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Melt Infiltrated Tungsten-Copper Composites as Advanced Heat Sink Materials for Plasma Facing Components of Future Nuclear Fusion Devices

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Abstract

The exhaust of power and particles is regarded as a major challenge in view of the design of a magnetic confinement nuclear fusion demonstration power plant (DEMO). In such a reactor, highly loaded plasma facing components (PFCs), like the divertor vertical targets, have to withstand both severe high heat flux loads and considerable neutron irradiation. Existing divertor target designs make use of monolithic tungsten (W) and copper (Cu) material grades that are combined in a PFC. Such an approach, however, bears engineering difficulties as W and Cu are materials with inherently different thermomechanical properties and their optimum operating temperature windows do not overlap. Against this background, W-Cu composite materials are promising candidates regarding the application to the heat sink of highly loaded PFCs. The present contribution summarises recent results regarding the manufacturing and characterisation progress of such W-Cu composite materials produced by means of liquid Cu melt infiltration of open porous W preforms. On the one hand, this includes composites manufactured by infiltrating powder metallurgically produced W skeletons. On the other hand, W-Cu composites based on textile technologically produced fibrous reinforcement preforms are discussed.

Keywords: *tungsten; copper; composite material; plasma facing component; heat sink*

1. Introduction

The exhaust of power and particles is regarded as one of the ultimate challenges with respect to the design of a nuclear fusion demonstration power plant (DEMO) [1]. The tolerable peak power load on highly loaded plasma-facing components (PFCs), like the divertor targets, represents a key constraint on the design of such a reactor and will determine its operating scenario [2]. Corresponding highly loaded PFCs, like the divertor targets, have to withstand both severe high heat flux (HHF) loads and substantial neutron irradiation [3] which is expected to lead to degradation of thermophysical and mechanical properties of the PFC materials. The performance of a PFC is most closely linked to the properties of the materials that are used for its design. A fundamental improvement of the performance of such components can hence be first and foremost be achieved by applying advanced materials with improved properties compared to the current state-of-the-art. Existing divertor target designs make use of monolithic tungsten (W) and copper (Cu) material grades that are combined in a PFC, as e.g. the design proposed for ITER [4]. Such an approach, however, implies engineering difficulties as W and Cu are materials with inherently different thermomechanical properties leading to the fact that their optimum operating temperature windows do not overlap. Against this background, W-Cu metal matrix composites (MMCs) are potential candidate materials regarding the application to the heat sink of highly loaded PFCs as will be discussed in the following sections.

2. Tungsten-Copper Composites

Composite materials offer flexibility due to the fact that their macroscopic properties, as e.g. the coefficient of thermal expansion (CTE), can be tailored - to some extent - by customising the microstructure through suitable arrangement and/or distribution of the constituing phases. Apart from that, composite materials can exhibit significantly superior mechanical properties compared to monolithic materials due to the presence of reinforcing inclusions which can e.g. be in the form of particles or high strength fibres. The use of W-Cu composite materials for PFC heat sink applications can be regarded as appropriate due to the following reasons: Monolithic W and Cu are materials that are already considered and qualified for PFC applications in magnetic confinement nuclear fusion experiments. Moreover, W-Cu composite materials feature a high thermal conductivity due to a coherent Cu or Cu alloy matrix. Furthermore, W-Cu composite materials can exhibit improved strength

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properties at elevated temperatures in order to extend the operating temperature range of a PFC heat sink. The heat sink material (HSM) currently favoured for PFC applications is the precipitation hardened Cu alloy CuCrZr [4, 5, 6, 7]. The recommended operating temperature window for this material ranges from approximately 180 °C to 300 °C due to embrittlement under neutron irradiation at lower and loss of strength at elevated temperatures [3]. Apart from that, it is a basic requirement for materials envisaged for the use in a future nuclear fusion reactor that they are capable of being manufactured in an industrial environment and on a corresponding scale. For W-Cu composite materials this is an achievable goal as the constituent materials are readily available from various manufacturers. Furthermore, such materials can straightforwardly be produced by means of liquid Cu melt infiltration of open porous W preforms due to the following reasons [8, 9]:

- the material system W-Cu does not show any interfacial reaction or mutual solubility
- there is a distinct difference in the melting points of Cu ($T_{m,W}$ = 1083 °C) and W ($T_{m,W}$ = 3400 °C)
- the wettability of W with Cu melt is very good

3. Tungsten-Copper Composite Metals

One promising class of W-Cu materials of interest with regard to PFC applications are W-Cu composite metals. Such materials can be produced by means of Cu melt infiltration of powder metallurgically produced open porous W skeletons. Following such an approach, the typically realisable material composition ranges from 60wt.%W-40wt.%Cu to 90wt.%W-10wt.%Cu which corresponds to approximately 40vol.%W-60vol.%Cu to 80vol.%W-20vol.%Cu. It has long been recognised that such composite metals offer an interesting combination of material properties [10]. Nowadays, W-Cu composite metals are for example used as contact materials in high voltage applications due to their high thermal and electrical conductivity, their high temperature stability, as well as their high ablation resistance [11]. This also implies that the manufacturing of such materials in an industrial environment is established. In Fig. 1, an optical image of a typical microsection of a W-Cu composite metal with 60wt.%W-40wt.%Cu is shown. The two different phases can clearly be distinguished. Furthermore, it can be seen that the material is fully infiltrated with Cu and that it does not show any plainly visible porosity which is a prerequisite for acceptable thermophysical and mechanical properties of the material. Moreover, this indicates a high manufacturing quality as well as a considerable industrial maturity of these materials.

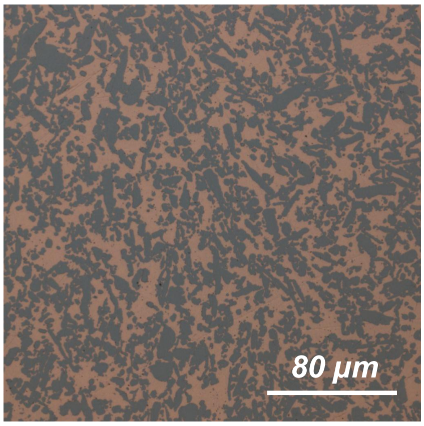

Fig. 1: Typical optical micrograph of a melt infiltrated W-Cu composite metal with a composition of 60wt.%W-40wt.%Cu.

The material illustrated in Fig. 1 has been manufactured according to the following process conditions:

1) powder metallurgical production of an open porous W skeleton by means of uniaxial cold pressing
2) sintering of the preform at 1150 °C for 2 h under hydrogen atmosphere
3) Cu melt infiltration of the preform at 1150 °C for 2 h under hydrogen atmosphere

In Fig. 2, the thermal conductivity of W-Cu composite metals based on laser flash analysis (LFA) measurements for different compositions is shown. It can be seen that, as expected, the thermal conductivity increases with increasing Cu content and that the material with a composition of 60wt.%W-40wt.%Cu exhibits a thermal conductivity of up to approximately 260 W/mK near room temperature decreasing to values slightly below 240 W/mK at 1000 °C. For reasons of comparison, the thermal conductivity of pure W is also included in Fig. 2 and it can be seen that the W-Cu composite metals show indeed a considerably superior thermal conductivity compared to pure W.

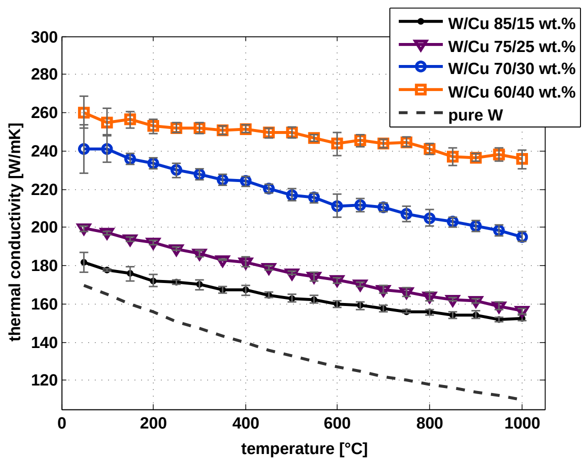

Fig. 2: Measured thermal conductivity of melt infiltrated W-Cu composite metals with differing W-Cu compositions (60wt.%W-40wt.%Cu, 70wt.%W-30wt.%Cu, 75wt.%W-25wt.%Cu, 85wt.%W-15wt.%Cu) in comparison to pure W.

In Fig. 3, the ultimate flexural strength of W-Cu composite metals with three different compositions measured by means of three point bending tests for temperatures up to 800 °C under high vacuum conditions is shown. It can be seen that there is an increase in strength values for increasing W contents. Furthermore, it can be seen that, as expected, the flexural strength decreases for increasing test temperatures. In particular, it can be seen that the material with a composition of 70wt.%W-30wt.%Cu - which corresponds to approximately 50vol.%W-50vol.%Cu - exhibits a flexural strength of more than 1000 MPa at room temperature as well as a flexural strength of significantly more than 600 MPa at a testing temperature of 425 °C. It can be stated that this indicates good mechanical performance if compared to well-established materials as e.g. plain steels which typically exhibit flexural strength values of 500 MPa to 700 MPa [12].

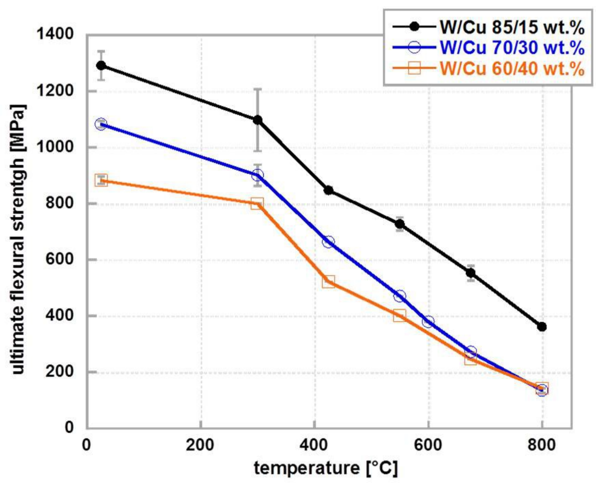

Fig. 3: Ultimate flexural strength of W-Cu composite metals with three different compositions (60wt.%W-40wt.%Cu, 70wt.%W-30wt.%Cu, 85wt.%W-15wt.%Cu) measured by means of three point bending tests.

4. Tungsten Fibre-Reinforced Copper Composites

W-Cu composite materials with potentially superior mechanical properties compared to the composite metals described above are W fibre-reinforced Cu (W_f-Cu) composites. The preferred reinforcing fibres for such a material are commercially available drawn potassium (K) doped W fibres. These fibres exhibit very beneficial mechanical properties due to their microstructure which consists of elongated and intertwined grains resulting from the drawing process during manufacturing (cf. Fig. 4c). The tensile strength of such fibres is about 2.7 GPa for material with a diameter of 150 µm in an as fabricated state and tested at room temperature [13]. Furthermore, ductile fracture behaviour of such fibres has been confirmed for annealing temperatures up to 1900 °C. It has already been mentioned that regarding materials for a future nuclear fusion reactor industrially viable production is a very important consideration. One crucial aspect regarding the fabrication of W_f-Cu composite materials is hence the production of suitable preforms for a Cu melt infiltration process. On the one hand, such a fibrous preform needs to have a defined architecture, i.e. the arrangement of the fibres has to be defined, in order that the later composite part exhibits the desired properties. On the other hand, these preforms need to be capable of being produced in an industrially viable process. In this respect, it is hence necessary to develop and adopt suitable textile technological fibre processing methods. In order to realise a heat sink pipe for PFC applications we have investigated the possibility to produce cylindrical preforms out of W fibres by means of braiding. The result of such an optimised braiding process is illustrated in Fig. 4a. The image shows a multi-layered cylindrical preform manufactured by means of overbraiding of a cylindrical mandrel. The fibres used have a nominal diameter of 50 µm while the braiding exhibits a regular 2/2 twill weave repeat pattern. Fig. 4b shows a scanning electron microscopy (SEM) image of the braiding with higher magnification illustrating the arrangement of the individual W fibres within the preform.

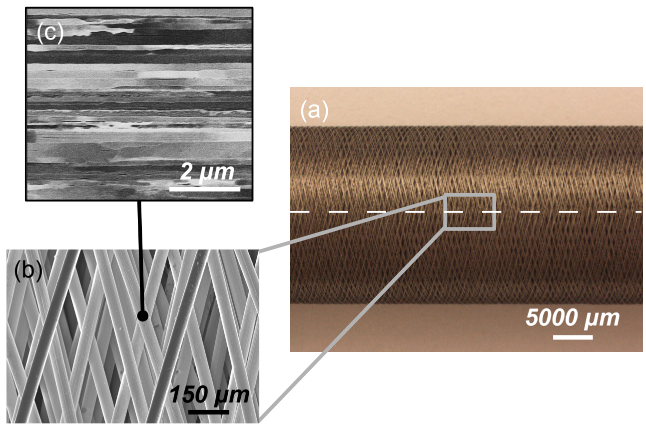

Fig. 4: (a) Cylindrical multi-layered braiding made out of continuous high strength W fibres with a nominal diameter of 50 µm; (b) SEM image of the braiding illustrating the arrangement of individual W fibres; (c) metallographic SEM image of a longitudinal cross section of a drawn K doped W fibre showing the typical elongated grain structure.

The fact that preforms as illustrated in Fig. 4 can be manufactured clearly indicates that W fibres are sufficiently flexible and ductile that they can be processed by means of established textile technological methods such as braiding. In Fig. 5, the result of a Cu melt infiltration of a fibrous preform as illustrated in Fig. 4 is shown. It can be seen that the infiltration is complete without any plainly visible porosity or voids which can again be regarded as an important prerequisite for acceptable thermophysical and mechanical properties of this material.

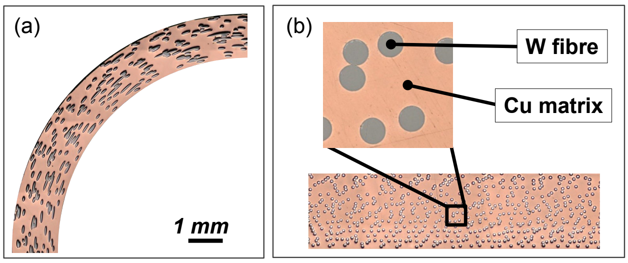

Fig. 5: (a) Transversal as well as (b) axial microsections of a W_f-Cu heat sink pipe produced by means of liquid Cu melt infiltration of a preform as illustrated in Fig. 4 imaged by means of optical microscopy.

In order to assess the beneficial properties of a W_f-Cu composite with regard to PFC applications, results of computations based on a homogenisation of a representative volume element (RVE) [14] are illustrated in Figs. 6 and 7. The RVE used for the computations is modelled according to the fibre architecture of the braiding illustrated in Fig. 4. The continuous W fibres are modelled as elastic inclusions while the matrix is modelled as elastoplastic material according to a J2 plasticity model with isotropic hardening. Fig. 6 illustrates the computed stress-strain behaviour at 300 °C of a W fibre-reinforced composite with a CuCrZr matrix. It can be seen that the mechanical performance of the material is significantly enhanced due to the presence of the reinforcing fibres. Furthermore, this enhancement is especially pronounced in the hoop direction due to the high braiding angle of the preform with respect to the pipe axis (cf. Fig. 4). Already for a fibre volume fraction of 0.2, it can be seen that the stress-strain behaviour shows a significant enhancement of more than a factor of two in hoop direction in comparison with the CuCrZr matrix material.

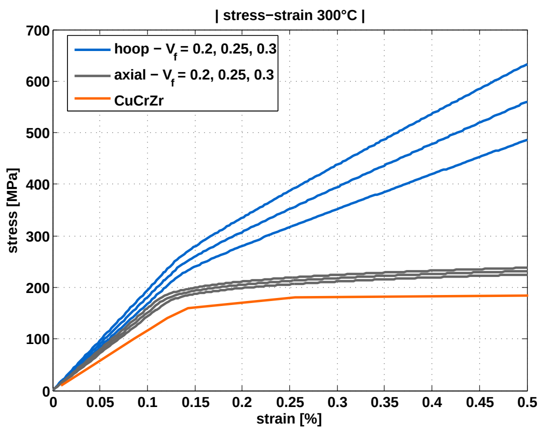

Fig. 6: Stress-strain behaviour of a W_f-CuCrZr composite predicted by means of homogenisation of a RVE for different fibre volume fractions (0.2, 0.25, 0.3) in comparison with the matrix material; the RVE is based on the fibre architecture as illustrated in Fig. 4.

Another beneficial effect, apart from the enhancement of the stress-strain behaviour, of a W fibre-reinforced composite is the fact that the CTE of such a composite is reduced in comparison to Cu or Cu alloys which would in a PFC design reduce thermal stresses during cyclic HHF loading. In Fig. 7, this effect is illustrated. The computations are again based on the same assumptions and RVE as mentioned above. It can be seen that the CTE in hoop direction at 300 °C is reduced from $18 \times 10^{-6}\,\mathrm{K}^{-1}$ to below $13 \times 10^{-6}\,\mathrm{K}^{-1}$ for a fibre volume fraction of 0.2.

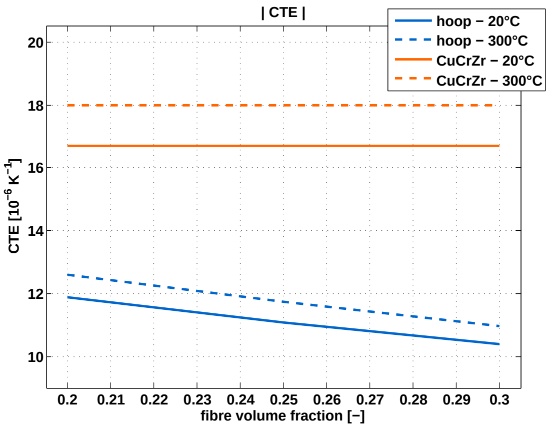

Fig. 7: CTE of a W_f-CuCrZr composite predicted by means of homogenisation of an RVE for different fibre volume fractions in comparison with the matrix material; the RVE is based on the fibre architecture as illustrated in Fig. 4.

5. Conclusions

It has been pointed out that W-Cu composites can be regarded as promising materials with respect to heat sink applications in PFCs of future nuclear fusion devices. In principle, the constituent materials for these composites are readily available and they can be manufactured straightforwardly by means of liquid Cu infiltration of open porous W preforms which can be regarded as an industrially viable production route. Within the present work, two classes of W-Cu composites have been described: W-Cu composite metals and W fibre-reinforced composites. It has furthermore been discussed that W-Cu composite materials exhibit suitable thermophysical and mechanical properties with respect to their intended application. The future work regarding the discussed materials comprises the optimisation of the manufacturing processes in an industrial environment accompanied by comprehensive thermophysical and mechanical material characterisation as well as manufacturing and HHF testing of corresponding PFC mock-ups.

Acknowledgement

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