Available online at www.sciencedirect.com
ScienceDirect
Acta Materialia 61 (2013) 7060–7071
Acta MATERIALIA
www.elsevier.com/locate/actamat

In situ synchrotron tomography estimation of toughening effect by semi-ductile fibre reinforcement in a tungsten-fibre-reinforced tungsten composite system

J. Riesch [a], J.-Y. Buffiere [b], T. Höschen [a], M. di Michiel [c], M. Scheel [c], Ch. Linsmeier [a,1], J.-H. You [a,*]

[a] Max-Planck-Institut für Plasmaphysik, EURATOM Association, 85748 Garching, Germany
[b] GEMPPM, INSA Lyon, 20 Av. A. Einstein, 69621 Villerbanne Cedex, France
[c] European Synchrotron Radiation Facility, BP 220, 38043 Grenoble, France

Received 8 March 2013; received in revised form 21 June 2013; accepted 16 July 2013
Available online 12 September 2013

Abstract

Tungsten-fibre-reinforced tungsten composites (W_f/W) are supposed to enable enhanced toughness owing to extrinsic energy dissipation mechanisms such as interface debonding and plastic deformation of fibre. In particular, the latter is an effective source of toughening, since ductile tungsten fibres can absorb a considerable amount of plastic work. For a precise evaluation of the toughening capability, the energy dissipation mechanisms need to be analysed in detail. To this end, single-fibre tungsten composite specimens are fabricated and the stress–strain behaviour of the tungsten fibre bridging a matrix crack is measured by means of in situ high-energy synchrotron microtomography during a uniaxial tensile test. Despite the high X-ray attenuation in tungsten, a sufficiently high resolution is achieved and clear images of crack extension and deformation are obtained. The amount of absorbed energy due to plastic deformation of the tungsten fibre is determined and compared with values obtained conventionally from single-fibre tensile tests.

Keywords: Tungsten; Fibre-reinforced composite; Toughness; Synchrotron tomography; In situ tension test

1. Introduction

Due to its unique combination of desired properties, tungsten is the most favoured candidate material for the plasma-facing components of fusion reactors [1]. However, the inherent brittleness of tungsten below the ductile-to-brittle transition temperature is a critical concern. This temperature is very much dependent on mechanical, chemical and microstructural material parameters [2]. For example, highly deformed tungsten like thin foils or wires are ductile at room temperature whereas recrystallized tungsten is brittle up to 633 K. Furthermore, embrittlement due to recrystallization or neutron irradiation may greatly restrict the applicability of tungsten in plasma-facing components [1,3]. Metallurgical efforts to overcome such an essential limitation have been focused on the enhancement of ductility via microstructural refinement or mechanical alloying of dispersed particles, but the state of the art of these approaches is still far from the design requirements. Comprehensive reviews on this topic can be found in the literature [4,5].

Recently, a number of authors have proposed a new toughening concept for tungsten, wherein the material is reinforced by tungsten wires with an engineered interface [6–9]. In this tungsten-fibre-reinforced tungsten composite (W_f/W), the toughness is enhanced by extrinsic mechanisms of energy dissipation, which we refer to as

---

* Corresponding author. Tel.: +49 89 3299 1373; fax: +49 89 3299 1212. *E-mail address:* jeong-ha.you@ipp.mpg.de (J.-H. You).
[1] Present address: Forschungszentrum Jülich, IEK-4, EURATOM Association, 52425 Jülich, Germany.

1359-6454/$36.00
http://dx.doi.org/10.1016/j.actamat.2013.07.035

extrinsic toughening. This toughening mechanism is widely applied in fibre-reinforced ceramic matrix composites [10,11]. After the first theoretical reflection by Aveston et al. [12], huge efforts were untertaken to understand these mechanisms [13–17]. Good overviews are given by Evans [18] and Steinbrech [19]. The deformation energy stored in the composite is mostly dissipated through the debonding and frictional sliding at fibre/matrix interfaces, while matrix cracks are bridged by the fibres being pulled out. These dissipative processes lead to considerable energy absorption accompanied by mitigation of stress intensity near a crack tip. As the underlying mechanism is based on a purely mechanical effect, it is expected to be hardly affected by additional embrittlement in fusion reactor environment.

In the case of W_f/W composites, an additional effective source of energy dissipation is available, i.e. plastic deformation of the tungsten fibres. Tungsten wires, fabricated by a drawing process, have been widely used as reinforcements before in copper matrix composites. Initially developed as a low-cost and easy-to-produce ideal fibre composite, these copper composites have evolved into high-thermal-conductivity composite materials for high-heat-flux elevated-temperature applications; the historical development of this class of material is described by McDanels [20]. Tungsten wires are capable of plastic deformation and can undergo tensile elongation up to several per cent. Thus, the plastic work conducted by semi-ductile tungsten fibres is an additional, presumably considerable, contribution to the toughening of W_f/W composites. For a quantitative estimation of the amount of energy absorbed by the plastic work of tungsten fibres, the actual stress–strain behaviour of the constrained fibres has to be measured under realistic loading conditions [21].

The mechanisms leading to energy absorption in a Ti/SiC metal matrix composite (MMC) under load have been extensively studied during synchrotron in situ experiments using three-dimensional (3-D) tomographic imaging or diffraction, or a combination of both techniques. Thanks to the ability of synchrotron radiation to probe highly attenuating metals, the authors of these studies have obtained a detailed view of the development of damage during tensile [22–25] or cyclic [26,27] deformation. Measurements of the fibre/matrix interfacial strength have been obtained and, more importantly, its evolution during straining at room or at high temperature has been quantified. In this fibre/matrix system, the thermal clamping residual stresses are key factors that control the interfacial strength by frictional sliding. This effect vanishes, however, at temperatures close to 870 K or when cyclic damage (wear) occurs at the fibre/matrix interface. The redistribution of stresses induced by fibre cracking has also been quantified in detail. It should be noted that, compared to the composite studied in the present work, the SiC fibres are fully brittle reinforcements.

In this paper, we present a tomography-based method for direct observation of fibre deformation and interface debonding in W_f/W composites. Since this technique enables in situ observation of the deformation and fracture process during loading, the progress of plastic work can be quantified as a function of the applied load. The strong X-ray absorption of tungsten on the one hand and the need for in situ experiments on the other hand require high-energy synchrotron radiation for the tomographic measurements. Only with high-energy X-rays are both a sufficient sample penetration and a fast data acquisition (fast tomography) feasible. However, the trade-off between energy and spatial resolution in X-ray tomography raises technical challenges for the high Z metal tungsten. In the following, we describe the results of an experiment performed at ESRF on beamline ID-15A. A tomography-based methodology for assessing the plastic work by fibre deformation is presented. The results are compared to those of single-fibre tension tests on free fibres. Finally, the contribution of plastic fibre deformation to the toughening of a multi-fibre composite system is estimated.

2. Toughening by the plastic work of fibre deformation

The chemically deposited tungsten used as matrix material in the W_f/W composite shows brittle behaviour [28] and can therefore be described by linear elastic fracture mechanics. In such materials toughness and therefore the contribution of fibre reinforcement can be expressed in terms of energy release rate G, which is defined as the change in elastic potential energy per unit area of an extending crack. If G is higher than the critical value G_c, then the material will fail. Thus, G_c (fracture energy) is a measure of material's resistance against brittle fracture [29].

For the W_f/W composite, the total toughness consists of two contributions:

$$G_c = G_0 + \Delta G$$

where G_0 denotes the fracture energy in the absence of reinforcement and ΔG is the increment of fracture energy due to the extrinsic toughening effect. The amount of plastic work to be dissipated depends on the stress between the crack surfaces bridged by a tungsten fibre and its evolution in time. For a single crack, the plastic work per unit area of crack face, ΔG_{pl}, is given by Refs. [18,21]:

$$\Delta G_{\mathrm{pl}} = V_f \cdot w_{\mathrm{pl}}^* = V_{\mathrm{f}} \int_0^{u_{\max}} \sigma(u)\mathrm{d}u \quad (1)$$

with V_f is the volume fraction of reinforcements [–]; w_{pl}^* specific plastic deformation energy [J m^{-2}] $u_{\max}$ is the maximum crack opening [m] and $\sigma(u)$ stress distribution in reinforcements [MPa].

Assuming that the fibre yield stress increases linearly with tensile strength, and further that the ultimate plastic strain is proportional to the fibre radius, Ashby et al. [21] suggested the following empirical relationship between the toughness increase and the plastic behaviour of the reinforcing fibre: