Journal of Nuclear Materials 455 (2014) 225–228

Contents lists available at ScienceDirect

Journal of Nuclear Materials

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

Preparation of tungsten fiber reinforced-tungsten/copper composite for plasma facing component

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ARTICLE INFO

Article history:
Available online 22 May 2014

ABSTRACT

W fiber reinforced-W/Cu composite is designed as a transition layer between CuCrZr heat sink material and W plasma facing material. A novel method was developed for the preparation of W fiber reinforced-W/Cu composite by combining combustion synthesis with centrifugal infiltration. Cu melt with a transient temperature over 2000 °C produced by the thermite reaction was infiltrated into the W powder and fiber bed with the assistance of a high gravity field. It was found that the W particles were sintered and bonded to the W fibers due to the high temperature produced by the thermite reaction. The bending strength of W/Cu composite improved 12.7% through W fibers reinforcement.

1. Introduction

Due to its high melting point, high sputtering resistance, low deuterium/tritium retention, and high thermal conductivity, tungsten has been recognized as the most promising candidate of plasma facing materials (PFMs) for fusion reactors [1,2]. Meanwhile, copper based alloys have been proposed as the heat sink materials behind the plasma facing material due to its excellent thermo-mechanical properties [3,4]. The joining of W to copper based heat-sink (CuCrZr) remain a main problem in the development of plasma facing component (PFC) due to the large difference in the coefficient of thermal expansion (CTE) between these two materials [5,6]. An added transition layer with moderate thermal expansion coefficient, high thermal conductivity and excellent thermo-mechanical properties like tungsten copper (W/Cu) composites, W fiber reinforced-copper (W_f-Cu) composites, silicon carbide copper (SiC/Cu) composites and SiC fiber reinforced-copper (SiC_f-Cu) composites have been developed to join W with CuCrZr [6–9]. To eliminate and release the thermal stress of PFC, the concept of W/Cu and SiC/Cu functionally graded materials (FGMs) have also been proposed and received much attention in recent years [5,9]. However, the reliability of PFC will face more challenges as the thermal loads continue to increase in future fusion reactors [10]. Depending on the divertor design, a high operating temperature up to 550 °C at the interface between W and CuCrZr may be reached in future fusion reactors like DEMO (demonstration reactor) [11]. Therefore, the development of a reliable transition layer with desired thermal conductivity, CTE and improved high temperature mechanical properties remain an important problem.

As the strength and toughness of many ceramic matrix composites have been successfully improved by fiber reinforcement [12], the development of fiber reinforced-copper matrix composites may provide some references for solving this problem. W fiber can be a good choice for the reinforcement of copper matrix composites owing to its high thermal conductivity and strength (2.5–3 GPa). However, to the best of our knowledge, W fiber reinforced-W/Cu composites have never been purposed and fabricated as a transition layer between W and CuCrZr (Fig. 1(a)). To date, W/Cu composites are produced mostly by the infiltration of a tungsten skeleton with Cu melt. However, it remains difficult to prepare full-densified W/Cu composites because of the poor solubility and large CTE difference between W and Cu [8,13]. It is believed that, an increased preparation temperature is beneficial for improving the wettability between W and Cu, which may result in an improved relative density of the W/Cu composites [14]. Recently, we have reported a novel method for the preparation of W/Cu composites by combining combustion synthesis with centrifugal infiltration [15,16]. In this method, high temperature Cu melt produced by thermite reaction was infiltrated into the W powder bed placed under it with the assistance of a high gravity field, and W/Cu composites can be fabricated in a furnace-free way by only one step. In this work, W fiber reinforced-W/Cu composite was fabricated by combustion synthesis and centrifugal infiltration.

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http://dx.doi.org/10.1016/j.jnucmat.2014.05.026
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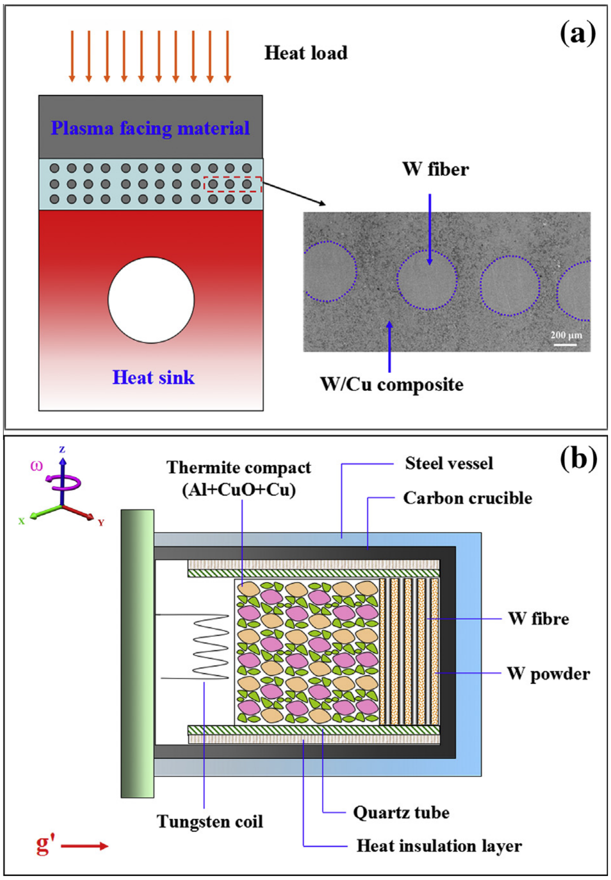

Fig. 1. (a) W fiber reinforced-W/Cu composite as a transition layer in PFC. (b) A schematic illustration of the reaction chamber.

Microstructure and mechanical property of the prepared W fiber reinforced-W/Cu composite were investigated.

2. Experimental

Commercial powder of Al (100 μm, 99.9% purity), CuO (45 μm, 99.9% purity) and Cu (45 μm, 99.9% purity) were mixed according to the thermite reaction Eq. (1), in which x presents the amount of copper diluents added, and had a value of 4 in this study.

$$2Al + 3CuO + xCu \rightarrow Al_2O_3 + (3 + x)Cu \tag{1}$$

A batch of 300 g thermite mixtures were mixed and homogenized for 1 h by roller ball grinder with a speed of 60 r/min, and then cold-pressed into a thermite compact with a diameter of 40 mm and porosity about 50%. Commercial W powder (5 μm, 99.9% purity) of 50 g and W fibers (diameter:0.5 mm, length:15 mm) of 5 g were used as the raw materials to prepare a W powder and fiber bed in a quartz tube with a diameter of 40 mm. The W powder was packed in the quartz tube with porosity about 60%. To form an organized structure, W fibers were inserted in the W powder layer by layer, as illustrated in Fig. 1(b). The thermite compact was placed above the W powder and fiber bed in the quartz tube. Then, the quartz tube was put into a graphite crucible with a heat insulation layer between them. The crucible was coated with a carbon cap and then put into a steel vessel, which was mounted into a reaction chamber to perform combustion synthesis and centrifugal infiltration in a home-made equipment. The reaction chamber was evacuated to a vacuum of ~100 Pa. A high gravity field with an acceleration of 1000g_o (g_o = 9.8 m s^{-2}) was induced by centrifugation. The thermite reaction was triggered by passing an electric current about 10 A through a tungsten coil closely above the thermite. A large amount of heat was created by the thermite reaction and molten Cu and Al_2O_3 were produced and separated in the high gravity field due to their density difference. The separated high temperature Cu melt was rapidly infiltrated into the W powder and fiber bed to form the W fiber reinforced-W/Cu composite. For comparison purpose, W/Cu composite has also been fabricated by following the same steps without the inserted W fibers. After cooling and solidification ceramic and metal ingots were obtained. The metal ingots were machined and polished for later characterization.

The microstructure was examined by scanning electron microscopy (SEM; S-4300, Hitach, Japan). The bulk density was measured according to the Archimedes principle. The three-point bending mechanical property was measured according to China National Standard GB/T 14452-93. The gauge length was 24 mm and gauge cross-section was 4 mm × 3 mm. The samples were tested at a strain rate of 1 mm min^{-1} at room temperature.

3. Results and discussion

Fabrication of W fiber reinforced-W/Cu composite by combustion synthesis and centrifugal infiltration involving a serious of physical and chemical processes such as combustion reaction, phase separation, infiltration and solidification. The temperature profile of the thermite reaction in Eq. (1) was measured by a tungsten-rhenium thermocouple, as shown in Fig. 2. Once the reaction was trigged the temperature directly rose to the highest about 2250 °C, which is higher than the melting point of Al_2O_3 (2050 °C). The temperature of the molten products quickly dropped to the melting point of Cu (1084 °C) in about 30s. During that period of time, Al_2O_3 and bubbles are separated from the Cu melt with assistance of high gravity filed [17]. The high temperature Cu melt was infiltrated into the W powder bed to form the W/Cu composite. As shown in the inset of Fig. 2(b), two separated layers were obtained after the experiment. The upper layer is the Al_2O_3 layer, and the bottom part is the Cu matrix composite.

Fig. 3 shows the SEM images of the prepared W/Cu composite and W fiber reinforced-W/Cu composite. The prepared sample composed of two layers as extra Cu has been produced by the thermite reaction. No pores and Al_2O_3 particles have been detected on the upper Cu layer, as can be seen from Fig. 3(a). Due to the large density difference between Cu and W, a clear boundary between Cu layer and W/Cu composite layer was formed. W particles with a small size are diffused into the Cu layer at the boundary, as shown in Fig. 3(c). This gradually transition between Cu layer

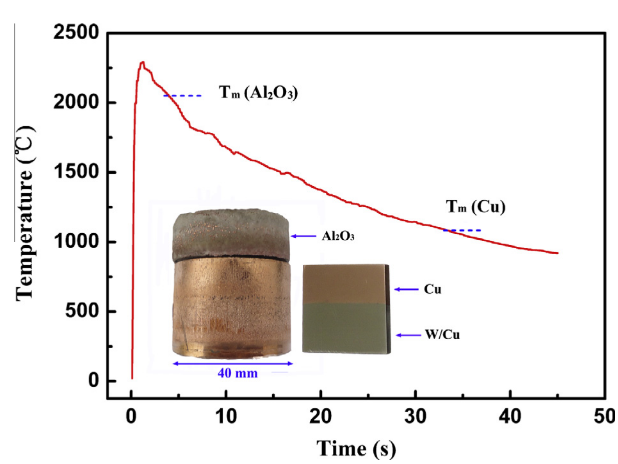

Fig. 2. Temperature profile of the thermite reaction.