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Effect of alloying addition and microstructural parameters on mechanical properties of 93% tungsten heavy alloys

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ABSTRACT

Liquid phase sintering, heat treatment and swaging studies on three tungsten heavy alloys, 93W–4.9Ni–2.1Fe (wt%), 93W–4.2Ni–1.2Fe–1.6Co (wt%) and 93W–4.9Ni–1.9Fe–0.2Re (wt%) were carried out in detail with respect to microstructure, tensile and impact properties. All the alloys were sintered and swaged to 40% deformation. The results indicate that Re addition reduces the grain size of the alloy compared to W–Ni–Fe and W-Ni-Fe-Co alloys. W–Ni–Fe–Re alloy shows superior tensile properties in heat treated condition as compared to W–Ni–Fe and W–Ni–Fe–Co alloys. SEM study of fractured specimens clearly indicates that the failure in case of W–Ni–Fe–Re was due to transgranular cleavage of tungsten grains and W–W de-cohesion. W–Ni–Fe and W–Ni–Fe–Co alloys also failed by mixed mode failure. However, in these cases, ductile dimples corresponding the failure of the matrix phase was rarely seen. Thermo-mechanical processing resulted in significant changes in mechanical properties. While W–Ni–Fe–Re alloy showed the highest tensile strength (1380 MPa), W–Ni–Fe–Co exhibited the highest elongation (12%) to failure. A detailed analysis involving microstructure, mechanical properties and failure behavior was undertaken in order to understand the property trends.

1. Introduction

Tungsten alloys have found increasing applications in kinetic energy penetrators, radiation shielding, balance weights and electrical contacts due to high density, good physical and mechanical properties [1–3]. Tungsten heavy alloys (WHA), prepared by liquid-phase sintering, are composite materials in which quasi-spherical shaped hard bcc particles are embedded in the ductile Ni–Fe–W solid solution fcc matrix. Liquid phase sintering (LPS) offers advantages of relatively low sintering temperature, enhanced densification, microstructural homogenization and near theoretical sintered densities. In addition, LPS also enables high material utilization (> 95%), near-net shaping, high productivity, and superior properties [4]. Tungsten heavy alloys offer a unique combination of properties such as high density (16–18 g/cm^3), high strength (1000–1700 MPa), high ductility (10–30%), good corrosion resistance, and easy machinability. One of the strategic applications for these alloys is in ordnance, such as kinetic-energy (KE) penetrators. While the high density of tungsten heavy alloy helps in realization of higher depth of penetration, their excellent mechanical properties such as high strength, ductility and impact property ensure the survival of penetrator from the rigors of extremely demanding conditions experienced during their launch and terminal ballistics [5]. The as-sintered WHAs are generally vacuum-annealed followed by oil quenching to remove trapped hydrogen, ensure homogenization of the matrix and also reduce the interfacial segregation of impurities [6–8]. Mechanical properties of the sintered heavy alloys can be further improved by thermomechanical processing that involves repeated heat treatment and swaging. Islam et al. [9] conducted experiments on heat treated W–Ni–Fe alloys and showed that the binding strength between W and the matrix phase has a major influence on the ductility of WHAs. This can be addressed by either heat treatment or suitable alloying additions. Increasing tungsten (> 93%) results in increase in the density of the alloy leading to higher depth of penetration. However, the alloys containing higher tungsten exhibit inferior mechanical properties [10,11]. Since, 90% W with nickel and iron are widely used composition and alloys with higher tungsten have received less attention, it was decided to study alloys with 93% tungsten base alloys with minor additions of Co and Re and correlate mechanical properties with underlying microstructure. Although W alloys with improved mechanical properties were successfully developed [10–13], limited results are available on the effect of higher tungsten content (93%) alloys on tensile and Charpy impact properties in the thermo-mechanically processed condition [14]. In the present investigation, WHAs that

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comprise about 93% W and balance matrix alloy containing Ni, Fe, Co and Re have been investigated in detail with respect to microstructure, tensile properties and impact toughness. The effect of relative volume fraction of tungsten and the matrix phase on mechanical properties of heavy alloys have also been discussed.

2. Experimental

Three tungsten heavy alloys, namely WNF (93W–4.9Ni–2.1Fe), WNC (93W–4.2Ni–1.2Fe–1.6Co) and WNR (93W–4.9Ni–1.9Fe–0.2Re) were prepared by powder metallurgy route. The characteristics of the initial powders used in the present study are shown in Table 1. Tungsten powder was admixed with elemental powders such as Ni, Fe, Co and Re in the required proportions using a ball mill with BPR (Ball to Powder Ratio) 2:1 at a speed of 50 rpm for 48 h. The mixed powders were then filled in a 55 mm diameter and 400 mm length PVC mold and cold iso-statically pressed (Make: National Forge, Belgium) at 250 MPa pressure for 20 min. The cold pressed tungsten heavy alloy rods were sintered in a hydrogen sintering furnace (Therelek Furnace, Hyderabad, India) at a temperature of 1480 °C for 2 h. The sintering cycle employed for the present study is shown in Fig.1. The densities of the sintered blanks were measured with the Archimedes water immersion method. The sintered tungsten heavy alloy blanks were subjected to vacuum heat treatment (1100 °C/2 h/oil quench) followed by swaging (20%), vacuum heat treatment (1100 °C/2 h/oil quench) and final swaging to 40% reduction.

Samples were prepared for microstructural evaluation by standard metallographic procedures involving cutting, mounting, grinding and polishing. The size of the tungsten grains, volume fraction of the matrix phase, contiguity of the sintered WHAs were measured from scanning electron micrographs taken from several locations of a specimen. The volume fraction was measured using an image analyzing software. The grain size data was acquired by determining the area of the grain, then by assuming a spherical grain, the equivalent diameter was calculated. The co-ordination number was measured using the following method. One grain from scanning micrograph was selected, and the number of grains that are in contact with it are counted. The process is repeated over several grains. A minimum of 500 grains were used for all microstructural measurements. The co-ordination number reported is an average of those values. Contiguity defined as the relative fraction of W–W interfacial area was determined by placing grid lines over the binary image and counting the number of tungsten–tungsten and tungsten–matrix intercepts. It was calculated using the equation

$$\left(CSS = 2N_{SS}/(2N_{SS} + N_{SL})\right) \quad (1)$$

where N_{SS} and N_{SL} are the number of W–W grain boundary and W–matrix interface boundary intercepted, respectively.

EDAX analysis of the matrix composition of all the alloys was also carried out using Scanning Electron Microscope. All the swaged samples were subjected to tensile testing. The tensile specimens were prepared as per ASTM standard T-145 and tested at room temperature using universal tensile testing machine (INSTRON 5500R, UK). Three specimens for each condition were tested at a cross speed of 1 mm/min which results in the strain rate of 6.6×10^{-4}. Charpy impact specimens were prepared as per ASTM standards (E23) [15] and evaluation was carried out in a pendulum type impact tester at room temperature. Fractography of the failed tensile and impact test pieces were carried out using Scanning electron microscope (Make: FEI, Quanta-400, Netherlands). Bulk hardness of the alloys was measured using Vickers hardness tester (Vickers Instruments, Model: 1965, UK). All tests were conducted at a load of 30 kg and indentation time of 30 s was maintained. The Vickers hardness value for each sample was an average of five readings taken at random locations throughout the sample of 10×10 mm^2 area. Micro-hardness of the tungsten grains and the matrix phase in as swaged condition were measured separately by micro-hardness tester (Make: MAT-SUZAWA, Japan).

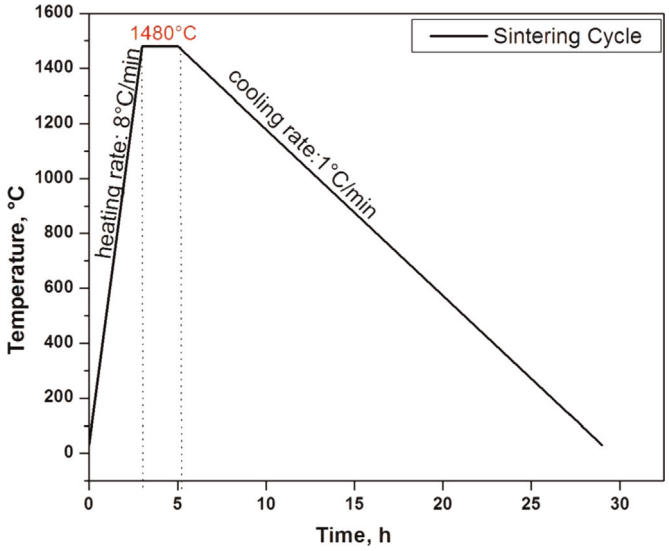

Fig. 1. Sintering cycle for the heavy alloys.

3. Results and discussion

3.1. Microstructure

Scanning electron micrographs of the sintered tungsten heavy alloys are shown in Fig. 2. As can be seen, the tungsten particles in WNF (Fig. 2a) and WNC (Fig. 2b) are coarser than those in WNR (Fig. 2c). The difference is attributable to the difference in solubility of tungsten in the matrix phase of the alloys. The final grain size is a result of Ostwald ripening that results in the coarsening of grains with the volume fraction of liquid phase remaining

Table 1
Characteristics of the powders used in the present study

Powder	W	Ni	Fe	Co	Re
Vendor	Blue star metals	Blue star metals	Blue star metals	Electronica	Corporate associates
Purity, wt%	99.9	99.6	99.6	99.6	99.5
Fabrication method	Reduction	Carbonyl	Atomization	Reduction	Reduction
Particle size (d_{50}), μm	8	6	5	4	12
Shape	Cuboid	Spherical	Spherical	Irregular	Irregular
Theoretical density (g/cm^3)	19.3	8.9	8.9	8.8	20.8
Apparent density (g/cm^3)	4.8	1.0	3.2	2.2	-
Tap density (g/cm^3)	5.8	1.4	3.5	2.8	-