Advanced Materials Research Vol. 59 (2009) pp 192-197
online at http://www.scientific.net

Brazing Technology For Plasma Facing Components In Nuclear Fusion Applications Using Low And Graded CTE Interlayers

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Keywords: plasma facing components, fusion, CFC, graphite, brazing, interlayer, residual stress.

Abstract. In Plasma Facing Components (PFCs) for nuclear fusion reactors, the protective material, carbon based or tungsten, has to be joined to the copper alloy heat sink for optimum heat transfer. High temperature vacuum brazing is a possible joining process as long as a proper interlayer is introduced to mitigate the residual stresses due to the mismatch of thermal expansion coefficient (CTE). Pure copper can act as plastic compliant layer, however for carbon based materials a proper structuring of the joining surface is necessary to meet the thermal fatigue lifetime requirements. In this work pure molybdenum and tungsten/copper Metal Matrix Composites (W-wires in Cu-matrix) interlayers have been studied as alternative to pure copper for carbon based protective materials in flat tile configuration. Finite element simulations of the brazing process have been performed to evaluate the expected residual stress reduction near the metal-carbon interface. In fact it has been demonstrated that stiff low CTE interlayers can shift the peak stresses from the weak carbon-metal interface to the strongest metal-metal one. Relevant samples have been manufactured and subjected to preliminary metallographic and thermal shock tests. Results obtained so far are encouraging and active cooled mock-ups are being prepared for high heat flux testing. Research work is in progress as regards monoblock configuration with both Wf/Cu MMC and graded Cu/W plasma sprayed and HIPped layers.

Introduction

In Plasma Facing Components (PFCs) for nuclear fusion reactors, optimum heat transfer has to be achieved between the protective material (CFC or W) and the heat sink one, so that mechanical joining is not sufficient. The reference joining technology for ITER divertor components is Hot Isostatic Pressing (HIP), without additional filler metals [1,6,7], on the CuCrZr heat sink side; activation of the CFC surface and casting of pure Cu are performed before HIPping. High temperature vacuum brazing is a possible joining process too. In both processes a copper compliant layer (1 or 2 mm thick) is used in order to mitigate the residual stresses produced by the large CTE mismatch between the heat sink (CuCrZr) and the protective materials. Moreover a complex structuring of the surface to be joined is required in the case of CFC, in the form of holes or grooves, to increase the thermal fatigue lifetime up to the required limits. The above considerations apply to the two existing PFCs configurations, flat tile and mono-block. In this work another route for the reduction of residual stresses in PFCs has been preliminary explored; it entails the use of high strength and high thermal conductivity, but low CTE or graded CTE interlayers, to be brazed in between the low CTE protective material and the high CTE heat sink. The purpose is the transfer of the joining residual stresses from the interface with the relatively weak C-based material to the interlayer near the metal-metal interface. The interlayer material, 1 to 2 mm thick, has to show a CTE value as similar as possible to the CFC one; in practice CTE values from 4 to 8 x 10^{-6} K^{-1} are acceptable. Its thermal conductivity has to be at least about 150 W/mK (Mo is just at the lower limit). The expected advantage is the simplification of the joining technique with respect to the state-of-the-art one, since no surface structuring will be necessary. The easiness of industrialization and the costs reduction of the brazing process could be completely exploited.

Finite Element Modeling

Finite Element Modeling (FEM) has been used in order to calculate the expected residual stress reduction near the metal-carbon interface with respect to the pure Cu compliant layer. Calculations have been performed for graphite flat tile configuration with different interlayers, from simple Mo to different kinds of W-wire reinforced Cu-matrix MMCs. The analysis has been performed by means of ANSYS code. The simulation consists of a heating phase, up to the brazing temperature (1035 °C), followed by a cooling down to room temperature. During the first heating phase the heat sink, interlayer and protective material are free to expand while in the successive cooling the nodes at the interfaces are locked to simulate brazing. Stresses generated during cooling down have been calculated according to the isotropic hardening model, using multilinear elastic-plastic material properties. No effect of creep relaxation has been included to reduce numerical difficulties in this comparative analysis, although this is expected to be an important effect. Properties of metallic materials have been obtained from the databases of the fusion community [2][3]; for graphite, the properties of the commercial Toyo Tanso IG43 (GTT) grade have been adopted. The MMCs have been simulated by means of proper solid reinforced elements, with copper as matrix and tungsten as reinforcing material. It should be noted that, due to the poor knowledge of the material stress-strain curves at high temperature, the results cannot be fully representative of the real stress intensity but can only provide useful information about their distribution and about the capability of different interlayers to reduce manufacturing stresses. The typical geometry of test samples has been taken into consideration for the calculations (Fig. 1). The calculations performed in this comparative analysis are summarized in Table 1, where the results are compared in terms of *failure criterion* in the carbon based material.

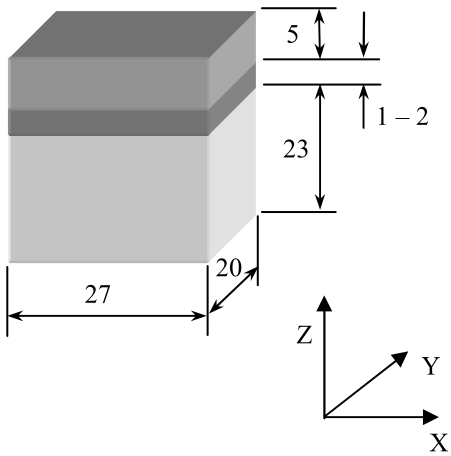

Fig. 1 – Typical geometry of divertor sample with 5 mm thick protective material brazed to a CuCrZr heat sink via a 1-2 mm thick interlayer

Interlayer	**CTE [10^{-6} K^{-1}]**	**Thickness [mm]**	**FailSmax (max. value)**	**Extension of the failure zone (FailMax >1)**
Cu	15 -22	1 mm	1.6	whole metal-carbon interface
		2 mm	1.4	whole metal-carbon interface (Fig. 2.a)
Mo	5-6	1 mm	1.8	large area of metal-carbon interface
		2 mm	1.9	very limited along the edges (Fig. 2.b)

Table 1 – Brazing residual stress: summary of FEM analysis

In the isotropic graphite the failure criterion states that the failure is expected when the principal stresses exceed specified values (tensile and compression strength). ANSYS calculates and plots the parameter FailSmax that represents the ratio between the local calculated stress and the strength of the material. Failure is expected in the zones where FailSmax > 1.

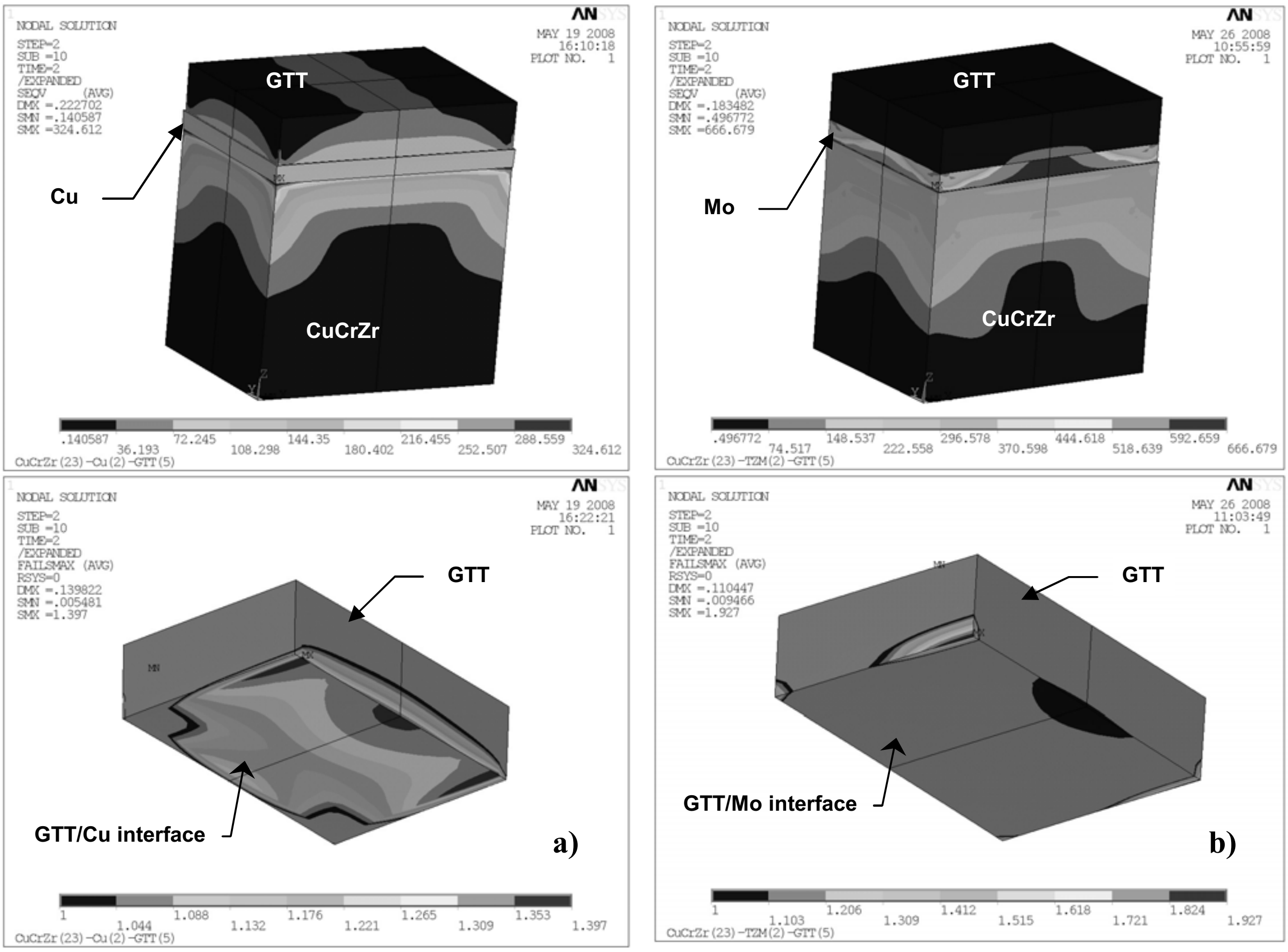

Fig. 2 - Residual brazing stress: stress contour on the whole sample (Von Mises, MPa) and failure zones (FailSmax > 1) in GTT with Cu interlayer (a) and with Mo interlayer (b). - FailSmax contours are plotted on half tile to show their extension in the bulk of the carbon material - .

The results of the calculation with 2 mm thick copper and molybdenum interlayers are shown in figure 2. It can be noted that in the case of Mo interlayer the extension of the failure zone (FailSmax > 1) is limited and located along the edges of the brazed seam where, in the real component, the discontinuities are generally smoothed by the filler alloy. There is also an increasing of the equivalent stress in the interlayer from about 80 MPa (Cu interlayer) up to about 660 MPa (Mo interlayer). These theoretical results have been confirmed by experiments (see below).

Experiments and results

Single flat tile compounds formed by CuCrZr blocks brazed to carbon materials with different interlayers have been realized and tested. The correlation between tensile and shear tests with the capability of the joint to withstand thermal fatigue stresses induced by high heat fluxes is not clear. So, an ad-hoc thermal shock test has been developed in order to load the junction in quasi-real conditions. The test consists in slow heating up to 450 °C, followed by quenching in room temperature water. The joint degradation is verified by microscopic inspections after 30 cycles, but the test is considered as passed if ≥ 20 shocks are performed without visible failures. The test is considered as passed if the sample survives without major damages, like complete tile detachment or propagation of large cracks in carbon based material. The thermal shock is a representative and cheap preliminary test prior to the validation by means of the much more expensive electron beam fatigue tests on actively cooled mock-ups. According to experience a joining process that fails the thermal shock test has no chance to pass the successive validation fatigue tests [4].

Compounds formed by CuCrZr blocks brazed to Ti-doped isotropic graphite tiles with 1 and 2 mm thick Cu and Mo interlayers, have been prepared using an active brazing alloy (92.75 Cu, 2.25 Ti, 2 Al, 3 Si) in contact with the C-based material and a Cu-Ge alloy on the other side of the interlayer.

Both brazed joints have been prepared in a single heat treatment (vacuum, 1035 °C, 18 minutes stay at temperature), followed by fast cooling and ageing (3 hours at 475 °C) in order to restore CuCrZr properties.

The samples with Cu interlayer did not survive the manufacturing process. Large defects where visible in the graphite tiles even far from the joining seem (Fig. 3). The sample with 1 mm thick Mo interlayer failed the thermal shock test while the 2 mm thick one (Fig. 4) survived 30 cycles without any degradation of the joint, confirming the results of the FEM analysis.

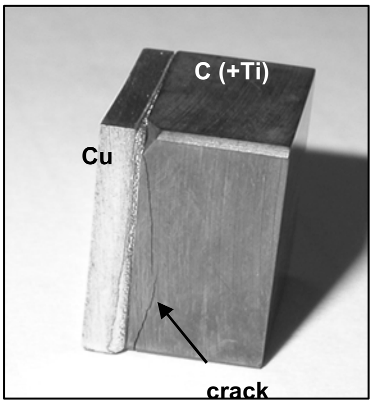

Fig. 3 – CuCrZr/Cu/Ti-doped graphite compound: failed just after brazing the Cu interlayer

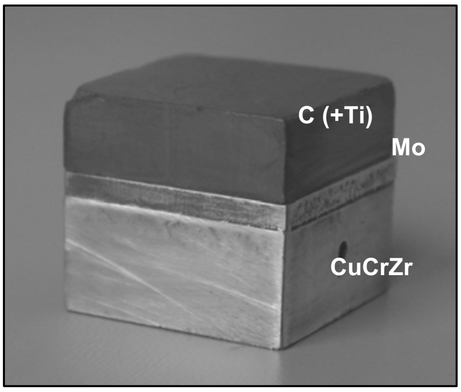

Fig. 4 – CuCrZr/Mo/Ti-doped graphite compound after 30 thermal shock cycles

Other similar compounds have been produced with the same procedure, using NB31 CFC instead of Ti-doped isotropic graphite. Thermal shock tests have been performed up to 30 cycles without failure. Similar compounds, with 2 mm Mo interlayer, have been prepared also with TiNx-coated NB31 CFC tiles, with different TiNx stoichiometry and thickness; TiNx is expected to act as a wetting promoter for the brazing alloy, improving the infiltration of filler alloy into the pores of CFC. A 0.2-0.5 mm deep infiltrated region acts as an additional interlayer with intermediate CTE that is beneficial for the lifetime of the joint under thermal fatigue (Fig. 5). TiNx stoichiometry and thickness have been optimized to enhance wetting and reduce the formation of detrimental intermetallic compounds at the interface. Satisfactory thermal shock test results have been achieved for all these compounds too, i.e. ≥ 20 shocks without visible failures

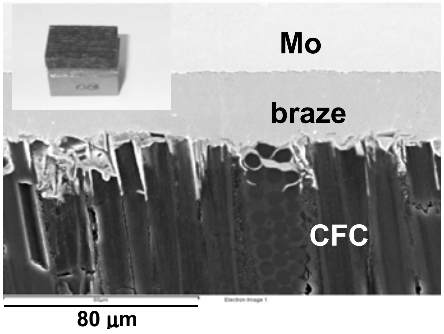

Fig. 5 – Mo-CFC brazed joint with 1 µm thick stoichiometric TiN coating, SEM x750.

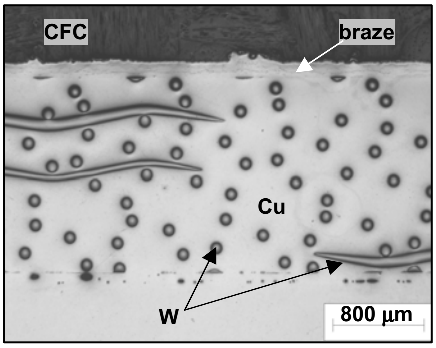

Fig. 6 –W reinforced Cu-matrix MMCs interlayer with 10 % volume fraction of W wires, optical x25

Other similar compounds have been produced using a 2 mm thick W-wire reinforced Cu-matrix MMC (W_f/Cu MMC) as low CTE interlayer. This concept is the evolution of the already tested one entailing the use of Mo plates as low CTE interlayers, with two advantages: no use of elements prone to high neutron activation and, more important, higher thermal conductivity (~ 300 W/mK). The Cu/W composite intermediate layer has been prepared by gas pressure infiltration technique. Nineteen W cloth layers have been arranged into a mould and infiltrated to obtain a two-dimensional structure. With a wire volume fraction of about 10 % a CTE of 5-7 $\cdot 10^{-6}$ K^{-1} in x and y direction and a thermal conductivity of 300 W/mK have been obtained. In the third direction, perpendicular to the layered planes of W cloths, CTE remains similar to pure copper (17-20 $\cdot$ 10^{-6} K^{-1}), but in this direction a high coefficient is acceptable because the interlayer is free to expand. Figure 6 shows a micrographic section of the MMC interlayer brazed to CFC protective material. Thermal shock tests on brazed CuCrZr/MMC/CFC samples produced satisfactory results.

Conclusions

The use of low or graded CTE interlayers as alternative to a pure copper compliant layer seems to be a viable route for the production through high temperature brazing of plasma facing components; complex and expensive machining steps, like CFC surface structuring by laser drilling, might be avoided; moreover, high conductivity and low CTE MMC interlayers can be considered as a significant step towards the development of new heat sink materials for nuclear fusion applications, potentially able to operate in the high temperature and irradiation conditions expected for future nuclear fusion power plants.

Results obtained so far are encouraging and active cooled mock-ups will be soon delivered for thermal fatigue tests in the high heat flux electron beam facility at Forschungszentrum Jülich, Germany, to validate the technology for fusion applications. In particular mock-ups with 3 flat tiles each are being prepared with different configurations: Mo interlayer with un-coated and TiNx-coated CFC, Mo interlayer with Ti-doped graphite and W_f/Cu MMC with CFC tiles.

Research work is in progress as regards monoblock configuration with both W_f/Cu MMC and graded Cu/W plasma sprayed and HIPped layers. Calculation activities on monoblock configuration and on MMCs interlayers are in progress. Collaboration with Demokritos, Athens, Greece, for the validation of the calculation models by means of residual stress measurements by neutron diffraction technique is in progress [5].

Acknowledgement

This work has been performed within the framework of the Integrated European Project „ExtreMat“ (contract NMP-CT-2004-500253) with financial support by the European Community. It only reflects the view of the authors and the European Community is not liable for any use of the information contained therein.

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