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Damage of actively cooled plasma facing components of magnetic confinement controlled fusion machines

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ABSTRACT

Plasma facing components (PFCs) of magnetic fusion machines have high manufactured residual stresses and have to withstand important stress ranges during operation. These actively cooled PFCs have a carbon fibre composite (CFC) armour and a copper alloy heat sink. Cracks mainly appear in the CFC near the composite/copper interface. In order to analyse damage mechanisms, it is important to well simulate the damage mechanisms both of the CFC and the CFC/Cu interface. This study focuses on the mechanical behaviour of the N11 material for which the scalar ONERA damage model was used. The damage parameters of this model were identified by similarity to a neighbour material, which was extensively analysed, according to the few characterization test results available for the N11. The finite elements calculations predict a high level of damage of the CFC at the interface zone explaining the encountered difficulties in the PFCs fabrication. These results suggest that the damage state of the CFC cells is correlated with a conductivity decrease to explain the temperature increase of the armour surface under fatigue heat load.

1. Introduction

In magnetic confinement controlled fusion machines, such as Tore Supra and International Thermonuclear Experimental Reactor (ITER) (Cadarache, France), plasma facing components (PFCs) which are in contact with the plasma have to withstand heat fluxes of about 10 MW m^{-2} at steady state for Tore Supra [1] and up to 20 MW m^{-2} during 20 s for ITER [2]. They are armoured with carbon fibre composite (CFC) tiles bonded to a copper alloy heat sink which is actively cooled to operate at steady state. During manufacturing and under operating conditions, PFCs are submitted to high stress ranges due to the thermal expansion mismatch existing between the CFC and the copper alloy, which can lead to the initiation of defects at the composite/copper interface. To predict damage in these actively cooled PFCs, a modelling approach is being conducted to take into account the CFC behaviour.

2. High heat flux plasma facing components in Tore Supra and ITER

In Tore Supra, a flat tile concept (Fig. 1(a)) has been retained whereas a 'monoblock' (tube-in-tile) concept (Fig. 1(b)) has been adopted for ITER. The CFC used for flat tiles is N11 [3] and the one foreseen for monoblocks is NB31 [4] or potentially NB41 [5]. The joining process combines a laser machining of the CFC surface with an active metal casting (AMC®) process. Thanks to copper spikes that infiltrate the composite, the bonding is mechanically improved. Under thermal loading, the interfacial damage that develops includes debonding or fracture of the copper spikes (Fig. 2).

For flat tiles, cracks initiate generally from the free edge since there is a stress singularity in this part of the assembly [6]. The monoblock geometry induces higher residual manufacturing stresses but lower operation stress range because the composite/copper joint remains at lower temperatures under heat load [2]. Indeed, the greatest absolute value of shear stresses after manufacturing for the flat tile is around 40 MPa while it is around 95–110 MPa for the monoblock (Fig. 3) (shear strength being around 15–20 MPa). Regarding σ_{yy} stresses, the greatest tensile value is very high (>100 MPa) at the singularity for the flat tile (strength around 50 MPa for the N11) whereas it is 70 MPa for the monoblock (strength around 120 MPa for the NB31). Calculations were done with the following hypothesis: CFC is orthotropic elastic, copper is perfect plastic and copper chromium zirconium (CuCrZr) is elastic plastic with kinematic hardening. Two dimensional finite element simulations were performed with Cast3M under plane strain conditions.

3. Damage modelling of CFC

The CFC used has a non-linear and anisotropic mechanical behaviour. It is evidenced during mechanical tests by the

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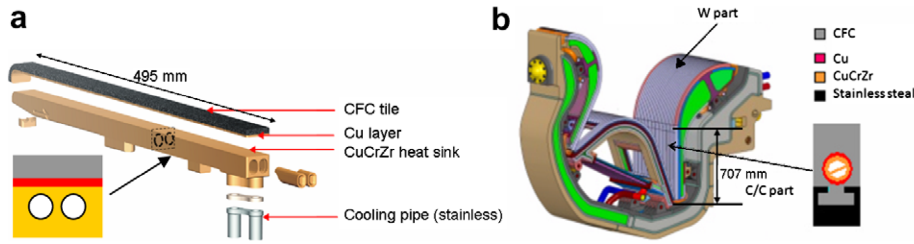

Fig. 1. (a) Flat tile concept and, (b) monoblock concept.

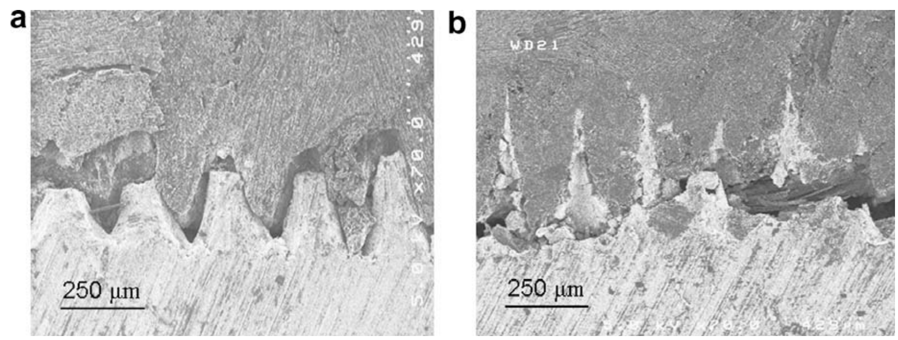

Fig. 2. Damage of the composite/copper interface within a thermally cycled PFC: (a) debonding of the copper spikes, (b) fractured copper spikes.

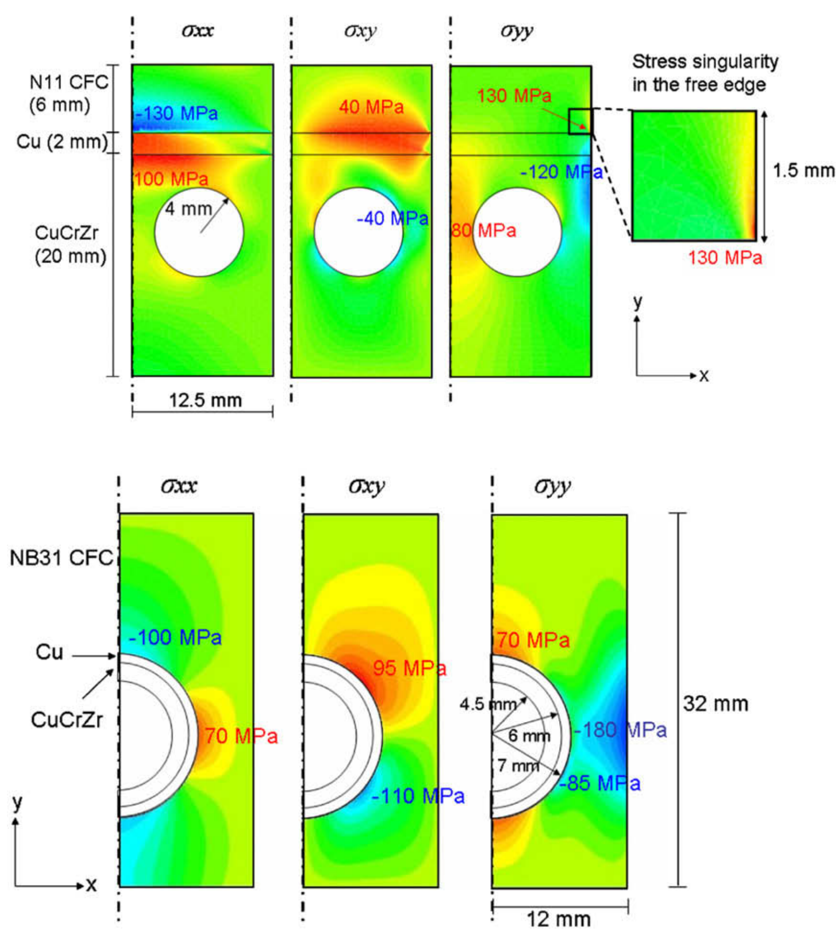

Fig. 3. Manufacture residual stresses in the flat tile and the monoblock concept.

progressive decrease of the moduli for unloading/reloading cycles and residual strains upon unloading. The model used to describe the mechanical behaviour of CFC is the ONERA damage model (ODM) [7]. This macroscopic model was developed within the general framework of continuum thermodynamics with internal variables and describes the degradation mechanisms. It takes into account the initial and damage-induced anisotropy, the damage effects on the elastic behaviour, the unilateral character of damage and the residual strains due to the damage. Previous work has shown that the direction of microcracks does not depend on the orientation of applied loading in CFC. In this case, three scalar damage variables (d_1 and d_2 for the in-plane behaviour and d_3 for the out-of-plane behaviour) are sufficient to describe the effect of damage. The constitutive law is written:

$$\underline{\sigma} = \underline{\underline{C^{eff}}} : \underline{\varepsilon^e} = \left(\underline{\underline{S^0}} + \sum_{i=1}^{3} \eta_i d_i \underline{\underline{H_i^0}} \right)^{-1} : \underline{\varepsilon^e}$$

where $\underline{\sigma}$ is the stress tensor, $\underline{\varepsilon^e}$ is the elastic strain tensor, $\underline{\underline{S^0}}$ is the initial compliance tensor and $\underline{\underline{H_i^0}}$ is a damage effect tensor. The fact that the damage is not active under compression (the microcracks are closed) is taken into account by the deactivation index η_i.

The evolution of damage is analysed with the help of the following definition used for each damage variable:

$$d_i = d_i^c \left(1 - \exp - \left(\frac{\sqrt{y_i} - \sqrt{y_i^0}}{\sqrt{y_i^c}} \right)^{p_i} \right)$$

which introduces the thermodynamics forces y_i associated with each variable and depending on the elastic strains. In order to reproduce the phenomenon of microcracks saturation, an exponential form is used and the material parameters $(d_i^c, y_i^0, y_i^c, p_i)$ must be identified.

The model involves many parameters but the identification of the in-plane behaviour only requires three mechanical tests (0° and 90° on-axis, 45° off axis or a shear test). However, only monotonic tests were available for the N11 material, which do not allow the evaluation of residual strains after unloading. Consequently, a second material, here called HL1, has been characterised. This material is not optimised for nuclear applications but belongs to the same family (i.e. the fibrous perform is similar but the fibres and the high temperature treatment are different). Since the mechanisms involved during damage are identical for both materials, it was then assumed that the damage model identified for the HL1 material can also be used for the N11 material (after a scaling based on initial moduli). The mechanical tests performed on HL1 are the following:

(1) six cycled tensile tests (2 at 0° on-axis, 2 at 45° off axis, 2 at 22.5° off axis)
(2) four shear tests at 0° on-axis
(3) two alternate tensile–compression tests at 0° on-axis
(4) one alternate tensile–compression test at 45° off axis

Mechanical responses of HL1 samples confirmed the damaging non-linear elastic behaviour with residual strains after unloading.

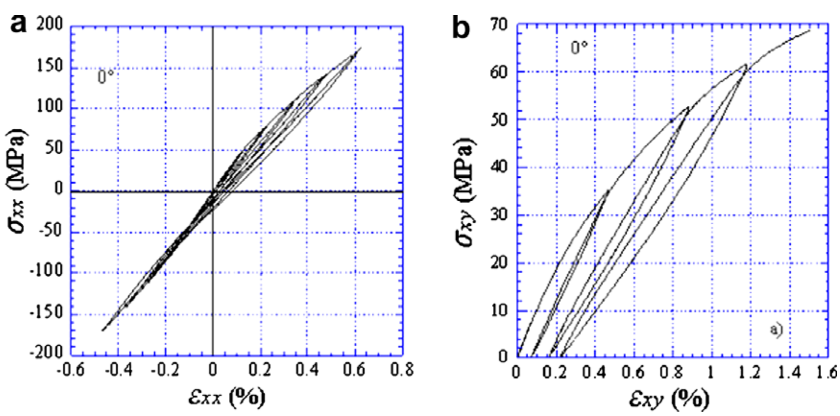

Fig. 4. HL1 material behaviour curves during (a) an alternate tensile-compression test in-axis and, (b) a cycled shear test in-axis.

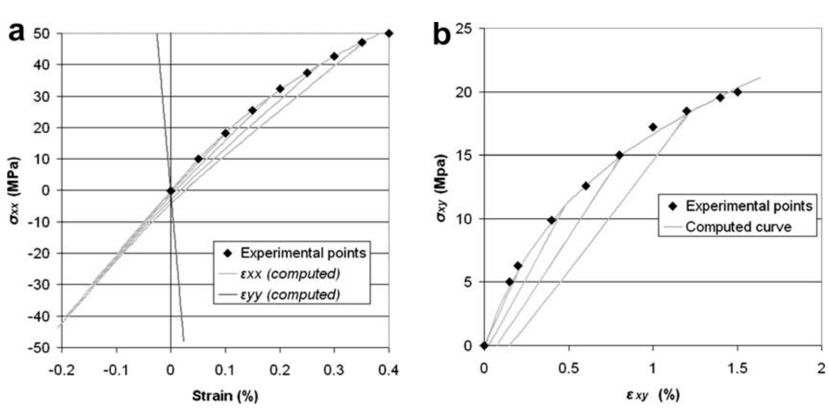

Fig. 5. Experimental points and computed model for: (a) the in-axis tensile behaviour and, (b) the in-axis shear behaviour of N11 material.

These observations were found both in tensile and compression tests at 0° on-axis (Fig. 4), and also in tensile test at 45° off axis [8].

An identification of the ODM parameters was made beforehand for HL1. The large quantity of experimental data from the tests listed earlier had allowed an accurate evaluation of the damage parameters of the model. As already mentioned, the mechanical behaviour of N11 was identified from monotonic on-axis tensile and shear tests [9]. HL1 experimental results were therefore rescaled to fit the mechanical behaviour of N11. Coupling and damage effect tensor coefficients were also assumed to be the same. Hence, the influence of the loading angle upon the propagation of damage is assumed identical for these two materials. Each set of parameters is not unique, but a good level of confidence can be expected in the set of parameters selected, due to the large number of mechanical responses which were used for the identification.

An in-axis alternated tension-compression test and a cycled in-axis shear test on N11 samples are simulated. The computed curves (Fig. 5) reproduce the behaviour of the CFC with the non-linearity of the behaviour, the modulus decrease and the presence of residual strains. Consequently, ODM appears to be a good model to describe the mechanical behaviour of N11.

4. Simulation of the manufacturing cycle with ODM

The ONERA damage model is introduced in the simulation of the manufacturing cycle of the N11 flat tile. The repartition of stresses in the flat tile is nearly the same between the simulation with this model and the simulation with the elastic model. As expected, the stress singularity at the free edge appears to be less severe with ODM than with an elastic model: 70 MPa instead of 130 MPa. Shear stresses remains at the same values.

Damage variables d_i indicate the CFC is mainly damaged near the interface (Fig. 6). The damage variables are nearly the same in both direction x and y. The greatest value is 1.8. The damage zone corresponds to the maximum shear zone.

This observation is also confirmed by the manufacturing cycle simulation of a monoblock (Fig. 7). This simulation was done using

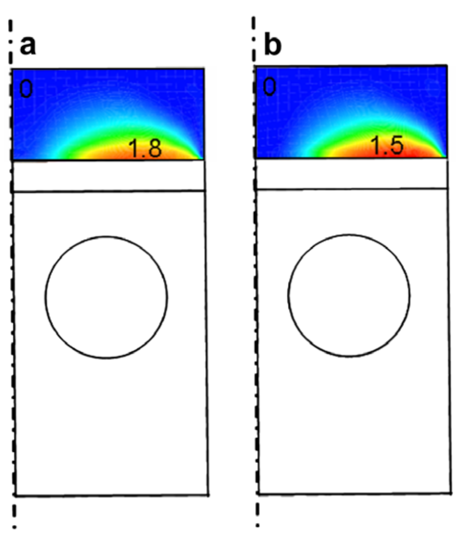

Fig. 6. Damage variables in CFC part of flat tile: (a) d_1 (x direction) and, (b) d_2 (y direction).

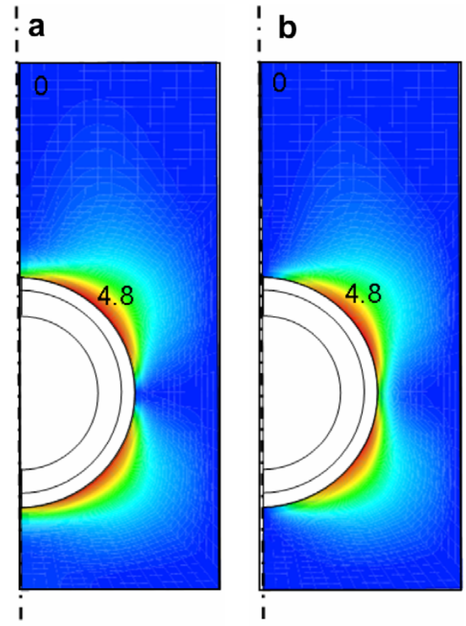

Fig. 7. Damage variables in CFC part of monoblock in: (a) x direction and, (b) y direction.

N11 properties for the CFC part. Values of damage variables are higher for monoblocks than values for flat tiles.

5. Conclusion

Defects in PFCs are located near the composite/copper interface in the CFC. The understanding of the damage development in these parts of the PFC is important to improve the life time of PFCs. In order to model the damage in the CFC, experimental results on HL1 were rescaled to fit the mechanical behaviour of N11 and the parameters of the ONERA damage model were identified. First simulations of the manufacturing of the flat tile and of the monoblock with ODM indicate that the damage of CFC takes place in the maximum shear zone. This model will be applied to the NB31 and the NB41 composite when mechanical tests will be performed and the same simulation will be done. Further studies will include a cohesive zone model [10] to better simulate the CFC/Cu interface, but the first results suggest that the CFC conductivity could be reduced under operation cycling as a consequence of damage development.

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