G Model
FUSION-7761; No. of Pages 4
ARTICLE IN PRESS
Fusion Engineering and Design xxx (2015) xxx–xxx
Contents lists available at ScienceDirect
Fusion Engineering and Design
journal homepage: www.elsevier.com/locate/fusengdes

Results of high heat flux testing of W/CuCrZr multilayer composites with percolating microstructure for plasma-facing components

Henri Greuner*, Alessandro Zivelonghi, Bernd Böswirth, Jeong-Ha You

Max Planck Institute for Plasma Physics, Boltzmannstr. 2, D-85748 Garching, Germany

HIGHLIGHTS

- Improvement of the performance of plasma-facing components made of W and CuCrZr.
- Functionally graded composite at the interface of W and CuCrZr to mitigate the CTE.
- A three-layer composite system (W volume fraction: 70/50/30%) was developed.
- Design of water-cooled divertor components up to 20 MW/m^2 heat load for e.g. DEMO.
- HHF tests up to 20 MW/m^2 were successfully performed.

ARTICLE INFO

Article history:
Received 22 September 2014
Received in revised form 3 February 2015
Accepted 10 February 2015
Available online xxx

Keywords:
Divertor
Tungsten/copper composite
Plasma-facing component
High heat flux

ABSTRACT

Reliable joining of tungsten to copper is a major issue in the design of water-cooled divertor components for future fusion reactors. One of the suggested advanced engineering solutions is to use functionally graded composite interlayers. Recently, the authors have developed a novel processing route for fabricating multi-layer graded W/CuCrZr composites. Previous characterization confirmed that the composite materials possess enhanced strength compared to the matrix alloy and shows reasonable ductility up to 300 °C indicating large potential to extend the operation temperature limit. Furthermore, a three-layer composite system (W volume fraction: 70/50/30%) was developed as a graded interlayer between the W armour and CuCrZr heat sink.

In this study, we investigated the structural performance of the graded joint. Three water-cooled mock-ups of a flat tile type component were fabricated using electron beam welding and thermally loaded at the hydrogen neutral beam test facility GLADIS. Cycling tests at 10 MW/m^2 and screening tests up to 20 MW/m^2 were successfully performed and confirmed the expected thermal performance of the compound. The measured temperature values were in good agreement with the prediction of finite element analysis. Microscopic investigation confirmed the structural integrity of the newly developed functionally graded composite after these tests.

1. Introduction

The divertor for future fusion reactors must allow steady-state operation under heat flux loads of at least 10 MW/m^2 and a limited number of slow thermal transients up to 15 MW/m^2 or higher. The current design of the water-cooled divertor for the DEMO reactor is based on an extrapolation of the ITER divertor design according to the European roadmap for fusion power [1] and the EU Power Plant Conceptual Study (PPCS) [2]. Tungsten as plasma-facing material bonded onto Cu based heat sinks is the basic design concept of the water-cooled divertor. A design concern is the large mismatch in the coefficients of thermal expansion (CTE) at 300 °C between W (4.6×10^{-6} K^{-1}) and Cu (17.6×10^{-6} K^{-1}) which is likely to produce high stresses during high heat flux (HHF) loading. Thus, the performance of the target component relies on the quality of the joining and reduction of mismatch stress between W armour and Cu heat sink.

One of the possible engineering approaches is to use a functionally graded composite interlayer at the bond interface in order to

* Corresponding author. Tel.: +49 8932991228.
E-mail address: henri.greuner@ipp.mpg.de (H. Greuner).

http://dx.doi.org/10.1016/j.fusengdes.2015.02.011

Please cite this article in press as: H. Greuner, et al., Results of high heat flux testing of W/CuCrZr multilayer composites with percolating microstructure for plasma-facing components, Fusion Eng. Des. (2015), http://dx.doi.org/10.1016/j.fusengdes.2015.02.011

mitigate the CTE mismatch and thus to reduce thermal stresses. Powder metallurgically sintered W/Cu composites have been commercially available for decades [3]. However, the joining technology for the manufacturing of reliable plasma-facing component (PFCs) is still immature.

As a new solution, the application of W/CuCrZr composites increases the strength at elevated temperatures compared to a pure Cu matrix and extends the operation temperature of the PFCs. A novel processing route for fabricating graded W/CuCrZr composites using a vacuum melt infiltration method was developed in close cooperation with the Dresden University of Technology, Institute of Materials Science, the Fraunhofer Institute for Manufacturing and Advanced Materials (Dresden) and the Max Planck Institute for Plasma Physics. Previous characterization showed that the composite materials possess enhanced strength compared to the matrix alloy but still maintaining excellent thermal conductivity and acceptable ductility [4–6]. A computational study was performed to understand the deformation and fracture behaviour of the composite on the basis of its microstructure [7]. All these results indicate the potential of these functionally graded composites (FGCs) to be applied to the DEMO divertor, in particular, in terms of operating temperature range.

In this study, we investigated the structural performance of a FGC-reinforced target component system under HHF fatigue loads. To this end, we fabricated three water-cooled mock-ups of a flat tile type consisting of W armour, FGC interlayer and Cu alloy heat sink bonded using electron beam welding (see Section 2). HHF fatigue tests were carried out at the neutral beam hydrogen beam test facility GLADIS [8]. The first results of the HHF fatigue tests are presented in Section 4. The focus of the investigation was placed on the thermal and mechanical performance of the FGC mock-ups under DEMO-relevant steady-state heat loads. Section 5 discusses the microstructural integrity of the FGC interlayer including the bond interfaces. These issues are discussed on the basis of thermal diagnostic data, microscopic damage analysis and nonlinear finite element analysis (FEA) simulations.

2. Mock-up manufacturing

2.1. Manufacture of graded composites

For the production of a porous graded W skeleton with three layers, mixed powders were pressed layer by layer and then sintered. In the second step, CuCrZr material was placed on top of the sintered W and heated to 1200 °C for 30 min. The molten CuCrZr flowed into the pores of the W skeleton and formed W/CuCrZr-composites. A continuous infiltration process was applied to fabricate a three-layer W/CuCrZr FGC laminate system (W volume fraction: 70/50/30%) in a single process. After infiltration, a 2 mm CuCrZr layer remained on the bottom side of the highly porous W skeleton. Finally the CuCrZr in the skeleton was precipitation hardened. The thermal conductivity κ of the three layers was calculated from thermal diffusivity data in the temperature range from 20 to 600 °C. The measured values (unit $\mathrm{W\,m^{-1}\,K^{-1}}$) at 20 °C are; $\kappa = 310$ for the W30 layer with 70 vol.% CuCrZr, $\kappa = 250$ for the W50 layer and $\kappa = 230$ for the W70 layer [5]. Further details of the synthesis and the thermo-mechanical properties of these W/CuCrZr composites are published in references [4,5]. The thicknesses and the compositions of the FGC interlayer were determined by a microstructure-based simulation study of their thermal- and mechanical behaviour [6]. This novel technique allowed one to achieve uniform and good quality joining at the bond interfaces resulting from the mutually percolating microstructure of the two phases.

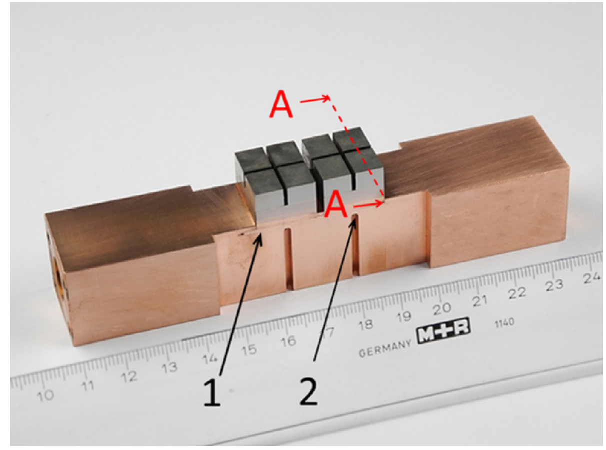

Fig. 1. Mock-up with a W/CuCrZr multilayer composite. Four W tiles are bonded on each individual multilayer composite. The electron beam welding between composite and cooling structure is marked (1), (2) shows the position of the TCs and the dashed line A–A marks the position of the micrographs shown in Section 4.

2.2. Manufacture of the component

One of the manufactured flat tile mock-ups is shown in Fig. 1. The overall dimensions are 140 mm × 27 mm × 35 mm. The cooling channel of the CuCrZr (ELMEDUR X, Thyssen Duro Metall GmbH) heat sink has 12 mm diameter. The bonding of the 12 mm × 9 mm × 5.5 mm W tiles onto the W/CuCrZr composite was performed simultaneously with the CuCrZr infiltration process. This method, similar to Cu casting, was used, as the direct bonding of the W tiles during the sintering process was not successfully. As an improvement of such type of PFCs, a direct bonding of W tiles to the W/CuCrZr composite would increase the thermal performance significantly. Each of the 4.3 mm thick W/CuCrZr composites is covered with four W tiles. To join the W/CuCrZr composite to the CuCrZr cooling structure, the above-mentioned CuCrZr layer was electron beam welded onto the heat sinks. Two holes for thermocouples (TC) are located centrally between the cooling channel and the electron beam welding; 3.5 mm below the W/CuCrZr composites.

3. High heat flux loading

HHF tests were carried out on three mock-ups in the HHF test facility GLADIS at IPP Garching. The loading parameters are measured with an accuracy of ±5%. The applied cooling conditions (water velocity 12 m/s, inlet temperature 15 °C and static pressure 1 MPa) ensure safe heat transfer in the regime of sub-cooled boiling up to 20 MW/m^2 heat flux and resulted in a maximum inner cooling wall temperature of ∼240 °C for 10.5 MW/m^2 and ∼290 °C for 15 MW/m^2 loading, respectively. Despite the low cooling water temperature, the resulting wall temperatures are comparable with the expected maximum inner wall temperature of 298 °C from the PPCS Model A reference design [2]. The central surface temperature of the exposed mock-ups was measured with one- and two-colour pyrometers as well as monitored by an infrared camera Infratec VARIOCAM HD. The two-colour pyrometer (Ø6 mm focus, $\lambda = 1.4$–1.75 µm, temperature range 500–1700 °C [9]) was used as reference for the emissivity determination of the one-colour pyrometer (Ø8 mm focus, $\lambda = 1$ µm, temperature range 650–2200 °C) [10] and the IR camera. The approach of adjusting the one-colour pyrometer to the data acquired with the two-colour pyrometer relies fully on the correctness of the temperatures measured by two-colour pyrometry. This is, however, only fully correct for a so-called “grey body”, where the emissivity is assumed to be

Please cite this article in press as: H. Greuner, et al., Results of high heat flux testing of W/CuCrZr multilayer composites with percolating microstructure for plasma-facing components, Fusion Eng. Des. (2015), http://dx.doi.org/10.1016/j.fusengdes.2015.02.011