International Journal of Refractory Metals & Hard Materials 67 (2017) 18–31

Contents lists available at ScienceDirect

International Journal of Refractory Metals & Hard Materials

journal homepage: www.elsevier.com/locate/IJRMHM

On structure property correlation in high strength tungsten heavy alloys

Anjali Kumari*, M. Sankaranarayana, T.K. Nandy

Defence Metallurgical Research Laboratory, Hyderabad, India

ARTICLE INFO

Keywords:
Kinetic energy penetrator
Depth of penetration
High strength tungsten heavy alloy

ABSTRACT

Detailed structure-property correlation has been carried out in high strength tungsten heavy alloys. Alloys of compositions 90W-6Ni-2Fe-2Co, 89W-6Ni-2Fe-3Co, 89.5W-6Ni-2Fe-2Co-0.5Mo, 89.75W-6Ni-2Fe-2Co-0.25Mo, 90W-6Ni-1.5Fe-2.5Co and 90W-6Ni-1Fe-3Co have been prepared by liquid phase sintering followed by large deformation during thermo mechanical processing and studied for microstructure and mechanical properties. Despite differences in composition, higher volume fraction of matrix and lower W-W contiguity in the microstructure result in superior tensile strength and impact toughness. Increasing W content in the matrix enhances mechanical properties by imparting solid solution strengthening, increasing the matrix volume fraction and reducing W-W contiguity. The alloy 90W-6Ni-1Fe-3Co shows superior balance of properties with ultimate tensile strength of 1600 MPa and average impact toughness of 121 J/cm^2.

1. Introduction

The present study is aimed at developing heavy alloys with enhanced strength and attempt a composition, microstructure, property interrelationship. The need for kinetic energy penetrator with enhanced ballistic properties is a continuous process in order to defeat improved armour materials that protect battle tanks [1]. Efforts continue to develop kinetic energy penetrators with increasing depth of penetration (DOP) that is in excess of 700 mm. One way for enhancing DOP is to increase the length of the penetrator since to a first approximation DOP scales up directly with penetrator length [2]. Higher DOP also demands that the penetrators are launched with greater muzzle velocity that necessitate higher level of acceleration experienced by the penetrator core as it travels inside the gun barrel. As a result, the core is subjected to greater tensile and compressive stress during firing [3]. Thus, efforts are made not only to increase the length of penetrator but also realize enhanced mechanical properties so as to withstand stress spikes during the launch.

Mechanical properties of liquid phase sintered tungsten heavy alloy, which is a two phase composite of BCC tungsten particles and FCC continuous matrix is strongly influenced by the alloy chemistry and thermomechanical processing [4]. Different alloying additions have been attempted in order to improve mechanical properties. Alloying additions such as Co [5–7], Mo [8], Ta [9] and Re [10] increase the strength of these alloys. Addition of Cr [10] leads to property degradation because of porosity and intermetallic formation. Co addition has been used extensively as it results in improvement of both strength and ductility [6]. Based on these information, it was decided to add Mo and Co to W-Ni-Fe base with 90% W. These alloys were prepared by liquid phase sintering followed by heat treatment and swaging to attain strength levels exceeding 1500 MPa. A typical heat treatment involves solution treatment of the alloy in partial vacuum at 1100–1200 °C followed by rapid quenching. Heat treatment is carried out to impart ductility to heavy alloy by suppressing intermetallic formation and also eliminating interfacial segregation that lead to impairment in properties [11]. Swaging deformation is imparted to introduce dislocations and defects in the material thereby leading to enhancement in strength. Nicolas [12] has shown that the tensile strength of heavy alloys can be increased significantly by imparting varying degree of swaging deformation. The present study is aimed at developing heavy alloy with improved properties by variation in chemistry and amount of deformation during swaging. This is followed by a detailed characterization of composition, microstructure, mechanical property and their correlation to understand the trends in mechanical properties.

2. Experimental work

The nominal compositions of all 6 alloys are listed in Table 1. The alloys were prepared by using elemental powders of tungsten, nickel, iron, cobalt and molybdenum with 99.95% purity. Fisher sub sieve sizes of the powders are given in Table 2. Powders were mixed in a conventional ball mill for 40 h using stainless steel balls with ball to powder ratio (BPR) of 1:1. The reduction of mixed powders was done at 700 °C for 2 h in a hydrogen atmosphere to remove oxide or oxygen

* Corresponding author.
E-mail address: anjali.kumari.met10@itbhu.ac.in (A. Kumari).

http://dx.doi.org/10.1016/j.ijrmhm.2017.05.002
Received 3 March 2017; Received in revised form 3 May 2017; Accepted 7 May 2017
Available online 08 May 2017

Table 1
Nominal chemical composition of the alloys investigated.

Sample	Composition (% wt)
1A	90W-6Ni-2Fe-2Co
2A	89W-6Ni-2Fe-3Co
3A	89.5W-6Ni-2Fe-2Co-0.5Mo
4A	89.75W-6Ni-2Fe-2Co-0.25Mo
5A	90W-6Ni-1.5Fe-2.5Co
6A	90W-6Ni-1Fe-3Co

Table 2
Powder characteristics.

Property	W	Ni	Fe	Co	Mo
Avg. particle size (μm)	4 ± 0.3	3 ± 0.5	6 ± 0.7	1.4 ± 0.3	5 ± 2.1
Manufacturer	Blue Star Metals, Mumbai	Blue Star Metals, Mumbai	Blue Star Metals, Mumbai	Sandvik Asia Pvt. Ltd., Pune	HAPP, Trichy
Purity (%)	99.9	99.7	99.5	99.7	99.9
Major impurities (ppm)	C (38) S (8) O (736) Ca (39)	C (2418)	S (7) O (1664) Ca (17)	C (392)	O (993) Ca (45)

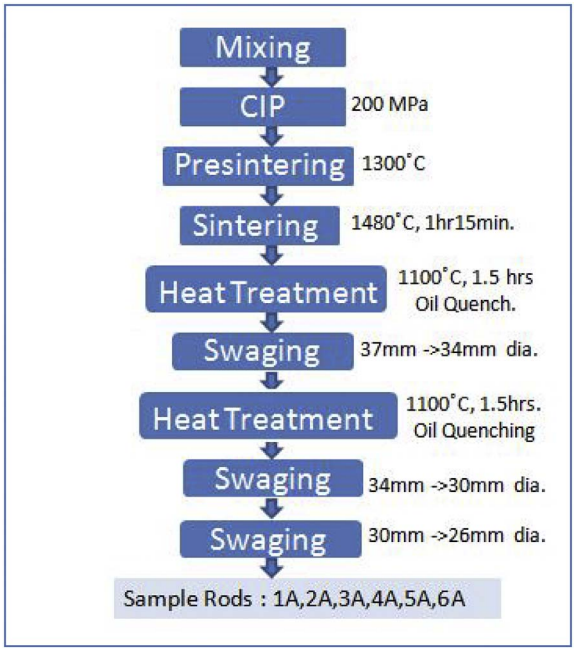

Fig. 1. Processing flow chart of tungsten heavy alloy.

enriched layer formed during mixing. The powder mix were cold isostatically pressed (make: National Forge, Belgium) at 200 MPa in order to obtain cylindrical rods. A pusher type furnace (FHD Furnaces Ltd., England) with hydrogen atmosphere (− 35 °C dew point) was used for conventional liquid phase sintering of rods. The blanks were pre-sintered at 1300 °C for 1 h, followed by liquid phase sintering at 1480 °C for 75 min. The heating rate was maintained between 3 and 5 °C/min. The metallic lustre and oval cross section of the as sintered rods was used as a preliminary guide for ascertaining the completion of sintering, which was also confirmed by determining density and examining of microstructure. The sintered rods were machined to 37 mm diameter and 360 mm long cylindrical rods. This was followed by heat treatment of rods in vacuum heat treatment furnace at 1100 °C for 1.5 h followed by oil quenching. During heat treatment, vacuum was maintained at 10^{-4} bar.

All rods were swaged from initial dia. of 37 mm to 34 mm dia. and then heat treated again at 1100 °C for 1.5 h followed by oil quenching. 2 more swaging steps are performed on the rods: (1) from 34 mm dia. to 30 mm dia. and (2) 30 mm dia. to final 26 mm dia. The final dimensions obtained after these swaging steps were: 26 mm dia., 600 mm length. The processing route to obtain 26 mm dia. rods is shown in Fig. 1. The pictures of alloy rods acquired at different stages of processing are shown in Fig. 2.

Samples for microstructural examination were prepared for all 6 alloys following standard metallographic techniques and examined using scanning electron microscope (FEI Quanta 400 ESEM). From the acquired SEM images, microstructural parameters such as average W grain size, contiguity of W particles and volume fraction of the matrix phase were determined. Contiguity (C_g) was obtained using line intercept method in which the number of tungsten-tungsten contacts (N_{WW}) and tungsten-matrix contacts (N_{WM}) were counted for an average of 100 measurements. The contiguity was determined using the formula:

$$C_g = \frac{2N_{WW}}{2N_{WW} + N_{WM}} \quad (1)$$

Microstructures of as swaged alloys were also examined using scanning electron microscope. An image analysis software (Image J) was used for the determination of volume fraction and particle size. Compositional analysis was performed using Electron Probe Micro Analysis (SX-100, Cameca, France) on all six samples to determine the composition of both matrix and W-rich phase.

Tensile tests of the as swaged samples (2 from each alloy) were performed using a screw driven tensile testing machine (Model: Instron 5500R Universal tensile testing machine). The tests were conducted at crosshead speed of 1 mm/min (strain rate = 6.6×10^{-4}/s). UTS, 0.2% YS and % plastic elongation to failure values were determined from the stress-strain curves. True stress-true plastic strain data were extracted from the stress-strain curves in order to carry out work hardening analysis. Longitudinal sections of the failed tensile specimens were cut and polished for examining voids/crack nucleation near the fracture surface. Charpy impact testing was carried out on 3 samples of each alloy using un-notched specimen of dimensions 10 mm × 10 mm × 55 mm (Fuel Instruments – India, model: IT 30 ASTM, 0 to 300 J). Fractographs of the failed tensile and impact specimens were examined using scanning electron microscopy.

3. Results

3.1. Microstructure

Back scattered electron micrographs of the alloys in as sintered plus