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CFC/Cu bond damage in actively cooled plasma facing components

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Abstract

Carbon fibre composite (CFC) armours have been successfully used for actively cooled plasma facing components (PFCs) of the Tore Supra (TS) tokamak. They were also selected for the divertor of the stellarator W7-X under construction and for the vertical target of the ITER divertor. In TS and W7-X a flat tile design for heat fluxes of 10 MW m^{-2} has been chosen. To predict the lifetime of such PFCs, it is necessary to analyse the damage mechanisms and to model the damage propagation when the component is exposed to thermal cycling loads. Work has been performed to identify a constitutive law for the CFC and parameters to model crack propagation from the edge singularity. The aim is to predict damage rates and to propose geometric or material improvements to increase the strength and the lifetime of the interfacial bond. For ITER a tube-in-tile concept (monoblock), designed to sustain heat fluxes up to 20 MW m^{-2} , has been developed. The optimization of the CFC/Cu bond, proposed for flat tiles, could be adopted for the monoblock concept.

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(Some figures in this article are in colour only in the electronic version.)

1. Introduction

The Tore Supra (TS) team has large experience in the fabrication of water-cooled high heat flux (HHF) components for the fusion tokamak [1]. After two generations of brazed carbon tiles on a metallic heat sink, a new bond was developed between carbon fibre composite (CFC) tiles and copper by using an active metal casting (AMC[®]) technique [2]. Developed by Plansee company (Austria), this process allowed the manufacture and the installation of a complete toroidal pump limiter (TPL) in the TS machine, composed of more than 12 000 CFC tiles, hence providing remarkable plasma performance [3]. This technique is now being applied for the fabrication of HHF elements for the W7-X stellarator [4] and is foreseen for the future ITER fusion machine [5].

However, reception tests and HHF fatigue tests of TPL prototype or series elements showed possible damage of the

tile bond [6]. Hence, studies were launched in order to better understand the manufacture residual stresses and to model the mechanisms of the tile bond degradation.

2. Rejection rate of elements at the reception tests for the TS TPL

The concept of the TPL elements and their process of fabrication have been described extensively [1, 6]. Soft copper is first cast onto the laser-structured tile surface to be bonded, in order to form a CFC/Cu assembly; then this assembly is electron beam welded onto a CuCrZr heat sink, in which water channels are drilled. The elementary component is armoured with 20 flat tiles (each about $23 \times 22 \text{ mm}$ and 6 mm thick), plus a cylindrical shaped tile at one end allowing a leading edge to be formed. The element is 495 mm long (figure 1). A few tiles (1–3%) were found to be faulty at the end of

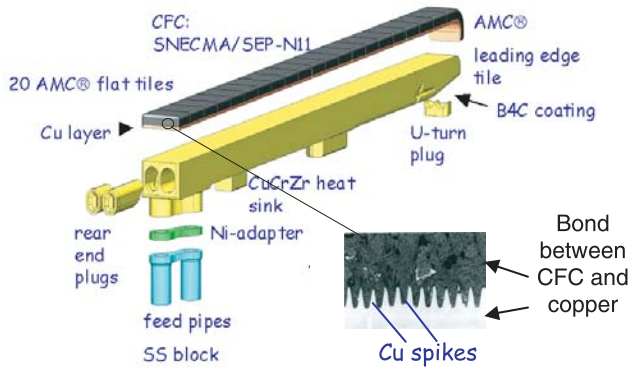


Figure 1. TPL finger manufacturing process.

fabrication, increasing up to 8% with the use of a new batch of CFC material (N11-98). The crack appears generally in the CFC just above the structured interface and could be detected both by infrared [7] and visual inspection. It is suggested that this mode 1 crack (opening) occurs due to residual stresses at the bond.

3. Degradation of the tile performance during HHF fatigue tests

The TPL elements were qualified at the stage of prototypes by HHF tests in the FE200 facility: two elements were fatigue tested under a cycling heat load of 10 MW m^{-2} up to 4500 cycles [8]. These tests were also done on series elements (figure 2): the test was interrupted after about 4000 cycles due to faulty tiles [9]. In figure 3 (cycling of series element S25) one can see that at the beginning of the cycling test the surface temperature of the tiles are in a wide range of $820\text{--}1020 \text{ }^\circ\text{C}$, which is attributed to resistive interfaces in some tile bonds. The tile temperature evolution can be compared with those of prototypes for which the data of two tiles are plotted in figure 3 (tile T6 and T10 of element PL2.4). It has to be noticed that the ‘hot’ tiles have a tendency to evolve during cycling. However, on the prototypes the tiles did not fail whereas the tile T8 of S25 failed after 1800 cycles and tile T9 after 3800 cycles (due to a sweeping by zone, tests were interrupted when one tile was faulty). The fracture mode is a partial opening of the bond at the CFC/Cu interface visible at the tile edge. With the help of a thermographic analysis, a tentative representation of the crack area versus fatigue heat loading was done during HHF tests on prototypes (figure 4). For W7-X HHF component prototypes, defects were observed as well even at the beginning of the fatigue cycling [10].

4. Characterization of the CFC material

The N11 material was used for TS whereas NB31 material is used for W7-X and retained for ITER. Both materials are fabricated by SPS (Bordeaux, France) and made from carbon fibres with a carbon matrix. N11 is a Novoltex[®] material: polyacrylonitril (PAN) fibres are weaved and then ‘needled’ in the third direction to make a 3D preform which is then carbonized, densified by chemical vapour infiltration (CVI)

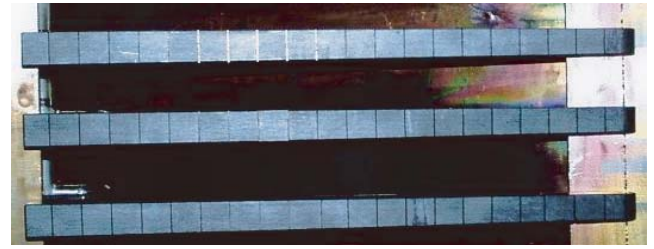


Figure 2. TPL elements installed in the HHF-EB facility chamber.

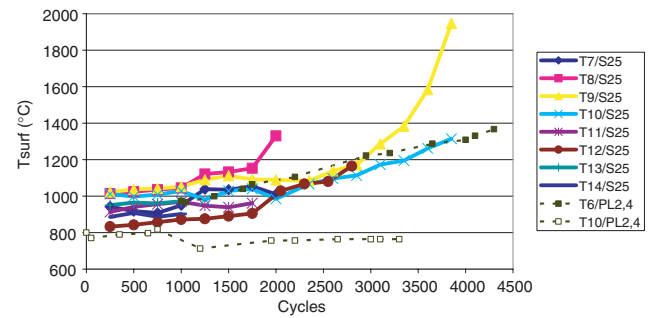


Figure 3. Surface temperature evolution of the tiles versus fatigue heat cycling at 10 MW m^{-2} for the element S25 fabricated with the grade N11-92.

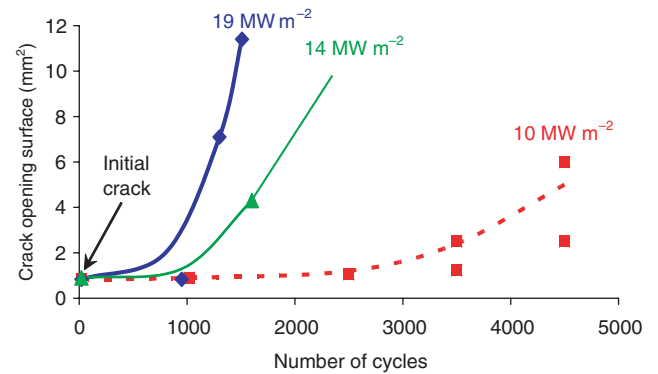


Figure 4. Tentative damage representation of CFC/Cu joints versus HHF fatigue cycling for prototype elements.

Table 1. Typical mechanical properties of the used N11 and NB31 CFC (tensile and shear strengths in MPa).

	T	S_{xx}	S_{yy}	S_{zz}	S_{xy}	S_{xz}	S_{yz}
N11	$20 \text{ }^\circ\text{C}$	50	50	19	24	18	18
N11	$1000 \text{ }^\circ\text{C}$	60	60	28			
NB31	$20 \text{ }^\circ\text{C}$	30	110	15	9–19	9	15

and graphitized [11]; this material is balanced (warp and weft directions are equivalent) and orthotropic (Z direction is weaker). NB31 is made of ‘ex-pitch’ fibres (warp direction) and ex-PAN fibres (weft direction) and is produced by applying an additional liquid impregnation. Tables 1 and 2 provide the main properties of these materials (in the axes they are used), which maintain good behaviour at high temperature.

These CFCs exhibit a damageable behaviour resulting from the regularly distributed micro-cracks that develop inside the material under loading. The constitutive law for such materials is based on a macroscopic approach with scalar

Table 2. Typical thermal properties of the used N11 and NB31 CFC (λ : $\text{W m}^{-1} \text{K}^{-1}$; C_p : $\text{J Kg}^{-1} \text{K}^{-1}$; ρ : kg m^{-3}).

	T	λ_{xx}	λ_{yy}	λ_{zz}	C_p	ρ
N11	20 °C	220	220	166	670	1950
N11	1000 °C	90	90	70	1750	1920
NB31	20 °C	100	250	80	780	1900
NB31	800 °C	50	125	40	1820	

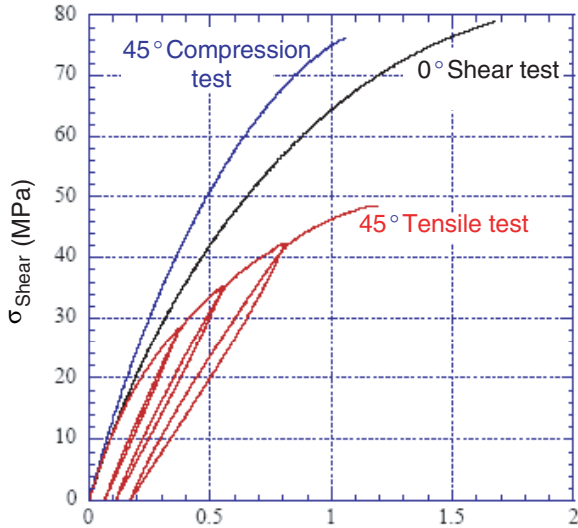


Figure 5. Typical shear behaviour of a high strength Novoltex CFC material in xy plane.

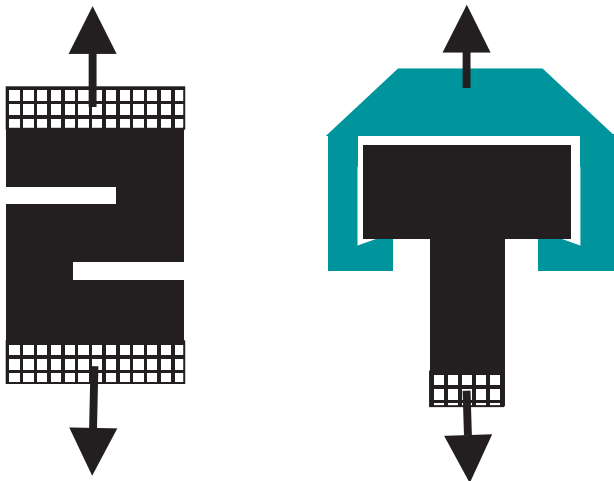


Figure 6. Typical S and T samples allowing a complex strain field to be monitored during a tensile test.

damage variables since micro cracking does not affect the initial orthotropy of the material [12]. As N11 and NB31 are only available in small sized blocks, it is rather difficult to machine adequate samples for tensile, compression and shear tests. Therefore, it was proposed to develop first a complete model on a similar high strength Novoltex CFC material available in large plates (as shown in figure 5) and then to extrapolate to N11 or NB31 with the help of T or S shaped samples (figure 6).

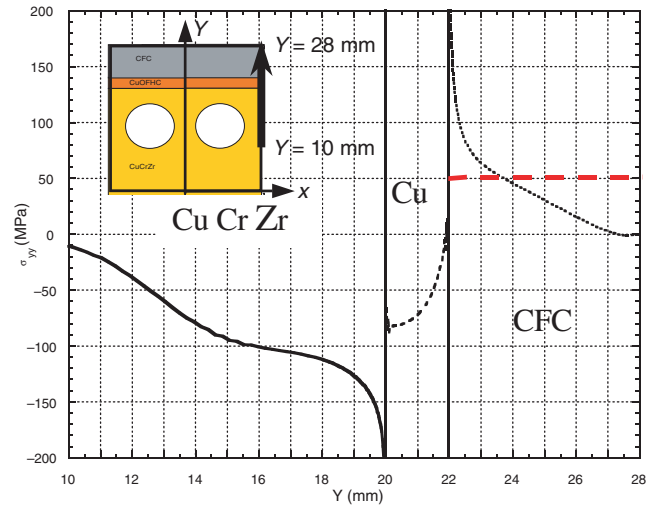


Figure 7. FE calculation of the σ_{yy} stress along the edge of the element (compared with the tensile strength of 50 MPa for N11 in this direction).

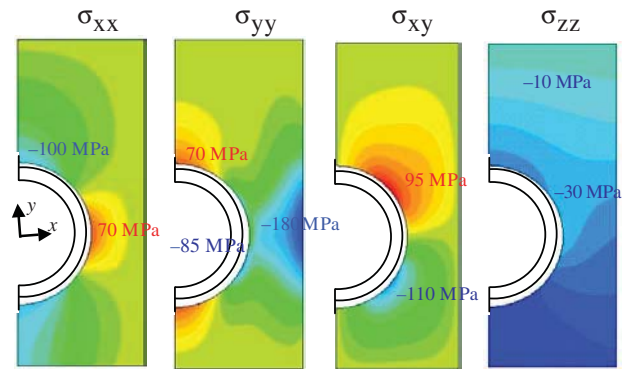


Figure 8. FE calculation of the residual stress field for a NB31 monoblock.

5. Residual stresses

For the flat tile design the calculated residual stresses are very high at the singularity (CFC/Cu interface) on the edge of the tile. In figure 7, a very localized tensile stress is visible near the tile edge and increases the risk of damage initiation within the composite (stress free temperature is taken at 450 °C). In the case of the NB31 monoblock design the residual stresses are even more severe increasing the risk of cracks. The calculation shows important plastic deformation around 2% in the copper layer and high σ_{xx} and σ_{xy} stresses compared with the tensile strengths (figure 8). One can assume a possible crack initiation due to residual stresses and crack propagation under cycling during operation, which induces a lower stress range.

6. Crack initiation and propagation

Two modes of fracture of the CFC/Cu bond were described in [6, 8, 13]. Observations performed on cycled components reveal de-cohesion (mode I) or shear fracture (mode II).

The stress concentration at the edge of the CFC/Cu interface can be written in (r, θ) coordinates as $\sigma_{ij}(r, \theta) = k, r^{\delta-1} \cdot S_{ij}(\theta) + \dots$. The generalized intensity factor k

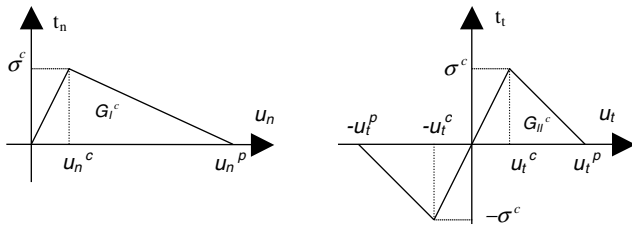


Figure 9. Damage law between two face-to-face nodes of the CZM (t, u being force and displacement, n for normal and t for tangential, G is the triangle area).

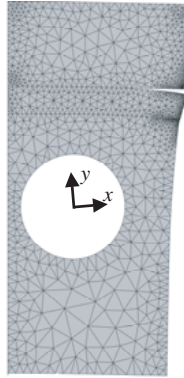


Figure 10. Example of crack propagation calculation under heat load after a few cycles using cohesive zone modelling.

depends on the loading and on the global geometry, the exponent δ depends only on the local geometry (i.e., the angles made by the two materials) and $S_{ij}(\theta)$ is a shape factor. A fracture criterion, which combines a strength and a toughness condition [14], enables prediction of the initiation of interfacial failure with the condition $k = (G^c/A)^{1-\delta} \cdot (\sigma^c - \sigma^{\text{int}})^{2\delta-1}$ where σ^c is the interfacial tensile strength and G^c the interfacial toughness, A is a geometrical parameter and σ^{int} depends on the residual stress and the plastic strain. This asymptotic approach shows that interfacial cracking can be initiated by residual stresses if the interfacial properties are too poor.

Numerical simulations were also performed to analyse the initiation and the propagation of the interface failure using the Alfano–Crisfield cohesive zone model (CZM) [15, 16]. This bond-damaging model (cf figure 9) uses three parameters: σ^c the tensile strength of the bond, G_I^c and G_{II}^c the toughness of the bond in mode 1 (opening) and 2 (shear). Using a set of parameters ($\sigma^c = 60 \text{ MPa}$, $G_I^c = G_{II}^c = 100 \text{ J m}^{-2}$) the calculations have shown crack propagation under heat load of 10 MW m^{-2} (figure 10). For those parameters damage is governed by the low value of G^c . That emphasizes the need for bond characterization, which was investigated in [13] and still is a matter of ongoing research [17]. Using previous tensile and shear bond test results [6, 13] to identify the parameters, the following set of parameters was identified at room temperature: $\sigma^c = 43 \text{ MPa}$, $G_I^c = 1900 \text{ J m}^{-2}$, $G_{II}^c = 3000 \text{ J m}^{-2}$. In this case one can suppose that the bond damage is governed by the low value of σ^c . Characterization in [13] shows clearly very scattered results, which can explain various tile bond qualities as depicted in figure 4.

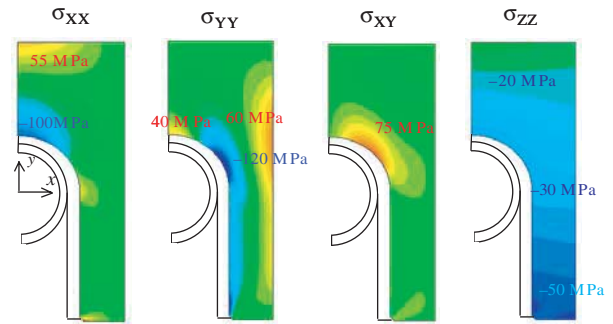


Figure 11. Calculated residual stress field showing decreased stresses due to geometry change.

7. Possible improvements and conclusion

At this level of the study various kinds of improvements can be suggested. The first one is to change the local geometry of the CFC/Cu bond, for example a filler at the edge leading to a CFC/Cu angle of 120 or 135°C (gain of about 50% on k [13]). This can be done on flat tiles but also on the longitudinal edges of the monoblocks. The second one is to change the global geometry when it is possible; for example the change of the monoblock tile in a U shaped tile to a U shaped Cu compliant layer leads to a decrease of the residual stresses, as shown in figure 11 (however still insufficient). The third one is to change the CFC to a more adequate one (compliant to the thermal expansion) and/or the strength (σ^c , G_I^c , G_{II}^c) of the bond (change in the laser structuring, carbide formation etc...).

To study the bond damage of a CFC tile or monoblock, the constitutive behaviour law for the CFC and strength parameters of the bond are needed. A lot of tests are still necessary to achieve this task. Nevertheless it has been shown that the bond damage can be calculated using a CZM model. This opens the way to an optimization of the design concepts (local and global geometry, materials properties...).

Acknowledgments

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