Fusion Engineering and Design xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Melt infiltrated tungsten–copper composites as advanced heat sink materials for plasma facing components of future nuclear fusion devices

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HIGHLIGHTS

- W–Cu composites for plasma facing component applications are presented.
- Two classes of W–Cu composites are discussed: W particle and W fibre-reinforced Cu.
- The investigated materials show promising thermophysical and mechanical properties.

ARTICLE INFO

Article history:
Received 3 October 2016
Received in revised form 19 January 2017
Accepted 24 January 2017
Available online xxx

Keywords:
Tungsten
Copper
Composite material
Plasma facing component
Heat sink

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 targets, have to withstand both severe 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 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.

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 have to withstand both severe high heat flux (HHF) loads and substantial neutron irradiation [3–5] 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 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)

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http://dx.doi.org/10.1016/j.fusengdes.2017.01.042

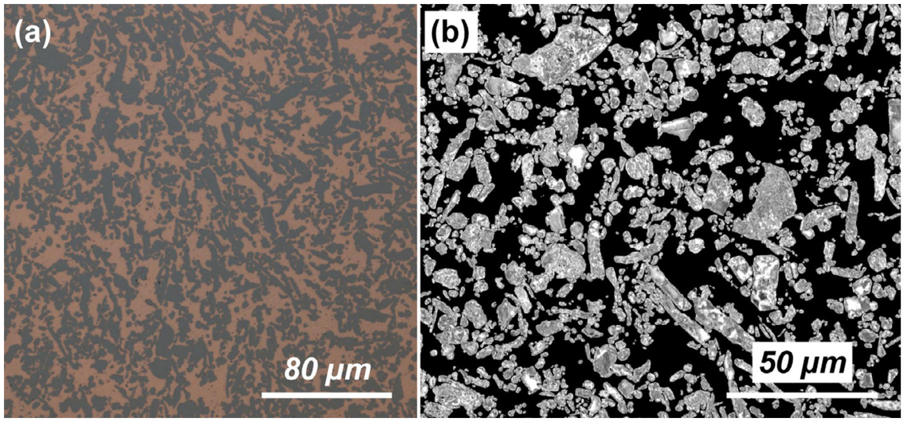

Fig. 1. Typical (a) optical as well as (b) scanning electron microscopy (SEM) micrographs of a W_p–Cu composite with a composition of 60 wt.%W–40 wt.%Cu (W–40Cu).

material grades that are combined in a PFC, as e.g. the design proposed for ITER [6]. 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. 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 constituting 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 [7]. Furthermore, W–Cu composite materials can exhibit improved strength 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 [6,8–10]. 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 [11,12]:

- 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 ($T_{m,Cu}$ = 1083 °C) and W ($T_{m,W}$ = 3400 °C),
- the wettability of W with Cu melt is very good.

2. Tungsten particle-reinforced copper composites

One promising class of W–Cu materials of interest with regard to PFC applications are W particle-reinforced Cu (W_p–Cu) composites. 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 60 wt.%W–40 wt.%Cu to 90 wt.%W–10 wt.%Cu which corresponds to approximately 40 vol.%W–60 vol.%Cu to 80 vol.%W–20 vol.%Cu. It has long been recognised that such composite metals offer an interesting combination of material properties [13,14]. Nowadays, W_p–Cu composites 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 [15].

In Fig. 1, typical micrographs of a W_p–Cu composite with 60 wt.%W–40 wt.%Cu (W–40Cu) are 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.

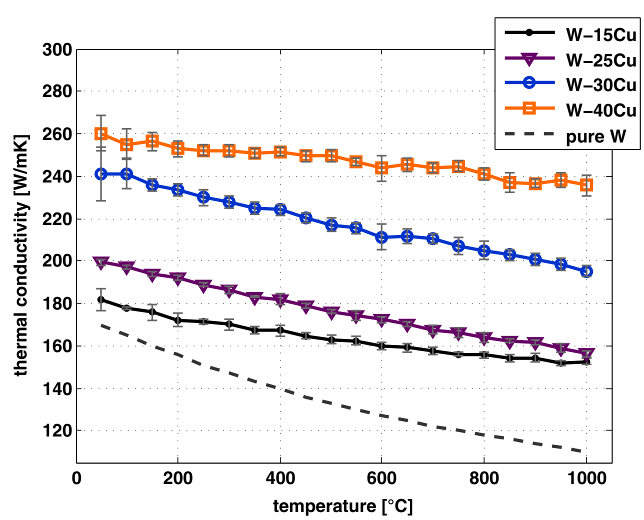

Fig. 2. Measured thermal conductivity of melt infiltrated W_p–Cu composites with differing compositions (W–40Cu, W–30Cu, W–25Cu, W–15Cu) in comparison to pure W; the measured samples exhibit at room temperature the following mass densities: ($\rho_{(W-15Cu)}$= 15.85 g/cm^3), $\rho_{(W-25Cu)}$ = 14.73 g/cm^3), $\rho_{(W-30Cu)}$ = 14.12 g/cm^3, $\rho_{(W-40Cu)}$ = 13.13 g/cm^3).