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Tungsten-zirconium carbide-rhenium alloys with extraordinary thermal stability

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ABSTRACT

The low recrystallization temperature (1200 °C) of pure W is a serious limitation for application as facing plasma materials in fusion reactor. In this paper, W-0.5wt.%ZrC-1wt.%Re (WZR) alloy with recrystallization temperature up to 1800 °C was prepared by mechanical milling and spark plasma sintering. The grain size of WZR alloy is about 2.6 μm, smaller than that of pure W (4.4 μm), which keeps unchanged until the annealing temperature increases to 1800 °C. Tensile tests indicate that the WZR alloys exhibit excellent comprehensive properties: the ductile to brittle transition temperature of WZR is in the range from 400 °C to 500 °C, about 200 °C lower than that of pure W prepared by the same process; the total elongation (TE) of WZR at 600 °C is above 30%, which is about 2 times that of pure W (at 700 °C). Meanwhile its tensile strength keeps ~450 MPa before and after 1800 °C annealing as well as its TE increases after annealing. WZR alloy exhibits higher hardness (489HV) than that of pure W (453HV) at room temperature. Microstructure analysis indicates that the strengthening of nano-sized ZrC particles dispersion and Re solid solution improve tensile properties and thermal stability of WZR alloy.

1. Introduction

Tungsten is a kind of refractory metals that keeps its body-centered cubic crystal structure from room temperature to its high melting temperature of 3410 °C. W exhibits excellent compatibility with liquid metals, high thermal diffusivity (67 mm^2/s), low sputtering yield, high stability and high hardness/strength, which all together can result in longer component lifetime, and are thus appealing for many important high temperature applications such as plasma-facing materials (PFMs) in future fusion reactors [1–3]. W based bulk materials have not successfully been applied to functional and structural materials, especially in high temperature and irradiation environments, because W exhibits the serious embrittlement in several regimes, i.e., low-temperature embrittlement (relatively high ductile-brittle transition temperature (DBTT) >400 °C), recrystallization embrittlement (recrystallization temperature ~1200 °C) and irradiation embrittlement [3–5]. Low recrystallization temperature of tungsten confines its application in intermediate temperature region since recrystallization embrittlement does not allow the application at very high temperatures. Alloying or dispersion strengthening methods of W matrix materials are expected to solve these problems by refining the grains, enhancing the recrystallization temperature and improving the mechanical properties, i.e., lowering the DBTT and increasing the strength/ductility [6–8].

Over recent decades, many efforts have been devoted to improve the ductility of W alloys as well as high temperature stability and strength. For W-Re alloys, it has been indicated that Re addition (5 wt.%) could significantly reduce the DBTT (from 900 °C to 600 °C) [9] and improve ductility. This is ascribed to the decrease of the Peierls stress and the increase of the toughness of tungsten material with Re alloying [10]. But most of earlier studies were focused on high proportion (>5 wt.%) of Re addition in tungsten, which is not suitable for large-scale application owing to the expensive Re. In addition, Re has to be restricted to fulfill low activation requirements [11] and to avoid the formation of brittle phases [12]. The first-principle calculations indicate that the cohesion effect of transition metals, such as Zr, Hf and Re on the grain boundaries (GBs) in

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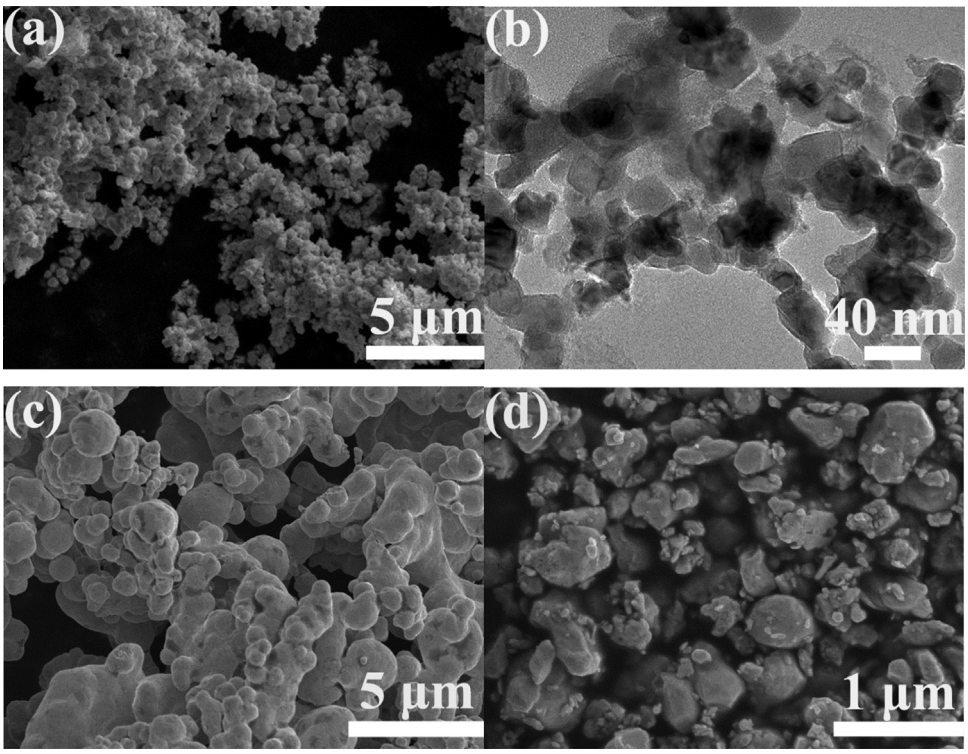

Fig. 1. SEM and TEM images of (a) as-received tungsten powders, (b) raw zirconium carbide powders, (c) raw rhenium powders, and (d) ball-milled powders.

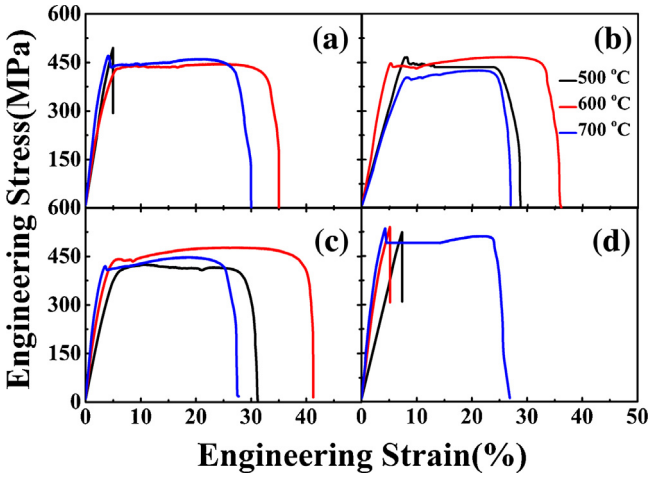

Fig. 2. Stress-strain curves of un-annealed and annealed samples tested at 500, 600 and 700 °C. (a) un-annealed, (b) 1700 °C annealed, (c) 1800 °C annealed and (d) 1900 °C annealed samples.

W could significantly strengthen the GBs [13]. Especially, for small amount of Re addition, the solid solution softening process [14] is active and leads to ductilization and toughening [9]. On the other hand, dispersing nanoscale particles, such as TiC, ZrC, La_2O_3 and Y_2O_3 in tungsten can effectively strengthen the GBs, pin the dislocations and thus enhance the high temperature stability and strength [15–18]. Among the strengthening phases, ZrC has a very high melting point (~3540 °C), high thermal stability and self-adjustment capability of the lattice constant, which makes it very attractive in the strengthening of W. In our previous works, spark plasma sintered (SPSed) W-1.0wt.%ZrC alloy exhibits the ultimate tensile strength (UTS) of 798 MPa at 600 °C, about 2.6 times that of pure W [16], which clearly illustrated the effectiveness of ZrC dispersion strengthening.

Combination of the Re micro-alloying and nano-sized zirconium carbide (ZrC) dispersion strengthening would be a good approach to improve the performance of W materials, particularly recrystallization temperature. In our previous work, it was certified that W-0.5wt.%ZrC component has better tensile properties (the larger product of strength and toughness) than that of W-0.2/1.0wt.%ZrC [19]. In this paper, W-0.5wt.%ZrC-1.0wt.%Re alloy was fabricated through SPS technique by adding trace solution element rhenium and dispersing nano-sized ZrC particles into W. The consolidation behavior, tensile behavior, hardness, microstructure, thermal stability and thermal conductivity were comparatively investigated.

2. Experimental procedure

W-0.5wt.%ZrC-1.0wt.%Re (designated as WZR) samples were fabricated from W powders (purity > 99.9% trace metal basis, chemical content listed elsewhere [16]), ZrC powders (average particle size 50 nm, purity > 99%) and Re powders (particle size 1–2 μm, purity > 99.99%), and all powders were characterized by field emission scanning electron microscope (FE-SEM) and transmission electron microscopy (TEM). Powders were ball-milled in a planetary ball-milling machine for 5 h in argon atmosphere. The rotation speed was 240 rpm and the ball-to-powder weight ratio was 8:1. In order to minimize the possible impurity contamination, tungsten carbide balls and mortars were used. The charge volume of a mill pot is 250 ml and 400 g (4 mill pots installed every time) mixed powders can be gathered after ball milling. After milling, the powders were less aggregated compared to the initial tungsten powders as characterized by FE-SEM.

The consolidation of the samples was carried out by SPS (furnace SE-607, FCT Group, Germany) technique. The as-prepared alloy powders were loaded into a graphite mold with graphite paper in the inner side. The temperature and pressure profile of the sintering