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Thermo-mechanical processing, microstructure and tensile properties of a tungsten heavy alloy

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ABSTRACT

The effect of heat treatment and swaging on microstructure and mechanical properties of a tungsten heavy alloy (WHA) of composition 90.5W–7.1Ni–1.65Fe–0.5Co–0.25Mo (wt%) has been examined in this study. The volume fraction and the contiguity of W-grains in the sintered microstructure decrease from 80% to 75% and 0.7 to 0.3, respectively, following an intermediate heat treatment comprising annealing at 1373 K followed by oil quenching. The average aspect ratio of W-grain increases with the increase in swaging deformation. While the bulk hardness of the alloy increases with increase in swaging deformation, a minor drop in hardness is observed following intermediate heat treatment. Peak broadening is observed in the X-ray diffractograms following thermo-mechanical processing with full width at half maxima (FWHM) of W_{110} peak exhibiting a similar trend as that of hardness. The as-sintered alloy exhibits low yield strength, tensile strength and very low elongation to failure. Subsequent thermo-mechanical treatment results in substantial improvement of both strength and elongation. A strength value of 1427 MPa with elongation of 5–6% has been achieved following 40% swaging. Work hardening behavior of the alloy in heat treated condition has been studied and the results are correlated with slip lines and dislocation behavior of the alloy.

1. Introduction

In the past five decades, extensive research has been done on tungsten heavy alloys (WHAs) in order to improve their mechanical properties. This has been achieved by employing the following approaches: (1) modifying the chemistry, (2) tailoring the microstructure and (3) thermo-mechanical processing. Bose et al. [1] showed that lowering the W content from 98 to 90 wt% caused an improvement in the ultimate tensile strength as well as elongation of the sintered WHAs. They also observed that 92.5% W–(Ni–Fe–Co) alloy deformed up to 95% showing a tensile strength of 1720 MPa and an elongation of 16%. Nicolas [2], on the other hand, was able to impart a tensile strength of 1850 MPa with an elongation of 5–8% in 93% W–5% Ni–2% Fe alloy by optimum combination of swaging, heat treatment and aging. Spencer [3] achieved an improvement of yield strength up to 1400 MPa in 90% W–8% Ni–2% Fe alloy by repeated heat treatment and swaging (with a total swaging deformation of 40%).

The effect of swaging on microstructure has also been studied independently. It has been found that increasing swaging deformation results in an increase in the aspect ratio of W-grains [4]. Subsequent heat treatment just above the melting point of the matrix leads to rounding and fragmentation of W-grains [5]. Cyclic heat treatment at 1423 K (repeated heating at 1423 K for short time and quenching to room temperature) was found to reduce the contiguity of W-grains in WHA [6]. The dependence of contiguity on thermo-mechanical treatment was clearly brought out by Kim et al. [7]. They showed that there is a substantial reduction in contiguity from sintering to the subsequent heat treatment. On the other hand, from heat treatment to swaging, the contiguity decreases only marginally and increases again following aging.

Although some of the above studies have been attempted to investigate the effect of thermo-mechanical processing on microstructure and mechanical properties, a detailed study has not been carried out so far to study the mechanical behavior of WHAs at different stages of thermo-mechanical processing. In the present study the effects of heat treatment and swaging on the mechanical properties, work hardening behavior, dislocation substructure and fracture behavior of a quinary tungsten heavy alloy, namely, 90.5W–7.1Ni–1.65Fe–0.5Co–0.25Mo, have been examined.

2. Experimental

Ball milling was employed to blend elemental W, Ni, Fe, Co and Mo powders taken in appropriate proportions. 12 mm diameter stainless steel balls were used and the ball-to-powder weight ratio was

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maintained at 1:1. Milling speed was kept at 35 rpm and the mixing was carried out for about 24 h. The powder mixture was compacted into a cylindrical rod in a cold isostatic press (CIP) supplied by National Forge Company, Belgium, at a pressure of 200 MPa. Pre-sintering of the compacted rod and subsequently liquid phase sintering of the pre-sintered rod were carried out at 1573 K and 1733 K, respectively, for 1.5 h in H_2 atmosphere in a continuous pusher type furnace (FHD Furnace Limited, England). The alloy was then heat treated at 1373 K for 1 h in vacuum and then oil quenched. The heat treated WHA was subjected to swaging at 773 K with an intermediate annealing heat treatment at 1373 K for 1 h followed by oil quenching. Swaging was carried out using a rotary swaging machine at a stroke frequency of 150/min. The thermo-mechanical processing schedule adopted in this study is presented in Fig. 1.

Specimens were metallographically polished with 600 grit emery paper followed by sylvet cloth polishing using 0.25 μm size diamond paste. Back scattered and secondary electron imaging using a Scanning Electron Microscope (Quanta 400) was employed to study the microstructures. The aspect ratios of the individual tungsten grains were measured by finding the ratio of the major axis to the minor axis. The ratios were determined for 15–20 grains (Table 1) in each case. SEM study was also carried out to observe slip lines and fractographs of failed tensile specimens.

A Phillips XRD machine (PW 3020) was used for the XRD study. X-pert high score plus software was used for phase identification and measurement of full width at half maxima (FWHM).

Tensile test samples (gauge length=20 mm) were machined as per ASTM standard (ASTM E 8 M) and tested using a Walter-Bai+Ag universal testing system (capacity 200 kN) at room temperature. Micro-hardness measurement was carried out using a micro-hardness tester (Leica VMHT Auto). 100 and 25 g loads were used for hardness measurement of W-grains and matrix, respectively. Bulk hardness of the alloys was measured by a Wolpert Vickers hardness tester using 30 kg load.

Compression test specimens of 5×5 mm^2 square cross section and 10 mm height were machined from heat treated blanks. The test was performed at room temperature (298 K) using a screw driven Instron machine (Instron 5500). Graphite paste was used as lubricant for the compression tests. Specimens with varying degrees of compressive deformation were produced. Foils from 2% deformed specimen were prepared from the slices cut at 45° to the compressive loading axis. These foils were used for transmission electron microscopy (TEM) study. TEM foils were prepared by ion milling using a GATAN precision ion polishing system. A TECNAI G^2 electron microscope was used at an operating voltage of 200 kV for studying the foils.

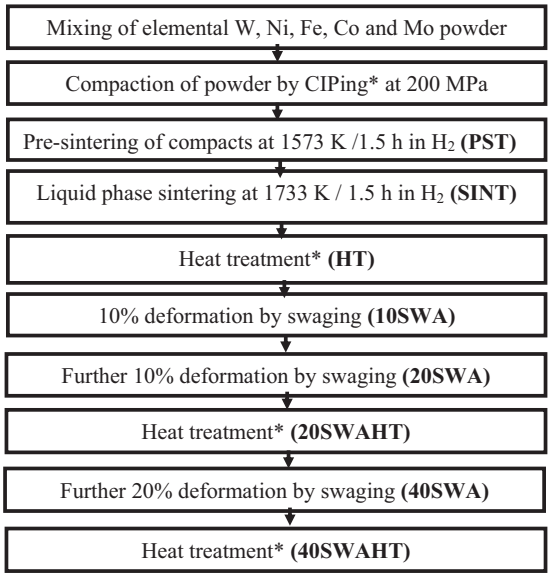

Fig. 1. Processing sequence adopted for the alloy. *Heat treatment consists of annealing at 1373 K for 1 h in vacuum followed by oil quenching; CIPing is cold isostatic pressing

3. Results

3.1. Microstructure

The microstructure of the alloy at different stages of processing is shown in Fig. 2. While pre-sintering (PST) at 1573 K results in the formation of porosity (shown by arrows in Fig. 2a), almost no porosity is observed in the as-sintered microstructure (Fig. 2b). Liquid phase sintering (SINT) results in rounded W-grains interspersed by a continuous matrix (Fig. 2b). Heat treatment (HT) at 1373 K for 1 h in vacuum followed by oil quenching (Fig. 2c) causes an increase in the volume fraction of the matrix phase and reduction in the contiguity of W-grains (Table 1). The microstructure of longitudinal section after 10% swaging deformation (10SWA) shows elongated W-grains (Fig. 2d) with an average aspect ratio equal to ~1.2 (Table 1). The aspect ratio of these elongated grains increases to ~1.5 (Table 1) with a further swaging deformation of 10% (total deformation of 20%, 20SWA) (Fig. 2e). While aspect ratio diminishes marginally to 1.46 (Table 1) after intermediate heat treatment (20SWAHT) (Fig. 2f), it increases again to 1.7 (Table 1) upon further 20% swaging, the total deformation being 40% (40SWA) (Fig. 2g). Again, a marginal decrease in aspect ratio (1.65) is observed following heat treatment (Fig. 2h). In general, the W-grains tend to get elongated in the direction perpendicular to the swaging direction (Fig. 2). Dislocation substructure in the matrix, as well as in the W-grains at different processing stages is shown in Fig. 3. Qualitatively, while the dislocation density in both the W-grain and the matrix phase increases with the increase in the swaging deformation (Fig. 3a–d), it decreases following heat treatment (Fig. 3e and f).

3.2. X-ray diffraction study

X-ray diffraction (XRD) patterns of the specimens after different stages of processing are shown in Fig. 4. Peaks from both the

Table 1
Variation of microstructural parameter with processing conditions.

Processing condition	vol% of W-grains	Contiguity	Average lateral dimension of W-grains, (μm)	Average longitudinal dimension of W-grains, (μm)	Aspect ratio=longitudinal dimension/lateral dimension
SINT	80	0.70	30	30	1.00
HT	75	0.33	30	30	1.00
10SWA	75	0.30	27	32	1.19
20SWA	77	0.29	25	38	1.52
20SWAHT	76	0.24	26	38	1.46
40SWA	75	0.20	23	39	1.70 ± 0.15
40SWAHT	75	0.20	23	38	1.65 ± 0.13