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W—Cu functionally graded material: Low temperature fabrication and mechanical characterization

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ABSTRACT

In this study, we fabricated and characterized a W—Cu functionally graded material (FGM) with 11 layers, including a pure copper layer. Samples were prepared by mixing a mechanically alloyed Ni—Mn—Cu powder with W and Cu powders, stacking the powders, pressing the stacked layers, and finally sintering at 1000 °C. The utilization of a Ni—Mn—Cu system may reduce the cost but without losing the good sintering behavior and physical and mechanical properties. The composition of the material was analyzed based on scanning electron microscopy images and by energy dispersive X-ray spectroscopy mapping, which indicated that in the presence of Ni and Mn, the Cu atoms could diffuse into the W particles. All of the layers had a very high relative density, thereby indicating their densification and excellent sintering behavior. We also found that the porosity values in the Cu phase remained unchanged at approximately 2.39% across the FGM. Mechanical measurements showed that the hardness (72%), modulus of elasticity (61%), and ultimate tensile strength (58%) increased with the W content across the W—Cu FGM, whereas the fracture toughness (K_{IC}) varied in the opposite manner (minimum of 4.52 MPa/m$^{0.5}$).

1. Introduction

The development of suitable plasma-facing components (PFCs) for future fusion reactors is a great scientific challenge [1]. PFCs are essentially tungsten-based refractory materials, which are characterized by their high melting temperature, high thermal conductivity, low tritium inventory, and low erosion rate under plasma loadings [2,3]. The PFCs designed for the International Thermonuclear Experimental Reactor comprise bulk W bonded to a Cu alloy heat sink [2]. The operational conditions impose cyclic thermal-driven mechanical loads (shocks) on the heat sink interface. The different thermal expansion coefficients of Cu and W are a serious problem that affects the coexistence of the two materials [2,4]. In particular, a critical issue is the quality of the interface between the plasma-faced W and the Cu substrate.

Functionally graded materials (FGMs) can significantly reduce the mechanical and thermal stress concentrated in many structural components, and they can be developed for specific applications [5]. W—Cu composites exhibit excellent resistance to electric discharges [6], a low coefficient of thermal expansion, high hardness, high melting point, low vapor pressure, and high arc erosion resistance due to tungsten, as well as the high electrical and thermal conductivity attributable to copper [7]. Hence, W—Cu FGMs have great potential for use as the first wall in fusion devices, heavy duty contact materials [8–10], welding- and arc-resistant electrodes [11,12], heat sink materials [12–14], electro-discharge machining devices [14,15], and power packaging for microelectronic applications [15–17]. However, the fabrication of a fully dense W—Cu FGM is an onerous process due to the large difference (~2300 °C) in the melting points of W and Cu. Moreover, W and Cu have no mutual solubility [18] and there is no overlap of their sintering temperature ranges [19].

Recently, it was discovered that the powder selected as the starting material (using W bimodal powders) plays a crucial role in enhancing the final properties of W—Cu composites [20]. Several recent studies have focused on the sintering of W alloyed with Mn—Co, Ni—Mn, or Ni—Cu—Mn compositions at 1360 °C, 1300 °C, or 1200 °C respectively [21]. Several methods for fabricating W—Cu FGMs have also been reported. In particular, W—Cu composite coatings can be fabricated using plasma spraying [22]. The main problems with plasma spraying are the limited thickness of the W layer and the inadequate bonding strength between the coating and substrate. It is difficult to spray W—Cu powders due to the large difference between their melting points (i.e., tungsten = 3410 °C and copper = 1083 °C). Furthermore, the thermal shock resistance and performance under a high heat load are not

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Table 1
Chemical compositions of the initial powders according to XRF.

Cu Powder		W Powder		Mn powder		Ni Powder	
Element	wt.%	Element	wt.%	Element	wt.%	Element	wt.%
Cu	99.96	W	99.92	Mn	99.96	Ni	99.97
Pb	0.030	S	0.06	S	0.024	Fe	0.012
Fe	0.006	Fe	0.02	Ni	0.016	Mn	0.011
Ca	0.004					S	0.007

Table 2
Operating conditions employed for preparing the binder.

Element	wt%	Mechanical Alloying Conditions			
Ni	40	RPM[a]	Time	B:P[b]	PCA[c]
Cu	26.67	300	10 h	20:1	Ethanol + Stearic acid
Mn	33.33				

[a] Revolutions per minute.
[b] Ball to powder weight ratio.
[c] Process control agent.

very good [23].

The infiltration technique has also been used widely, where the material undergoes a severe external pressure to initiate infiltration, although controlling the porosity is very difficult [23,24]. In addition, the pressure should be increased in order to further advance the melt copper front inside the W skeleton. W—Cu FGMs can be fabricated by using resistance sintering under ultra-high pressure [23,25] but micro-cracks may be formed on the surface of the pure W layer, as well as vertical cracks in the interface (not a common problem) [26]. The sintering time should be very short to avoid the copper overheating [27]. Chemical vapor deposition (CVD) can be employed to fabricate W layers with high purity and thermal conductivity on Cu substrates [28,29]. However, deposition at elevated temperatures may lead to stresses, which can cause mechanical instability. The CVD precursors can be highly toxic, explosive, or corrosive, and the reaction by-products can also be hazardous. The disadvantages of the mechanical alloying method and CVD are their high production costs (with long time required to form the layers) [30].

The typical liquid-phase sintering temperature for known tungsten heavy alloys varies from 1450 °C to 1650 °C. This sintering temperature range is significantly lower than that for pure tungsten but it is still too high for general powder metallurgy furnaces. These temperatures and processes are beyond the capability of commercial powder metallurgical production furnaces, and thus the increased production costs for the alloys limit the use of alloys produced by this method for many applications.

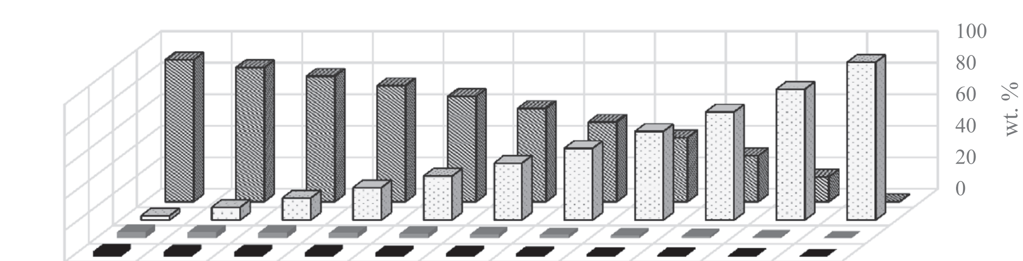
In this study, we developed a novel approach for fabricating W—Cu FGM specimens with homogeneous microstructures as well as enhanced densification and mechanical properties. We successfully fabricated a W—Cu FGM comprising 11 layers using a powder metallurgy technique comprising mixing, mechanical alloying, cold pressing, and vacuum sintering (vacuum level of 5×10^{-2} mbar) at a relatively low temperature. The sintering temperature was approximately 300–500 °C below those used for known heavy alloys. The matrix alloy comprised Ni alloyed with Mn, Cu, and a negligible amount of W, which was in solution. Theoretically, the W—Ni—Mn—Cu system is a promising alternative alloy system that can be processed at significantly lower temperatures. The matrix imparts ductility to the brittle tungsten and it also reduces the processing temperature for tungsten. We investigated the microstructure of the layers and their contiguity. Furthermore, the hardness of the layers, modulus of elasticity, ultimate tensile strength (UTS), and plane strain fracture toughness were measured. Other theoretical and experimental fracture assessments for W—Cu FGM specimens have been reported previously [31,32].

2. Experimental procedure

Commercial high-purity W, Ni, Mn, and Cu powders (>99.9% purity) were used as the starting materials. The particle size of W was 7.5–8.5 μm and the maximum particle sizes for Ni, Cu, and Mn were 10, 30, and 63 μm, respectively. The initial powders were examined by X-ray fluorescence (XRF) using an X'Unique II Ge111 spectrometer (detection limit = 1 ppm) and the results are shown in Table 1.

The Ni, Cu, and Mn metal powders were mechanically alloyed using a high-energy ball mill (SPEX 8000 Mixer/Mill) in order to create a binder alloy (BA). Table 2 shows the operating conditions employed for

Table 3
Chemical contents of the composite powders.



	1	2	3	4	5	6	7	8	9	10	11
Mn	3.333	3.15	2.948	2.724	2.473	2.19	1.87	1.503	1.08	0.585	0
Ni	4	3.7808	3.538	3.27	2.968	2.629	2.244	1.804	1.296	0.702	0
Cu	2.666	8.059	13.895	20.451	27.782	36.035	45.395	56.101	68.467	82.909	100
W	90	85.068	79.617	73.555	66.776	59.145	50.49	40.59	29.157	15.803	0

Layer No.