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One-step brazing process for CFC monoblock joints and mechanical testing

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ABSTRACT

A new method of joining CFC to copper (CFC/Cu) and CFC/Cu to CuCrZr alloy (CFC/Cu/CuCrZr) was previously developed for the flat-type configuration. The joining technique foresees a single-step brazing process: the brazing of the three materials (CFC, Cu and CuCrZr) can be performed in a single heat treatment using the same non-active brazing alloy. The composite surface was previously modified by solid state reaction with chromium with the purpose of increasing the wettability of CFC by the brazing alloy.

The feasibility of this process also for monoblock geometry is described in this work. The thermal fatigue resistance of the joined samples (quenching from 450 °C to RT; 50 cycles) was tested and the joints were characterized by apparent shear tests before and after thermal fatigue. The apparent shear strength of the CFC/Cu/CuCrZr joined samples was unaffected after these thermal fatigue tests.

1. Introduction

Plasma-facing components (PFCs) act as actively cooled thermal shields to sustain thermal and particle loads during normal and transient operations in the next step fusion machine ITER. The plasma-facing layer is referred to as "armour", which is made of either carbon fibre reinforced carbon composite (CFC) or tungsten (W). CFC is the reference design solution for the lower part of the vertical target of the ITER divertor, which intercepts the magnetic field lines, and therefore removes the heat load coming from plasma via conduction, convection and radiation. The armour is joined onto an actively cooled substrate, the heat sink, made of precipitation hardened copper alloy (CuCrZr) through a thin pure copper interlayer: it is mandatory to decrease, by plastic deformation, the joint interface stresses; in fact, the CFC to Cu joint is affected by the CTE mismatch between the ceramic and metallic material ($CTE_{CFC} = 0.7–1.3 \times 10^{-6}\ K^{-1}$ and $CTE_{CuCrZr} = 16–17 \times 10^{-6}\ K^{-1}$) [1].

Two configurations can be adopted for PFCs: the flat tile and the monoblock. In particular, the monoblock gives a more robust solution in comparison with flat tile for the vertical target and it is now considered the ITER reference geometry [2,3].

The monoblock design requires drilled blocks of CFC into which a CuCrZr tube is inserted and joined [4], also here, a thin layer of pure copper is necessary between CFC and the copper alloy in order to relax high joint interface stress [5]. The monoblock is preferred over the easier to manufacture flat tile design, because of the better heat flux performances and because of the observed tendency for flat tiles to suddenly and totally detach in high heat flux conditions [6].

Actually, the thermal stresses which occurred during the manufacturing process for monoblock geometry are appreciably higher than those of the flat tile, as discussed in Ref. [6] and attention should be given to solutions that mitigate or avoid the failures of armour/heat sink joints, for instance using lower manufacturing temperature.

In the past, high temperature brazing was the reference method for the ITER PFC joining. Brazes used in the past contain a certain amount of silver; today such alloys are not considered in order to avoid cadmium as a product of transmutation after neutron irradiation [7].

Currently, one of the possible solution for CFC to CuCrZr monoblock joint is the manufacturing route proposed by the Austrian company Plansee, the so called AMC® (Active Metal Casting) [8,9]. It involves the casting of Cu onto the CFC surface, which is previously structured by a laser beam to improve the joint strength and then activated by titanium in order to generate a carbide layer, which can be wetted by copper and adheres on the CFC surface. The Cu/CuCrZr joint is obtained using the hot isostatic pressing technique at relatively low temperature (about 550 °C) [4].

Other possible solutions were developed in Europe and Japan for the monoblock CFC/Cu/CuCrZr joining. A joining process for monoblock geometry was developed by ENEA [10]; the CFC monoblock tiles are prepared by pre-brazed casting (PBC) and then joined to the CuCrZr pipe by hot-radial pressing (HRP). PBC consists of a brazing process with a commercial Ti-based alloy and a successive copper casting under vacuum; the brazing alloy contains Ti which acts as an active element and allows the copper casting [11]. HRP [12] is based on pressurizing the internal CuCrZr tube and keeping the joining zone in vacuum at the required bonding temperature; with this process, a radial diffusion bonding between the cooling tube and the armour tile occurs.

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Another process for joining CFC armour to the copper-alloy heat sink was carried out by Ansaldo Ricerche [13]: the techniques involves the use of an active brazing alloy based on Cu, Ti, Al and Si where the Ti reacts with carbon to form a thin TiC layer that helps wetting. Moreover carbon fibres are added in the brazing alloy to smooth the transition between the composite and the Cu and to reduce the residual stress mismatch. The successive Cu/CuCrZr joint is obtained by brazing, by using a Cu–Ge based commercial alloy.

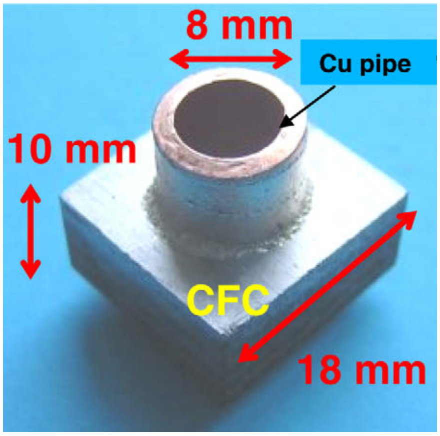

Fig. 1. CFC/Cu monoblock sample manufactured by one-step brazing process.

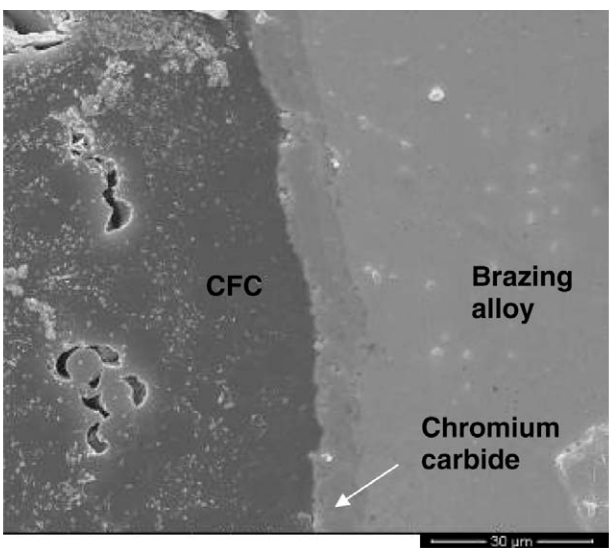

Fig. 2. Scanning electron microscopy of the chromium carbide modified CFC/brazing alloy interface.

Finally, the Japan domestic agency (JADA) [14] developed a brazing process where CFC armour tiles were brazed to the soft copper interlayer collar by using the Ni–Cu–Mn braze filler with prior Ti–Cu metallization on CFC tile surfaces. While, the soft copper interlayer collar was brazed to the CuCrZr cooling tube with Ni–Cu–Mn (NiCuMn37) braze filler. These braze processes were simultaneously made in a vacuum environment at 980 °C [14].

In this work, the possibility to simultaneously join CFC to copper and to CuCrZr alloy in the monoblock geometry by using the same brazing alloy and by a single heat treatment is demonstrated. Laser structuring or hot pressing is not required. The morphology and mechanical strength of the joined samples were investigated. The shear strength of the joints was measured before and after thermal fatigue tests.

2. Experimental

Monoblock samples were produced from high thermal conductivity 3D-CFC materials, CFC NB31 manufactured by SNECMA. Oxygen free high conductivity copper pipe (OFHC), from Goodfellow, and a pipe of CuCrZr ITER grade were used. The manufacturing of CFC/Cu alloy monoblock starts from drilling the CFC tiles along the *Z* direction (needling direction).

The process involves the modification of the CFC surface and then brazing with a commercial non-active brazing alloy, Gemco® (87.75 wt% Cu, 12 wt% Ge and 0.25 wt% Ni; Wesgo Metals). The surface modification process consists of chromium powder deposited by slurry technique on CFC and then a thermal treatment (1300 °C; 1 h; in vacuum) to obtain a continuous layer of chromium carbide through solid state reaction; this layer was proved to be wettable by non-active brazing alloys such as Gemco alloy [15]. The Gemco alloy is used for both the CFC/Cu and Cu/CuCrZr joints (brazing alloy foil thickness = 60 µm); three foils was used for each joint (CFC/Cu and Cu/CuCrZr).

The monoblock CFC/Cu/CuCrZr joints were manufactured by drilling the CFC; the Cr powder was deposited on the inner surface of the hole in the CFC. After the CFC surface modification process, three foils of Gemco were placed in contact with the modified CFC and the pure Cu pipe (10 mm external diameter and 1 mm

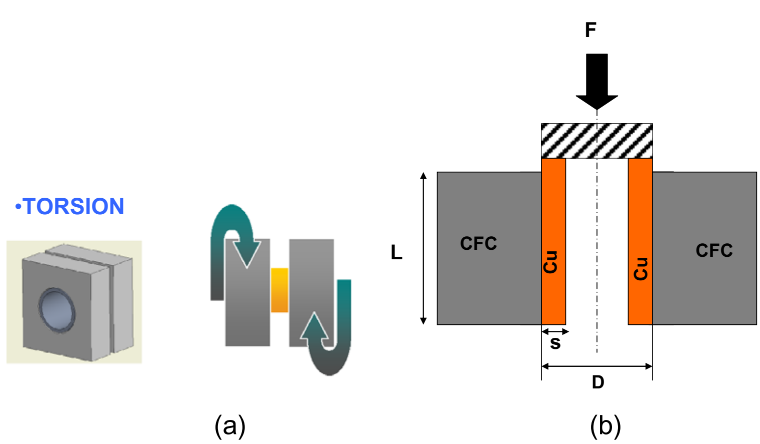

Fig. 3. Drawing of tested sample and proposed shear tests for CFC/Cu samples joined in the monoblock configuration: torsion (a) and shear by compression (b) tests. In (b) F = compression load, D = Cu tube external diameter, s = Cu tube thickness and L = CFC thickness.