G Model
FUSION-7518; No. of Pages 11
ARTICLE IN PRESS
Fusion Engineering and Design xxx (2014) xxx–xxx
Contents lists available at ScienceDirect
Fusion Engineering and Design
journal homepage: www.elsevier.com/locate/fusengdes

Thermal characterisation of ceramic/metal joining techniques for fusion applications using X-ray tomography

Ll.M. Evans [a,*], L. Margetts [b], V. Casalegno [c], F. Leonard [a], T. Lowe [a], P.D. Lee [a], M. Schmidt [d], P.M. Mummery [d]

[a] School of Materials, University of Manchester, Grosvenor Street, Manchester M1 7HS, UK
[b] School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Williamson Building, Manchester M13 9PL, UK
[c] Department of Applied Science and Technology, Politecnico di Torino, Corso Duca degli Abruzzi 24, I-10129 Torino, Italy
[d] School of Mechanical, Aerospace and Civil Engineering (MACE), University of Manchester, Manchester M13 9PL, UK

ARTICLE INFO

Article history:
Received 9 December 2013
Received in revised form 25 April 2014
Accepted 5 May 2014
Available online xxx

Keywords:
Thermal conductivity
Laser flash
X-ray tomography
Carbon fibre composites
Copper
Joining

ABSTRACT

This work investigates the thermal performance of four novel CFC–Cu joining techniques. Two involve direct casting and brazing of Cu onto a chromium modified CFC surface, the other two pre-coat a brazing alloy with chromium using galvanisation and sputtering processes. The chromium carbide layer at the interface has been shown to improve adhesion. Thermal conductivity across the join interface was measured by laser flash analysis. X-ray tomography was performed to investigate micro-structures that might influence the thermal behaviour. It was found that thermal conductivity varied by up to 72%. Quantification of the X-ray tomography data showed that the dominant feature in reducing thermal conductivity was the lateral spread of voids at the interface. Correlations were made to estimate the extent of this effect.

1. Introduction

ITER, the next step on the world's pathway to realising fusion energy, aims to demonstrate the feasibility of using fusion reactions to drive a power plant by successfully sustaining a controlled large scale plasma burn. As well as controlling the plasma, it must show that the construction materials will withstand the thermo-mechanical loading caused by the plasma and any disruptions experienced [1]. As such, the main role of the divertor plasma facing components (PFC) is to protect the machine from this loading by absorbing the energy released whilst minimising plasma impurities and retaining structural integrity [2]. ITER's design specifications will achieve this by active water cooling of the PFCs through heat sinks made from copper chromium zirconium (CuCrZr), a precipitation hardened copper alloy. Thus, the ability to join the PFCs to the CuCrZr is essential [3,4].

The divertor PFCs, which are the target at the intersection of magnetic field lines carrying the plasma, are expected to experience the highest loads, around 10 MW m^{-2}, as the kinetic energy is dumped over this region [5]. Under certain modes of operation these loads could exceed 10 MW m^{-2}, but this is not expected under normal in-service conditions. Materials selected for this component will be required to have high thermal conductivity and high thermal shock and fatigue resistance without impacting plasma purity. The two materials under consideration that meet these requirements are carbon fibre composites (CFC) and tungsten [6]. ITER was originally designed to have a two tier divertor, using both materials, with the CFC being replaced by tungsten at a later phase of ITER's lifecycle. As a cost reduction measure it was decided to use an all-tungsten divertor, however CFC components which require joining may be used elsewhere and in future fusion reactor designs [7].

The CFC region of the divertor consisted of rows of monoblocks along the cooling pipes. This design was chosen because other candidates, such as flat tiles or saddleblocks, suffered rapid and complete debonding [2,8]. The monoblock is a CFC cuboid with a cylindrical hole in the centre through which a CuCrZr coolant pipe runs, as shown in Fig. 1. The region between the two is the interface that requires joining. A large difference in the coefficient of thermal expansion of the two materials causes large internal stresses during operation, which can lead to failure. It has been suggested that a thin Cu interlayer might be used in order to mitigate these

* Corresponding author. Tel.: +44 1235 466524.
E-mail address: llion.evans@ccfe.ac.uk (Ll.M. Evans).

http://dx.doi.org/10.1016/j.fusengdes.2014.05.002

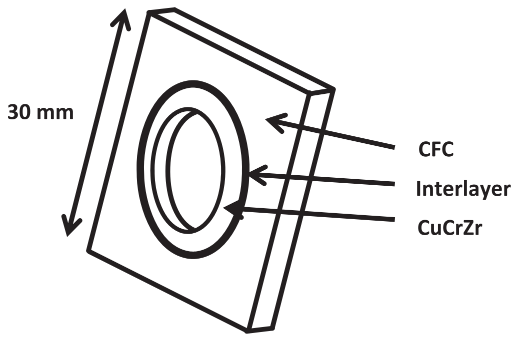

Fig. 1. Schematic of divertor monoblock.

stresses through its superior ductility. However, CFC does not bond well with pure Cu [9] since the wetting angle of molten copper on carbon substrates is very high, approximately 140°.

A wide range of techniques have been suggested to overcome this challenge [10–15]. This work investigates the thermal behaviour of four CFC–Cu joining methods, developed by Casalegno et al. [9,16,17], which involve introducing a thin layer of chromium carbide to improve adhesion. Thermal performance across the interfaces is investigated experimentally using laser flash analysis (LFA). The sample interfaces are then investigated by X-ray tomography. Particular interest is given to microstructural variations to identify mechanisms responsible for differences in thermal conductivity. The aim of this investigation is to determine which joining technique provides the greatest thermal conductivity across the CFC–Cu interface and which observable microstructures introduced in the joining process can impede thermal conductivity.

2. Materials

In order to create specimens suitable for thermal testing, tiles were manufactured in such a way as to represent the CFC–Cu interface present in the monoblock. Each tile consisted of a layer of CFC and Cu, with the interface created by one of the four differing methods of joining.

Two of these used a CFC where the interface surface is modified to form carbides by a solid state chemical reaction with chromium, which has been shown to improve wettability of Cu with CFC [18]. One sample (CFC–Cu_DC) was joined by a direct casting of a Cu slurry to the modified CFC by placing both materials adjacently in a holder and being heated to 1100 °C for 20 min. The other (CFC–Cu_OSB) was brazed using a commercial brazing alloy containing no active metals, where the tile is heated to 980 °C in an inert argon atmosphere and is kept at this maximum temperature for 15 min before being allowed to cool to room temperature. Adhesion between the two layers was facilitated by the use of a tungsten weight on the upper surface of the tile, exerting 1 kPa of pressure.

In a similar vein, the final two samples were brazed using the same brazing alloy and procedure but the chromium was precoated to the brazing foil rather than the CFC. This was achieved by a galvanic process (CFC–Cu_GG) and RF magnetron sputtering (CFC–Cu_GS). Coating the foil with chromium on a large scale would be technically less challenging than modifying the CFC surface of a monoblock and would therefore be a more cost-effective manufacturing process. The joining processes were performed at Politecnico di Torino according to the procedures detailed by Casalegno et al. [17].

The CFC used was Sepcarb NB31 (Snecma Propulsion Solid, France). The composite is composed of a 3D NOVOLTEX preform with needled ex-pitch (*z*-direction) and ex-PAN (*x* and *y* directions) fibres. Densification is performed by chemical vapour infiltration (CVI). The copper was an oxygen free high conductivity (OFHC) variety and the unmodified brazing foil was Gemco® (87.75 wt% Cu, 12 wt% Ge and 0.25 wt% Ni), both manufactured by Wesgo Metals, USA.

Further preparation, undertaken at The University of Manchester, was made to machine the tiles to appropriate dimensions for thermal analysis. This was achieved by using a lathe to produce cylindrical samples, except for the CFC–Cu_DC sample which was cored out of the tile using the appropriate drill bit. A sample thickness suitable for analysis was achieved using an aluminium oxide

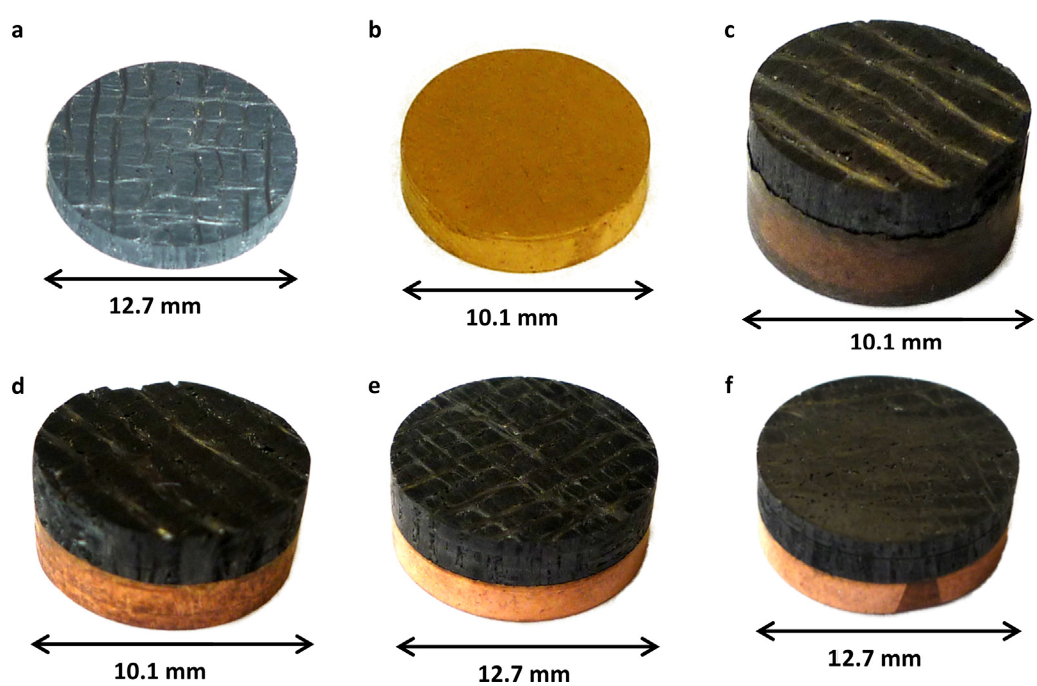

Fig. 2. Samples used for thermal analysis; (a) CFC, (b) Cu, (c) CFC–Cu joined by; direct casting (DC), (d) one step brazing (OSB), (e) braze coated by galvanisation process (GG), (f) braze coated by sputtering process (GS).

Please cite this article in press as: Ll.M. Evans, et al., Thermal characterisation of ceramic/metal joining techniques for fusion applications using X-ray tomography, Fusion Eng. Des. (2014), http://dx.doi.org/10.1016/j.fusengdes.2014.05.002