ASSESSMENT OF MECHANICAL BEHAVIOUR OF TUNGSTEN-BASED MATERIALS FOR FUSION DEVICES

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Abstract

During the operation of fusion devices, the plasma facing components are exposed to high thermal loads from the plasma resulting in mechanical stress formation, as well as to electromagnetic forces and severe particle fluxes. Materials used for this application have to sustain demanding operational conditions. Tungsten represents the material suitable for this application for its high melting point, high strength at elevated temperatures along with good thermal conductivity and high resistance to sputtering. High strength performance of the material is coupled with low ductility. Ductility and thermal conductivity of tungsten can be increased by introduction of copper. For these reasons, tungsten and tungsten-copper composite have been studied for their mechanical performance. Specimens from both materials were subjected to tensile test at high temperatures in the range from 300 to 600 °C. Elastic modulus along with yield and ultimate tensile strength were evaluated. Scanning electron microscopy was adopted to identify the character of the fracture mode. Typically, the tensile strength decreases as the testing temperature increases for both materials. Addition of copper resulted in significant increase in maximum elongation but also in the decrease of strength when compared to pure tungsten. Temperature related mechanical performance of the materials is discussed with respect to fracture morphology of the tested specimens.

Keywords: Tungsten-based materials, tensile testing, elevated temperatures, fractographic analysis, plasma facing materials

1. INTRODUCTION

In recent decades, the development of components designed for high heat flux applications in ITER and DEMO has become a challenging issue. It is necessary to assure the high structural stability of the components under severe neutron and thermal loads along with the sufficient heat removal capability for reliable operation of a future fusion reactor [1]. The ability of the components to withstand severe operational conditions is limited by the material.

Given that, the materials with specific performance such as high melting temperature, high sputtering resistance, high thermal conductivity and low neutron activation are demanded. Tungsten and tungsten-based materials are considered to be a prime candidate for this application.

Pure tungsten as a body-centered cubic (BCC) material exhibits ductile-to-brittle transition. Ductile to brittle transition temperature (DBTT) depends on material composition and its microstructure related to processing method. The temperature related fracture mode of tungsten material has been studied on commercially available grades as well as on spark plasma sintered tungsten [2-5]. Commonly, intergranular and transgranular brittle fracture was recognized on fracture surfaces of specimens subjected to tensile testing at approx. 300 °C. Gradual increase in temperature led to the change of the fracture mode. In addition to brittle intergranular and transgranular cracking, the formation of ductile dimples on fracture surfaces was identified as well.

Tungsten/copper (W/Cu) composites represent a class of materials exhibiting outstanding physical properties given by combination of these elements. Ductility and thermal conductivity of tungsten can be increased by introduction of copper. An extensive study has been performed on the mechanical behaviour of tungsten-based materials at temperatures up to 800 °C in vacuum (i.e., in fusion relevant conditions) [6]. Addition of copper resulted in improvement of the material ductility. The decrease in the tensile strength as the temperature of the exposure increases was documented. The specimen elongation reached its maximum at temperature of 425 °C then the mechanism of the fracture mode changes from intergranular and transgranular fracture of tungsten and plastic deformation of copper to predominant intergranular fracture of tungsten. Hao et al. [7] investigated the microstructure related ductility of tungsten/copper composites. The composites exhibited the maximum strength at room temperature and maximum elongation was measured at 300 °C. Ductility performance of the material can be improved by producing homogeneous structure of the composite.

The intention of the presented work is to report the mechanical behavior of tungsten and tungsten/copper material. Tensile testing in the temperature range from 300 to 600 °C was applied to assess the influence of copper addition on material performance. Fractographic analysis by means of scanning electron microscope (SEM) is adopted to characterize the temperature related fracture morphology.

2. MATERIAL AND EXPERIMENTAL PROCEDURE

Two tungsten-based materials were supplied by Plansee SE: pure W and W/Cu composite. Both materials were delivered in form of rods with diameter of 30 mm and length of 700 mm. The tungsten-based materials were produced by powder metallurgy and pure tungsten was subsequently normalized by forging. In case of W/Cu, the tungsten skeleton was infiltrated by copper. Additional material treatment was not performed. The chemical composition of both delivered materials according to the data sheets from the producer is given in **Table 1**.

Table 1 The nominal composition of studied materials in wt%. Composition of materials guaranteed by the producer

Material	**W (wt%)**	**Cu (wt%)**
W	> 99.97	-
W/Cu	Balance	23±3

From both tungsten-based materials, W and W/Cu, the specimens for the mechanical tensile test were machined parallel to the rod axis. Dog-bone shaped specimens with the overall length of 29 mm and gauge length of 10 mm having an effective cross section of 4 mm^2 were produced. The specimens were cut by electric discharge machine and no surface treatment was adopted.

Representative microstructure of W and W/Cu is documented in **Figure 1**. **Figure 1a** shows electron backscatter diffraction (EBSD) image of pure tungsten illustrating microstructure consisting of large, elongated grains oriented in the direction of rod axis. EBSD image of W/Cu composite is displayed in **Figure 1b**. Several grains of different scale can be recognized in the composite´s microstructure. The phase map included allows us to distinguish the tungsten skeleton from the pores infiltrated with copper, see **Figure 1c.**

All tests were performed by means of ZwickRoell universal testing machine Z250. The tensile tests were conducted according to the standards ASTM A370, EN ISO 6892-2 and ASTM E21 with respect to miniaturized dimensions of the tested specimens. Experiments were performed at high temperatures in the range from 300 to 600 °C. The constant strain rate of 2.5×10^{-5} s^{-1} was applied to determine the elastic modulus along with yield strength (YS) and constant strain rate of 10^{-3} s^{-1} for ultimate strength (UTS) evaluation. Specimen was heated up to required temperature and once stabilized, the tensile test was initiated after 45-minute hold time. At the onset of the tensile loading, the displacement and the strain were measured by means of the extensometer. Once the maximum strain range of the extensometer was reached (approx. 15%), the extensometer was removed, and tensile test was driven by the displacement control at displacement rate corresponding to selected constant strain rate.

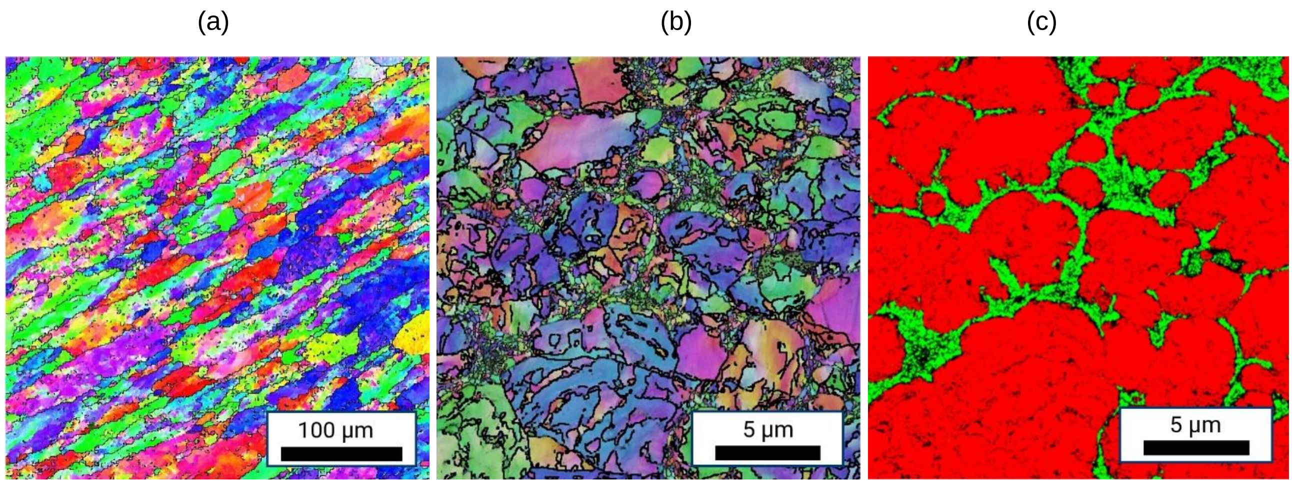

Figure 1 EBSD image of W (a), W/Cu material (b) along with the phase map included (c)

3. RESULTS

3.1. Tensile tests

Engineering stress-strain curves obtained for W and W/Cu specimens subjected to tensile testing at various temperatures are documented in **Figure 2.** Characteristic tensile parameters are summarized in **Table 2.** Generally, the tensile strength decreases as the testing temperature increases. This holds true for both materials investigated. Strain hardening ratio is higher for W/Cu material, meaning the more pronounced increase of the stresses from yield strength to the ultimate tensile strength is reached. Tensile strengths at temperature of 300 °C are substantially higher than those at higher temperatures for both materials.

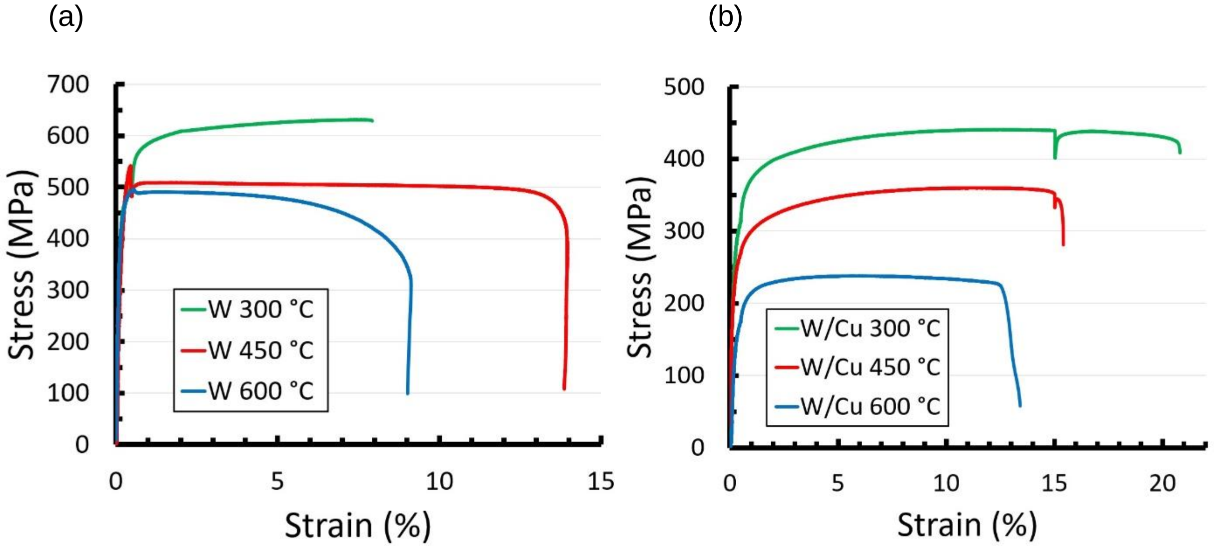

Figure 2 Tensile stress-strain curves of W (a) and W/Cu material (b) in the temperature range from 300 to 600 °C

The maximum strength was observed in the case of W specimen subjected to testing at the temperature of 300 °C. This behaviour can be attributed to the insufficient temperature for thermal activation of dislocation motion; thus, the higher stresses need to be applied as the driving force for dislocation mobility. W specimen exhibits the highest elongation when exposed to temperature of 450 °C. Young modulus (E_{mod}) along with the ultimate tensile strength decreases with the temperature increase. However, the highest yield strength was observed at 450 °C.

Concerning the W/Cu material, addition of copper resulted in significant increase in maximum elongation but also in the decrease of strength when compared to pure tungsten material. The highest specimen elongation is observed for the temperature of 300 °C. The elongation gradually decreases with temperature comparing to the pure tungsten material. Similar trend of temperature related elongation of W/Cu specimens was reported by Hao et al. [7]. The plot indicates that the material response at 600 °C leads to notable decrease in yield strength, ultimate tensile strength and Young´s modulus in comparison to lower temperatures applied.

Table 2 Tensile properties of W and W/Cu material. Temperature related characteristic tensile parameters are listed for both studied materials

Material	**Temperature**	***E_{mod}*** (GPa)	***YS*_{0.2%}** (MPa)	***UTS*** (MPa)	**Strain hardening ratio**
W	300 °C	365	481	631	1.31
W	450 °C	321	525	541	1.03
W	600 °C	320	479	496	1.04
W/Cu	300 °C	156	298	440	1.47
W/Cu	450 °C	160	249	360	1.45
W/Cu	600 °C	85	170	238	1.40

3.2. Fracture surface observation

Fractographic analysis of the fracture surfaces of W and W/Cu materials was conducted on specimens exposed to tensile loading at different temperatures, see **Figure 3** and **Figure 4**. Fracture surface of a W specimen exposed to 300 °C exhibits mixture of intergranular and transgranular brittle fracture.

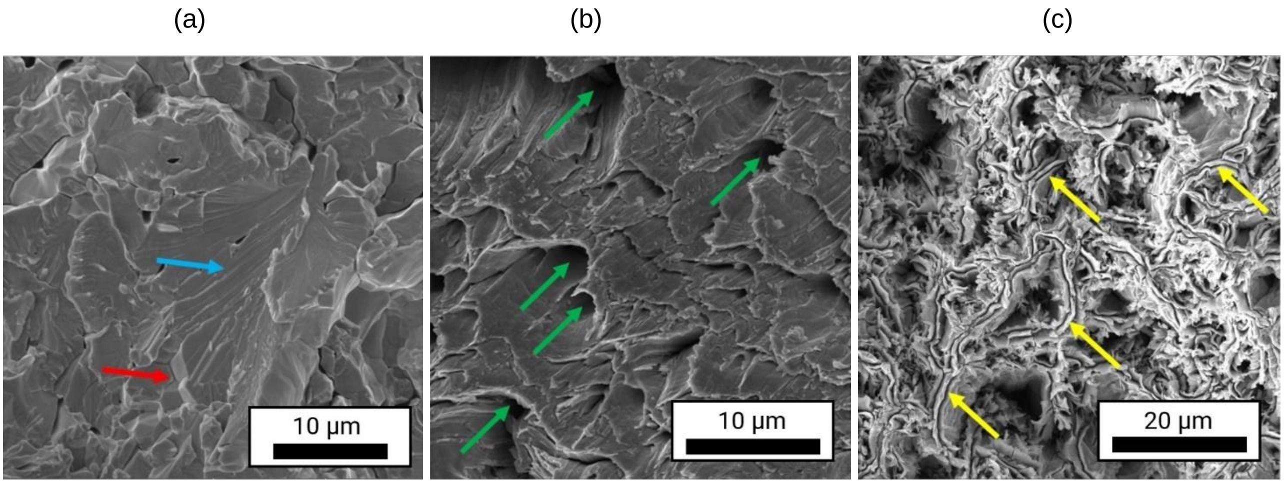

Figure 3 Fracture surface of W specimens exposed to tensile loading at (a) 300 °C, (b) 450 °C, (c) 600 °C

Faceted appearance reflecting intergranular crack propagation can be identified along and at grain boundaries, see red arrow in **Figure 3a**. River lines documenting the transgranular cracking are typically notable at the large areas restricted by cleavage facet, see blue arrow in **Figure 3a**. At 450 °C, a change in material fracture mode was identified, see **Figure 3b.** In addition to river-like markings typical for transgranular cracking, inhomogeneous distribution of dimples formed as a result of plastic deformation can observed as well (green arrow). Tear-like features (tongue features) can be recognized. Fracture surface of specimen subjected to tensile loading at 600 °C is documented in **Figure 3c.** The inspection revealed ductile dimple formation along with the secondary cracks developed dominantly on the oxidized grain boundaries, see yellow arrow. The highest elongation of the specimen subjected to testing at 450 °C can be associated with the large plastic deformation of the material (dimples formation), while the lack of plastic deformation due to reduced mobility of the dislocations at 300 °C resulted in the brittle intergranular and transgranular cracking. Premature fracture of a specimen exposed to 600 °C can be attributed to early necking of a specimen's gauge section (gradual decrease of the stresses identified at the beginning of a tensile test) and formation of a secondary cracks and their subsequent coalescence.

Representative images of the fracture surface of W/Cu specimens subjected to tensile testing at various temperatures are displayed in **Figure 4**. The fracture surface of specimen exposed to 300 °C allows us to clearly distinguish the copper material infiltrated in the tungsten skeleton and tungsten itself. Differences in their fracture modes demonstrates the material behaviour of these two phases when exposed to 300 °C. Brittle fracture of tungsten phase clearly dominates while plastic deformation of copper in the form of ductile dimples denoted by green arrows can be recognized. Intergranular cracking of tungsten phase is observed as well, see white arrows. Inspection of a fracture surface of specimens tested at the temperature of 450 °C and 600 °C revealed formation of oxide layer as documented in **Figures 4b and 4c.** Tensile testing at higher temperatures leads to development of uneven fracture surface containing valley-like features, also observed by Hao et al. [7], see **Figure 4b**. The gradual decrease in elongation of the specimens subjected to tensile testing as the temperature increases has been documented (see **Figure 2b**). This phenomenon can be attributed to degradation of the mechanical properties of copper [8]. Degradation of copper ductility due to intermediate temperature embrittlement may result in disruption of W and Cu interface, see protruding tungsten phase (**Figure 4b**, white arrows). The crack propagation via copper phase is thus bridged to intergranular fracture of tungsten [6,7]. Significant reduction in copper ductility in temperature interval from approx. 300 to 600 °C is considered to be the dominant factor for early failure of W/Cu composite [8].

(a) (b) (c)

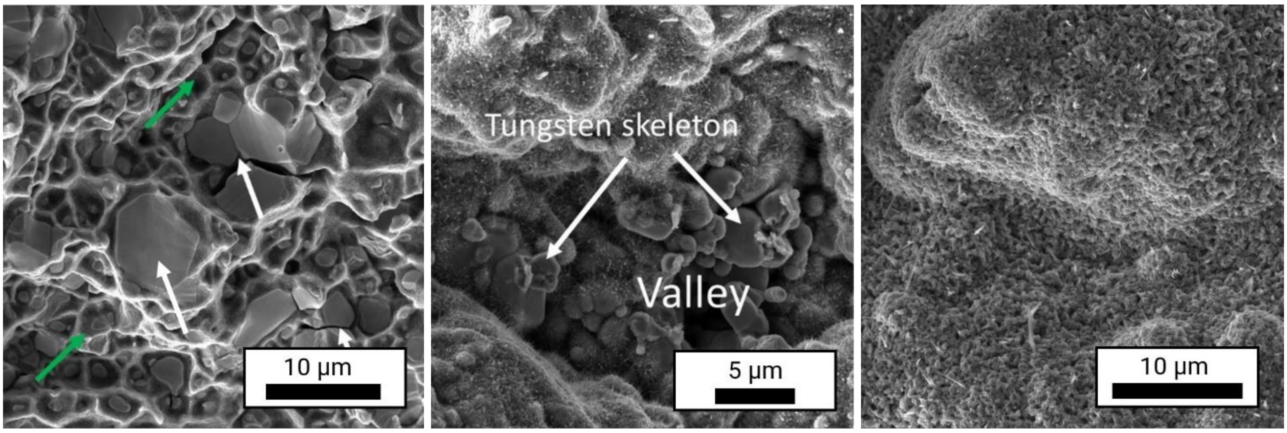

Figure 4 Fracture surface of W/Cu specimens subjected to testing at (a) 300 °C, (b) 450 °C, (c) 600 °C

4. CONCLUSION

Study of W and W/Cu materials under tensile loading in the temperature range from 300 to 600 °C leads to the following conclusions.

- The tensile strength decreases as the testing temperature increases for both studied materials. Addition of copper resulted in significant increase in maximum elongation but also in the decrease of strength when compared to pure tungsten.

- Typically, mixture of intergranular and transgranular brittle cracking was identified for tungsten specimen exposed to 300 °C. Testing at higher temperatures resulted in formation of plastic dimples reflecting the ductile fracture mode.
- Brittle fracture of tungsten phase along with the plastic deformation of copper in the form of dimples on fracture surface of tungsten/copper material at 300 °C can be recognized. Observation of fracture surface of specimens tested at the temperature of 450 °C and 600 °C revealed the oxidized uneven fracture morphology. Intergranular fracture of tungsten phase dominates.

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