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Toughness and microstructure of tungsten fibre net-reinforced tungsten composite produced by spark plasma sintering

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ABSTRACT

To enhance the toughness of tungsten based on the extrinsic energy dissipation mechanism, tungsten fibre net-reinforced tungsten composites (W/W_f) containing different tungsten fibre net layers were produced by spark plasma sintering method (SPS). The number of tungsten fibre net layers is 2, 4, 6, and 8, corresponding to a fraction of tungsten fibres as 11.35, 23.90, 32.78, and 39.75 wt%, respectively. The relative density of all SPSed samples is as high as 96.3–98.1% depending upon the fibre content. Close integration at low fibre content but a few voids at higher fibre content were detected between the fibres and matrix. Tensile tests indicate that the plasticity of W/W_f composites is higher than that of pure tungsten, which can be ascribed to the fibres pullout, interface debonding, and plastic deformation of fibres. In particular, the composite with four layers of tungsten fibre net exhibits the largest plasticity owing to the good bonding between the fibres and matrix.

1. Introduction

Due to its super refractory nature, good surface erosion resistance, excellent thermal conductivity and low tritium retention, tungsten is currently considered as the most favored candidate for the plasma-facing material of nuclear fusion reactors and target materials in spallation neutron source [1]. However, the problems of inherent brittleness and the embrittlement caused by recrystallization or irradiation have greatly limited the application of tungsten in the circumstance of neutron irradiation and hypothermia. So it is imperative to improve the toughness of tungsten and tungsten-based materials.

Previously, a lot of methods including micro-alloying, grain refining and composite production were exploited to improve strength and toughness of pure tungsten materials. In the field of conventional metallurgy, titanium, zirconium, hafnium and rare-earth elements like lanthanum are appropriate micro-alloying elements to improve the property of tungsten. However, most of them cannot meet the demand of the practical application. Only rhenium can indeed improve the toughness of tungsten but the high cost of rhenium prohibits its application in large scale. In the past years, sintering at lower temperature with nanoscale powders of tungsten [2] and tungsten alloys [3–5] has been investigated. The state of the art of these approaches was still far from the design requirements and it would be improved to get dense samples. Dispersion strengthening (DS) by adding oxides like Y_2O_3 [6,7] or carbides like TiC [8] and ZrC [9] particles into the tungsten have been investigated to improve the property of tungsten. It has been found that the materials obtained by DS method exhibit finer grains, high strength, superior promising radiation resistance and high density. In the case of W–ZrC materials [9], some of the ZrC particles at the grain boundaries transformed into Zr–O–C compounds which is beneficial to reduce the O content and pin grain boundaries. However, such tungsten alloys are still brittle and show poor fracture property from low to moderate temperatures [10].

In the other side, fibre reinforcement is considered as the most effective method to improve toughness based on the extrinsic toughening mechanism. Several types of composites with high hardness and good toughness have been developed. For example, the matrix of metallic glass [11], ceramics [12,13] and cement were reinforced by fibres of steel [14], SiC [15,16], Ta [17] and W [18–20]. The applied toughening mechanism was a controlled crack deflection at the engineered fibre/matrix interfaces, leading to internal energy dissipation by interface debonding or friction and release of local stress. In addition, the elastic and plastic deformations of the reinforcing fibres absorb the elastic energy released by the propagating crack, which contributes partially to

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improvement of the global fracture toughness. At a certain point during the tensile experiment where the matrix begin to fracture, the sample can still bear loading by the fibres, resulting in a large improvement in fracture toughness due to the large energy dissipation.

Riesch et al. [20,21] have reported that the miniaturized tungsten fibre-reinforced tungsten composites produced with chemical vapor infiltration exhibit an enhanced toughness as characterized by high energy synchrotron tomography. Du et al. have produced W/W_f matrix composites by depositing a thin layer of copper [22], ZrO_x [23] or carbon [24] on the surface of tungsten fibres, in order to achieve a higher fracture toughness of the composite. Other researchers have also studied the effects of coated fibres on the interface strengthening [25,26]. Although improvement in toughness was achieved, the interface was not strong enough. So it is necessary to exploit some other ways to improve the adhesion between fibre and matrix.

Spark plasma sintering (SPS) is a pressure-assisted sintering method that utilizes a large pulsed DC current (1000–5000 A), provides fast heating rate (up to 100 °C/min), reduces the duration of exposure at high temperature, and allows the synthesis of dense fine-grained products at lower sintering temperature. Owing to these characteristics of SPS the degree of inter-diffusion between W matrix and W fibres as well as the recrystallization of W fibres

Table 1
Chemical composition of the as-received tungsten fibres.

Elements	W	Al	As	Bi	CA	Cd	Co	Cr	Cu	Mg
Fraction (wt ppm)	Bal.	6	10	1	5	1	1	5	1	5
Elements	K	Mn	Mo	Na	Ni	Pb	Sb	Si	Sn	V
Fraction (wt ppm)	83	5	20	3	5	1	2	5	1	5

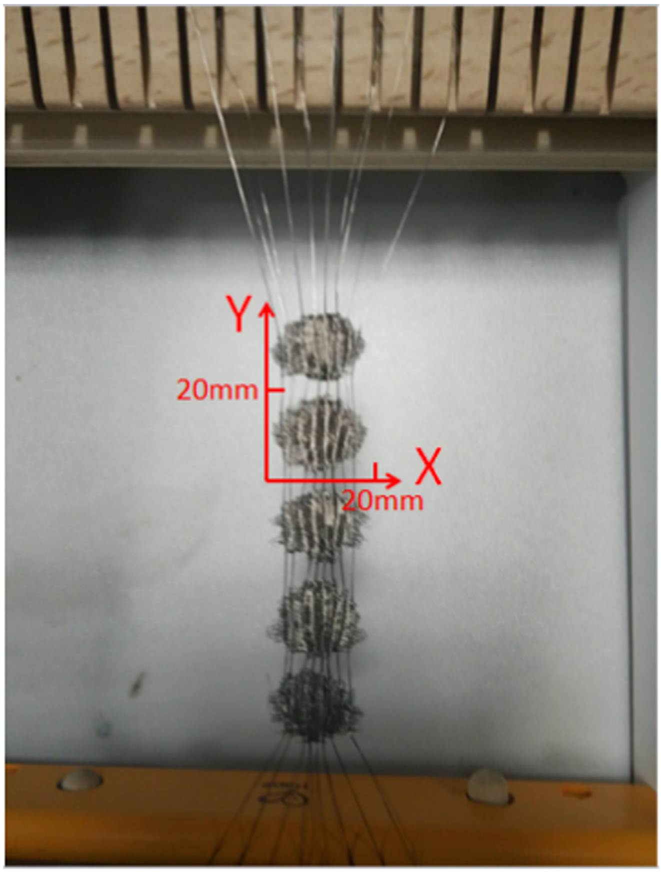

Fig.2. Photograph of tungsten fibre net.

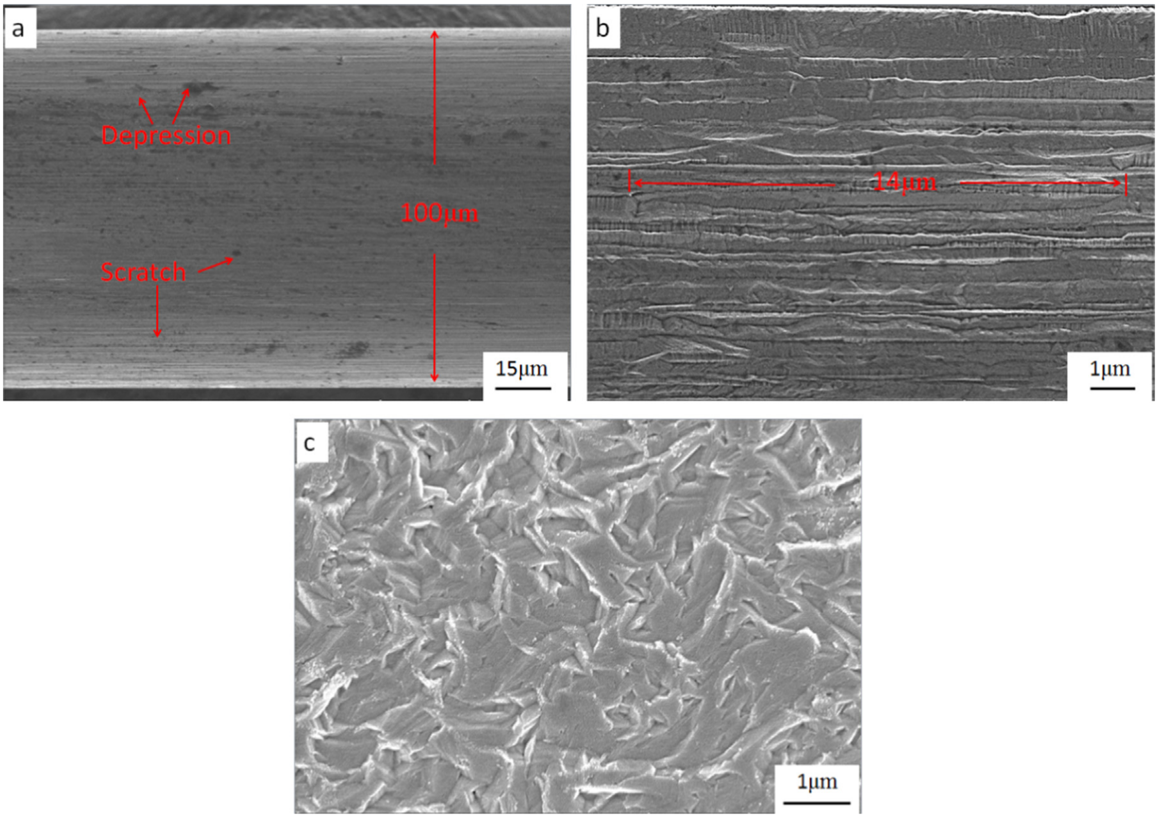

Fig.1. Micrograph of a tungsten fibre with100 μm in diameter: (a) surface, (b) longitudinal and (c) cross section.