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Effect of processing parameters on microstructure and mechanical properties of 90W–6Ni–4Mn heavy alloy

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ABSTRACT

In the present work, 90W–6Ni–4Mn alloy was prepared by an atmospheric controlling method, which can avoid the oxidation of elemental Mn during sintering, to obtain full density. Different sintering temperatures and holding times were employed to optimize the sintering process. Relative densities higher than 99.0% were achieved for 90W–6Ni–4Mn sintered at temperatures of 1200–1300 °C with various holds. Nearly full density of 99.65% was acquired with an average W grain size of 12.6 μm as sintered at 1250 °C for 60 min. When subjected to tensile testing, this alloy exhibits an ultimate tensile strength of 981 MPa and elongation of 20.6%. Higher sintering temperatures and longer holding times resulted in higher W content in the matrix phase, solid volume fraction and contiguity, due to solution–reprecipitation and grain coalescence during liquid phase sintering. Moreover, under such a circumstance, the insoluble inert gas (argon) trapped in residual closed pores caused the pores to coarsen, deteriorating the density and tensile properties of 90W–6Ni–4Mn alloy. Accordingly, a suitable sintering cycle is fundamental for full density 90W–6Ni–4Mn alloy with mechanical properties comparable to conventional tungsten heavy alloys, but 200–250 °C lower sintering temperature.

1. Introduction

Tungsten heavy alloys (WHAs) are a class of composites consisting of nearly spherical tungsten particles dispersed in a low melting point of Ni–Fe, Ni–Cu or Ni–Co matrix phase. In view of their unique combination of high density, low thermal expansion, good mechanical properties and corrosion resistance, the alloys have been used in various military and civil applications, such as kinetic energy penetrators, radiation shields, counterbalance weights, and welding rod holders [1,2]. For the past decades, depleted uranium (DU) has been a more effective penetrator material than an equivalent density of WHA, owning to the ability of self-sharpening which stems from the adiabatic shear band of penetrator during impart [3], while WHA forms a mushroom head instead. With mounting political pressure, DU has been limited to use in the light of its environment problem. Thus it is urgent and important to develop a substitute for DU.

Tungsten–nickel–manganese (W–Ni–Mn) is a novel heavy alloy which holds promise for applications such as high energy penetrator [4]. The replacement of Fe with Mn in conventional heavy alloys promotes the formation of adiabatic shear bands, since the thermal conductivity of Mn is as low as one-tenth of that of Fe [5]. In contrast to other nickel-based matrix phases, the Ni–Mn binary alloy phase diagram [6] predicts a lower sintering temperature for W–Ni–Mn alloy. The amount of W taken into solution within the Ni–Mn matrix phase could not be calculated precisely, since no phase diagram is available for the W–Mn binary system, but would be very limited based on previous reports [7], benefiting the refinement of W grain size. Besides, tests indicate that this alloy can produce intense shear bands at high strain rates [5,8].

Fortunately, the severe problem of pore formation caused by the high oxidation potential of elemental Mn has been solved by atmospheric controlling method [9]. The method is composed of rapid heating up to the reduction temperature (1150–1200 °C) under a high purity nitrogen atmosphere, holding after changing the atmosphere to dry hydrogen, then sintered at 1260 °C. Rapid heating under high purity nitrogen gas prevents elemental Mn from oxidizing by reduction of W and Ni oxides, and holding reduces the contained oxides in the as-received powders simultaneously. It is encouraging that full density 90W–6Ni–4Mn alloy is achieved, though no mechanical properties were reported.

We have previously proposed a new atmospheric controlling method that does not use hydrogen to fabricate full density 90W–4Ni–6Mn alloy [10]. This new method will also be employed in

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the present investigation. Compared with 90W–4Ni–6Mn alloy, 90W–6Ni–4Mn alloy possesses higher density, one of the key desired attributes for materials used in kinetic energy penetrators, and moderate Mn content, favoring the formation of adiabatic shear band of penetrator during impact, improving the depth of penetration. As a promising candidate for kinetic energy penetrators, 90W–6Ni–4Mn alloy is very attractive. Therefore, it is necessary to investigate the fully dense microstructure and mechanical properties of 90W–6Ni–4Mn alloy.

In the present study, liquid phase sintering (LPS) is carried out under controlled atmosphere. Different sintering temperatures and holding times are applied to optimize the sintering process. The objective of this research is to investigate the effect of processing parameters on the microstructure and mechanical properties of 90W–6Ni–4Mn alloy in order to fabricate this alloy with full density and better mechanical properties.

2. Experimental procedures

Characteristics of the as-received powders used in the present investigation are listed in Table 1. The desired composition is 90 wt.% W, 6 wt.% Ni and 4 wt.% Mn. Prior to blending, elemental powders of W and Ni were reduced for 1 h by H_2 atmosphere with a dew point of −50 °C at 850 °C and 350 °C, respectively, to make sure that the oxides on the powder surface were removed. According to the nominal composition, the powders were weighted and mixed for 20 h in a 500 ml jar which was filled with argon to prevent oxidation. After mixing, the powder mixtures were compacted into a cylindrical bar with diameter of 15 mm and height of 80 mm by cold isostatic pressing under a pressure of 200 MPa.

Subsequently, LPS was performed in a vacuum furnace under controlled atmosphere with high purity dry argon. The sintering cycle began with heating up to 500 °C in vacuum with a hold of 30 min. When half of the hold time was finished, the atmosphere was changed to dry argon. Following the hold, heating continued to the sintering temperature with a subsequent hold, as shown in Fig. 1. Heating in vacuum under 500 °C helped to remove the water vapor adsorbed on the surface of the W, Ni and Mn powders and sintering under argon atmosphere inhibited the evaporation and oxidation of Mn powder.

To obtain the optimum condition, sintering temperatures were varied from 1100 °C to 1300 °C for 60 min and sintering times at 1250 °C were varied from 5 to 120 min. After sintering, a post-sintering heat treatment (1000 °C for 1 h under dry argon followed by a water quench) was employed, to eliminate the formation of intermetallics during furnace cooling. Finally, according to ISO 6892-1:2009, tensile specimens were machined out from quenched samples.

Before density measurement, the quenched specimens were polished. Then Archimedes water-immersion method was applied to determine the relative density of the alloys. The quasi-static mechanical properties were carried out by an Instron 3369 (USA) testing system with a constant crosshead speed of 1 mm/min. Digital

Table 1
Characteristics of the as-received powders.

Powders	Particle size (μm)	Purity (wt.%)	Impurities (wt.%)			
			C	O	S	P
W	3	99.9	0.005	0.06	–	–
Ni	3.6	99.7	0.083	0.06	0.005	–
Mn	10	99.94	0.01	–	0.035	0.001

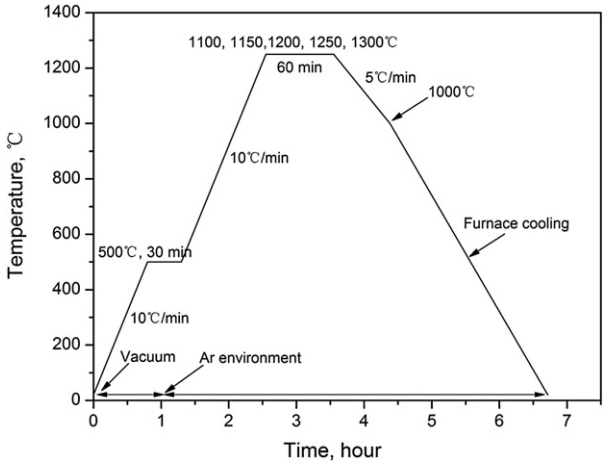

Fig. 1. Sintering cycle of 90W–6Ni–4Mn alloy.

display Rockwell Hardness Machine (200HRS-150) was used to measure the hardness of specimens. In all cases, three samples were tested for each measurement. Furthermore, the microstructure and fracture morphologies of these alloys were observed by scanning electron microscope (SEM, Jeol-6360LV) incorporating with energy dispersive spectroscopy (EDS, GENESIS 60S) to detect W content in the matrix phase. Determination of the average tungsten grain size was performed by liner intercept method based on the back-scattered electron images (BEI). The solid volume fraction was calculated using the software of Phase Analysis (Leica MV). Finally, tungsten/tungsten contiguity was measured by point counting technique, in which the number of tungsten/tungsten contact and tungsten/matrix phase contact was manually counted.

3. Results and discussion

3.1. Microstructure

Fig. 2 shows the variation of relative density and average grain size with sintering temperature. The W grain size at the lowest sintering temperature (1100 °C) could not be measured accurately. The relative

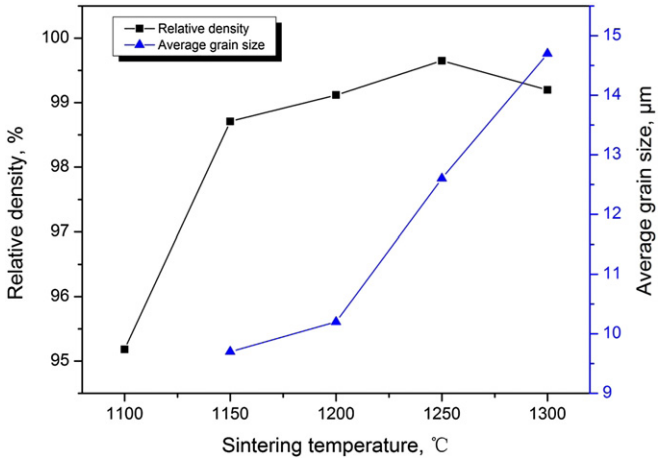

Fig. 2. The variation of relative density and average grain size of 90W–6Ni–4Mn alloy with sintering temperature from 1100 °C to 1300 °C for 60 min.