystallographic textures $\{001\}\langle 110\rangle$, $\{111\}\langle 110\rangle$ and $\{110\}\langle 110\rangle$ arose after rapid hot extrusion and the total volume fraction of these texture components was approximately 30%. Many lath-shaped subgrains with a small misorientation and low density dislocations could be observed in tungsten phase and γ-(Ni, Fe) phase respectively. These microstructure characteristics indicate that slight dynamic recovery-recrystallization process occurred during rapid hot extrusion. In contrast to as-sintered alloy, the as-extruded alloy possessed much higher ultimate tensile strength and hardness (HRC) but a relatively lower ductility (1570 MPa *vs.* 995 MPa; HRC48 *vs.* HRC29 and 6.5% *vs.* 24%). In addition, the fracture morphology shows that the predominant failure mode for the as-extruded alloy is cleavage failure of the tungsten particles, while the ductile rupture of the γ-(Ni, Fe) phase that can be frequently observed in the as-sintered alloy nearly disappeared after rapid hot extrusion.

1. Introduction

Plastic deformation strengthening has been widely used to enhance the comprehensive mechanical properties of liquid-phase sintered tungsten heavy alloys (WHAs) for the military application in kinetic energy penetrators [1–9]. Over the past several decades, several plastic processing technologies have been developed to further improve the mechanical properties of WHAs, including swaging [10–12] and hydrostatical extrusion [13–17]. Swaging, an extensive application of plastic deformation technique at present, has some drawbacks [13], such as small deformation amount (generally less than 20%) for one-pass, complicated processes due to the requirement of multiple intermediate annealing for obtaining large deformation extent and inhomogeneous metal flow as the result of the asymmetric deformation. Compared to swaging, hydrostatical extrusion can achieve a higher extrusion ratio (as high as 4:1) only by one extrusion operation. Besides, there is a more uniform plastic flow in billets during extrusion processing, resulting from the extrusion pressure transferred uniformly by fluid medium instead of a punch [13]. However, the production efficiency of hydrostatical extrusion processing is lower and the leak tightness of fluid medium in container should be constantly attached greater importance, which to some extent limits the widespread application of this technique in industrial production.

In addition, the previous investigations concentrated mainly on the deformation strengthening of conventional coarse-grained WHAs with a typically average grain size of 40–60 μm. The large tungsten grains are likely to create an inhomogeneous deformation and stress concentration during swaging or extrusion processing, so that some microcracks even cracking can be frequently observed on the surfaces of as-swaged or as-extruded billets. Furthermore, due to the ceramic-like brittle nature of coarse-grained tungsten, pure W or conventional WHAs materials must be hot-worked at the temperature below the recrystallization temperature of tungsten [18]. If the hot-worked duration is too long, the dynamic recovery even recrystallization process will take place sufficiently, which has a detrimental effect on the desired strain hardening.

In this study, we took advantage of rapid hot extrusion technique with an extrusion speed of ~100 mm/s to strengthen a fine-grained 93W–4.9Ni–2.1Fe–0.03Y (wt.%) alloy (average grain size of ~10 μm) fabricated by the liquid-phase sintering of nanocrystalline composite powders. The microstructure characteristics and mechanical properties of the as-extruded alloy were studied in detail. The rapid hot extrusion is significantly different from the conventional extrusion in the extrusion speed (generally

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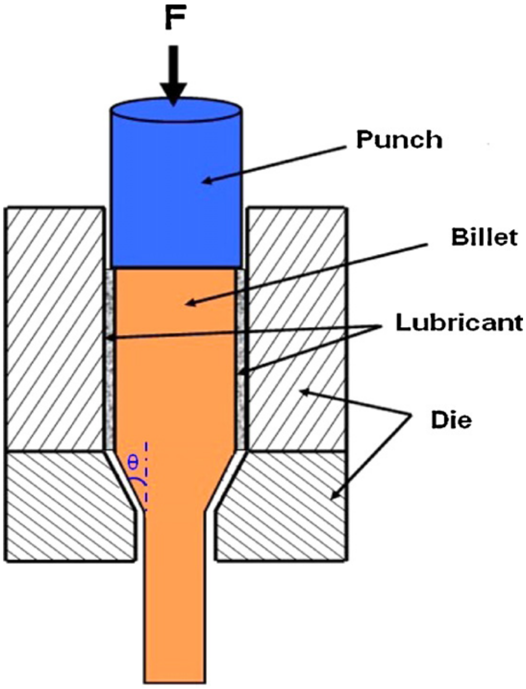

Fig. 1. Schematic diagram of rapid hot extrusion die.

10–20 mm/s for conventional extrusion). The high extrusion speed in this study was designed to realize higher production efficiency, to obtain a more uniform plastic deformation and to partly offset the negative effect of dynamic recovery-recrystallization process on tensile strength. In addition, WHAs with a fine microstructure was prepared to prevent cracking during hot extrusion and to introduce grain refining strengthening.

2. Experimental

The raw materials used in the study for fabricating the fine-grained 93W–4.9Ni–2.1Fe–0.03Y (wt.%) alloy were nanocrystalline W–Ni–Fe–Y composite powders that were synthesized by sol-gel spray drying and subsequent hydrogen reduction process. The detailed description about the preparation of the nanocrystalline composite powders can be found in our previous work [19]. The powders were pressed by means of cold isostatically pressing (CIP) to obtain cylindrical green compacts with a relative density of about 54%. The compacts were liquid-phase sintered at 1460 °C for 1.5 h in a molybdenum tube furnace under a flowing hydrogen atmosphere (dew point of −40 °C), followed by a treatment of vacuum annealing at 1200 °C for 2 h to remove the absorbed hydrogen and intermetallic compounds. The density of the as-sintered alloy was about 99.7% of the theoretical density. Cylindrical bars, having the dimensions of 24 mm in diameter and 50 mm in length, were extruded for one-pass at 1150 °C with the extrusion speed of $\sim$100 mm/s and the extrusion force of $\sim$260 tons. The resulting extrusion ratio was approximately 3.33:1 (the corresponding reduction of cross-section area was 70%). Before rapid hot extrusion, the mixture of glass and graphite was selected to lubricate the die and the heating temperature of the lubricant was 450 °C. Fig. 1 shows the schematic diagram of rapid hot extrusion die. The specification of rapid hot extrusion is given in Table 1. The chemical compositions of the fine-grained alloy before and after rapid hot extrusion processing are displayed in Table 2. Fig. 2 presents the photograph of the fine-grained 93W–4.9Ni–2.1Fe–0.03Y alloy bars after rapid hot extrusion. It shows that the as-extruded bars have quite smooth surfaces and precise dimensions (Ø 12 mm × 160 mm) and there are no transverse or longitudinal cracking in these extruded bars. Dog-bone shaped specimens were cut from these as-extruded bars using wire electrical discharge machining (EWDM). The quasi-static mechanical properties of these specimens were determined by a standard Instron 3369 material test machine (USA) and the applied tensile load axis was parallel to the extrusion direction. Hardness (HRC) was measured by Digital Rockwell Hardness Tester (200HRS-150). In order to respectively determine the hardness of tungsten phase and γ-(Ni, Fe) phase of the extruded bar, Ultra Nanoindentor tester (CSM, Switzerland) was employed. Scanning electron microscopy (SEM, JSM-5600LV), transmission electron microscopy (TEM, JEM-3010) and X-ray diffraction (XRD) technique were employed to characterize the microstructure of the as-extruded alloy.

Table 1
Specification of rapid hot extrusion.

Alloy component	Fine-grained 93W–4.9Ni–2.1Fe–0.03Y
Maximum extrusion force (tons)	260
Maximum extrusion pressure (GPa)	5.8
Punch speed (mm/s)	$\sim$100
Extrusion angle (θ/°)	60
Cylindrical billet dimensions (mm)	Ø 24 × 50
Lubrication heating temperature (°C)	450
Reduction of cross-section area (%)	70

Fig. 2. Photograph of the fine-grained 93W–4.9Ni–2.1Fe–0.03Y alloy bars after rapid hot extrusion.

Table 2
Chemical compositions of the fine-grained 93W–4.9Ni–2.1Fe–0.03Y% alloy before and after rapid hot extrusion processing (wt.%).

Elements	W	Ni	Fe	Y	Ca	K	Mg	Si	Zn	Na	O
Before rapid hot extrusion	93.0171	4.8900	2.0400	0.0320	0.0035	0.0005	0.0005	0.0020	0.0005	0.0015	0.0124
After rapid hot extrusion	93.0452	4.8600	2.0100	0.0310	0.0035	0.0005	0.0005	0.0025	0.0005	0.0015	0.0448