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Fabrication and properties of the W-Cu composites reinforced with uncoated and nickel-coated tungsten fibers

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ABSTRACT

In this work, novel high-voltage electrical contacts of the W-Cu composites reinforced with tungsten fibers (W_f) have been fabricated by hot-press sintering and infiltration processes. Considering microstructural homogeneity and fabrication repeatability of the composites, W_f with the content of 3.3 wt% was determined to be optimum for the reinforcement. By electroless deposition of ~2.5 μm thick nickel layer onto the surface of W_f, the connectivity between the W_f and its neighboring W-Cu matrix after sintering and infiltration was improved with the elimination of porosity. This was considered to be ascribed to the plastic deformation of Ni-coatings during the molding of green compacts and the improvement of rearrangement of tungsten particles (W_p) during the Ni-activated sintering. Compared with the traditional commercial W-Cu composites, the W-Cu composite reinforced with the Ni-coated W_f provided desirable increased tensile strength by ~15.8% and improved electrical breakdown strength by 65.3% after the interface tuning, which is applicable and transferrable to other refractory metals for property improvement.

1. Introduction

Due to the excellent combination of superior properties including high strength, excellent resistance to arc erosion and anti-welding, as well as good thermal and electrical conductivity [1,2], tungsten-copper (W-Cu) pseudo alloys [3] have raised great research interests during the past decades and have been widely used as high voltage electrical contacts, high current circuit breakers, heat sinks, welding electrodes, military rocket nozzle, microwave materials, electrical packages [4–6] and also most promising plasma facing materials [7] for International Thermonuclear Experimental Reactor (ITER) [8]. However, due to their large discrepancy in the melting point/density between W and Cu [9,10], as well as the immiscible mutual solubility in both solid and liquid states with a positive heat of formation of + 33 kJ/mol [11,12], it is challenging to obtain the desired W-Cu composite alloys by traditional processes. Therefore, the W-Cu composites are usually fabricated by powder metallurgy including solid state sintering, liquid phase sintering and infiltration [13].

Specifically, with the increasing demands for better performance used as ultrahigh-voltage switches with larger capacities, the conventional W-Cu composites cannot meet the urgent requirement in the application of Ultrahigh Voltage Power Grid [14]. In this context, two possible ways have been attempted. One is the fabrication of ultrafine or nano-grained W-Cu composites; the other is the introduction of the reinforcement. For the former method, the ultrafine or nano-grained W-Cu composite powders with a homogenous distribution have been successfully synthesized by co-precipitation [15], free drying [16], sol-gel procedure [17,18], mechano-chemical process [19], and nitridation-denitridation method [20]. Nevertheless, these processes are complicated and the resulted powders are usually too less for industrial production; besides, the abnormal grain growth of W particles or grain coarsening are hard to prevent during the high-temperature sintering [21–23].

In contrast, for the later method, commercially available tungsten fibers (W_f) have already been introduced to reinforce the tungsten alloys successfully. Related researches have proved that the ductile deformation behavior of W_f allows effectively the dissipation of substantial amount of energy [24] and their high strength of over 2.5 GPa [25] is very important for the bridging effect to provide an increased fracture toughness [26]. Therefore, in the present work, W_f with various content has been introduced into the conventional commercial W-Cu composite and the optimum content has been determined. Furthermore, the mechanical and arc resistance properties were further improved through the surface modification of W_f by electroless plated Ni-coatings, in order to provide useful clues regarding the design of W-Cu composites with better properties.

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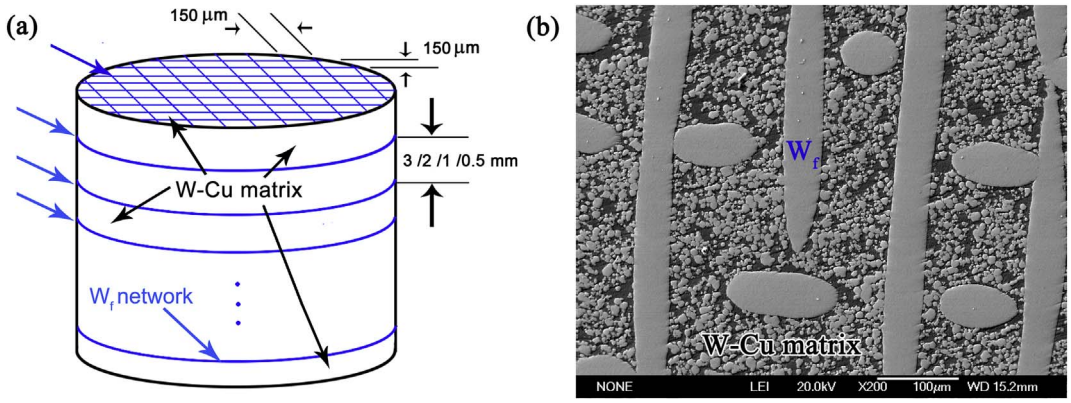

Fig. 1. Schematic architecture of the composite with inserted W_f (a) and the cross section of resultant infiltrated W-Cu composite reinforced with W_f (b).

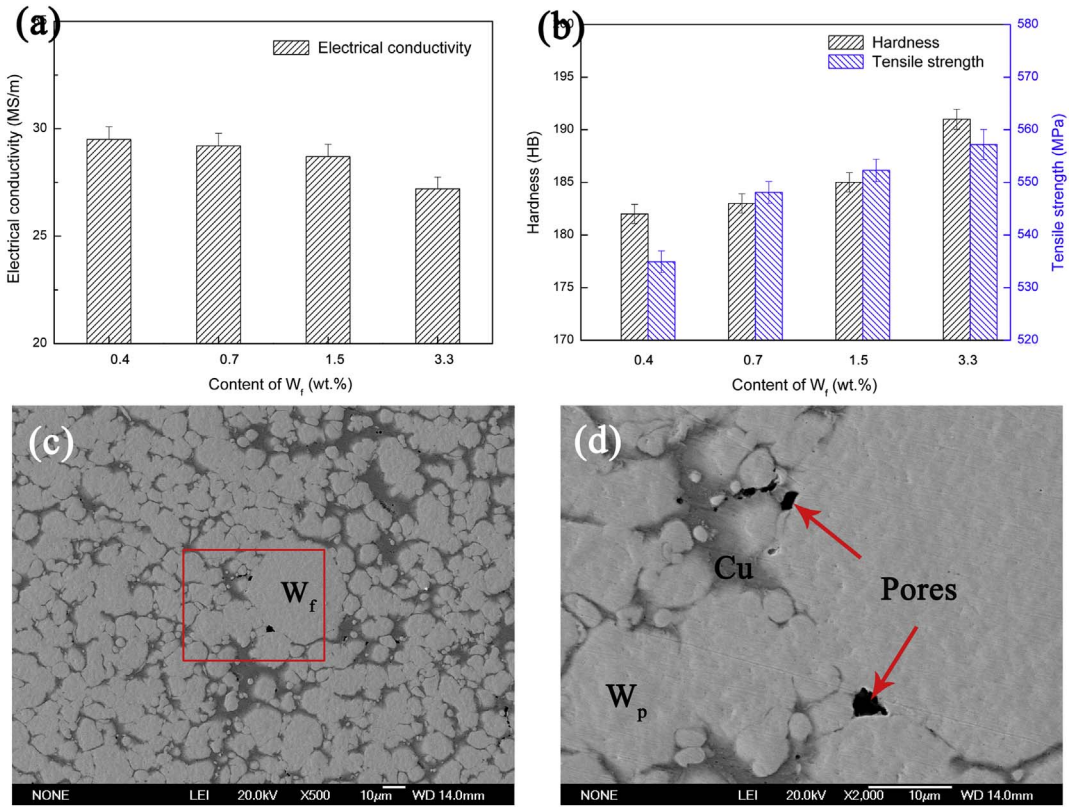

Fig. 2. The change of electrical conductivity (a) and hardness/tensile strength (b) of the W-Cu composites with the content of W_f (0.4 wt%, 0.7 wt%, 1.5 wt% and 3.3 wt%), as well as typical SEM image (c) and further magnified one (d) taken from the cross section of the W-Cu composite with 3.3 wt% W_f.

2. Materials and methods

W powders (W_p, 4–6 μm, purity > 99.8 wt%) and 15 wt% Cu powders (Cu_p, 50–70 μm, purity > 99.8 wt%) were blended in a V-type mixer for 6 h. Commercial W_f networks with the diameter of ~40 μm (Fig. 1(a)) were immersed in 40% HF liquor for 30 min to remove the surface oxide film, followed by ultrasonic clean in acetone and alcohol respectively. The W_f networks were assembled straightly into the pre-mixed powders with an average depth distance of 3 mm, 2 mm, 1 mm or 0.5 mm layer by layer for further preparation of the green compacts, as illustrated in Fig. 1(a). According to the mold size of φ51 × h12 mm and the distribution of W_f networks, the corresponding contents of W_f in the composites were calculated to be 0.4 wt%, 0.7 wt %, 1.5 wt% and 3.3 wt% respectively. In comparison with the above uncoated W_f, surface modified W_f was obtained by the following method: the surface Ni-coatings on the W_f were deposited by electroless deposition to be ~2.5 μm thick in the solution consisting of $NiSO_4{\cdot}6H_2O$ (15 g/L), $NaH_2PO_2{\cdot}H_2O$ (35 g/L), NH_4Cl (5 g/L) and $C_6H_8O_7$ (1 g/L), at 90 °C and pH value of 9 for 20 min.

The pre-assembled samples were firstly pressed into green compacts with dimensions of φ21 × 15 mm under the pressure of 340 MPa in a XTM-108-200T Hydraulic Press. Then, the samples were firstly hot-press sintered under a pressure of 20 MPa for 30 min at 970 °C, then held at 1300 °C for 2 h, and finally cooled to room temperature with furnace cooling. After that, liquid infiltration route of molten Cu into the sintered performs was carried out at 1300 °C for 2 h in hydrogen atmosphere followed by furnace cooling. The temperature precision of the sintering furnace is ± 5 °C. The metal ingots were machined and polished for later characterization. Typical cross section view of one resultant composite was shown in Fig. 1(b).

The electrical conductivity of the composites was measured by an Eddy Current Conductivity Meter. The Brinell hardness and room