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Damage modelling in plasma facing components

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ABSTRACT

The plasma facing components of controlled fusion devices are submitted to high heat fluxes in operating conditions (from 10 to 20 MW/m^2). These components are made of a carbon/carbon composite tile bonded to a copper alloy heat sink. Due to the thermal expansion mismatch between the composite and the copper alloy, significant stresses may develop during fabrication and under heat load inducing damage in the composite material as well as at the copper/composite interface. The present study describes a modelling approach aimed at predicting damage development in plasma facing components. For this purpose, damage laws related to the non-linear behaviour of both the composite material and the copper/composite joint have been identified. These constitutive laws were then introduced in a numerical model representative of a plasma facing component. Results show the development of damage within the assembly submitted to a heat load.

1. Introduction

The function of plasma facing components (PFC) in controlled fusion device is to remove a high heat flux between 10 and 20 MW/m^2. Carbon/carbon composites (C/C) have been selected as plasma facing materials due to their high temperature resistance and good thermal conductivity. Actual design of PFC includes the use of C/C tiles bonded to a copper heat sink that is actively cooled to maintain a reasonable surface temperature [1]. Nevertheless, the wide mismatch in thermo-mechanical properties between C/C and copper alloy induces high stresses under operating conditions. Significant damage may develop within the composite and failure of the joint may occur. Design tools are thus required in order to analyse the initiation and the propagation of damage in thermally loaded PFC.

This study gives a modelling approach aimed at predicting damage in PFC. For this purpose, use is made of constitutive laws to model the non-linear mechanical behaviour of both the C/C material and the Cu–C/C joint. A constitutive law able to handle the C/C behaviour under complex multiaxial loadings established within a classical thermodynamical framework and using damage variables, was then identified. Tensile and shear tests results, performed on Cu–C/C samples, were used in order to identify an interfacial law representative of the damageable behaviour of the joint. These constitutive laws were introduced in a numerical model representative of the PFC developed for Tore Supra. As depicted by Fig. 1, the geometry of this PFC includes a C/C flat tile (N11, Snecma Propulsion Solide) bonded to the copper heat sink with the help of the technology developed by PLANSEE Company (Reutte, Austria).

2. Modelling the damageable behaviour of the C/C

Carbon fibre reinforced carbon composites are high temperature structural materials with excellent thermo-mechanical properties. Snecma Propulsion Solide (Le Haillan, France) has developed tri-directional C/C composites in order to improve their delamination resistance [2]. A needling technology allows to link the bi-dimensional woven fabrics in the out of plane direction and the resulting tri-dimensional preform is well suited to the chemical vapour infiltration of the matrix. This class of materials exhibits a non-linear and anisotropic mechanical behaviour which is evidenced during mechanical tests by (i) the progressive decrease of the moduli for unloading/reloading cycles, (ii) residual strains upon unloading (Fig. 2). Microstructural analyses have demonstrated that various distributed families of micro cracks are progressively developed within the material during loading [3].

In order to model the mechanical behaviour of C/C, phenomenological approaches based on damage mechanics have proven to be efficient [3]. The model used in this study is the damage model ODM developed by ONERA (Chatillon, France) [4] and implemented in the finite element code ZeBuLon [5]. Three scalar variables d_i (with $d_i = 0$ for the undamaged material and d_i increasing for the damaged material) represent the damage in the local orthotropy axes of the composite (and this symmetry is maintained through the damage development) with

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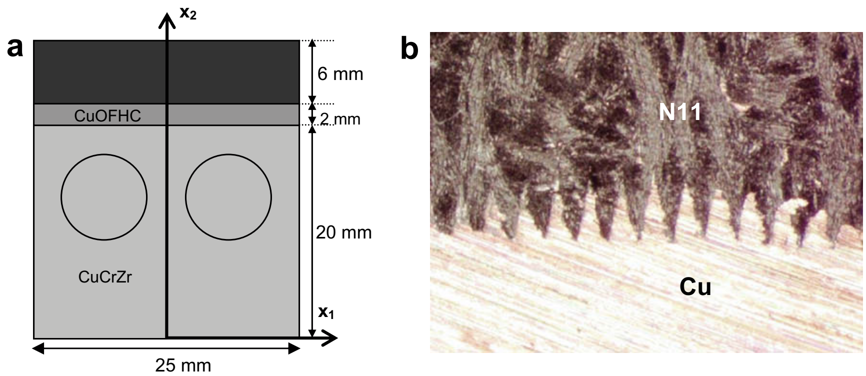

Fig. 1. Geometry of a PFC: (a) schematic representation of the component developed for Tore Supra, (b) optical micrograph of the Cu–C/C interfacial zone.

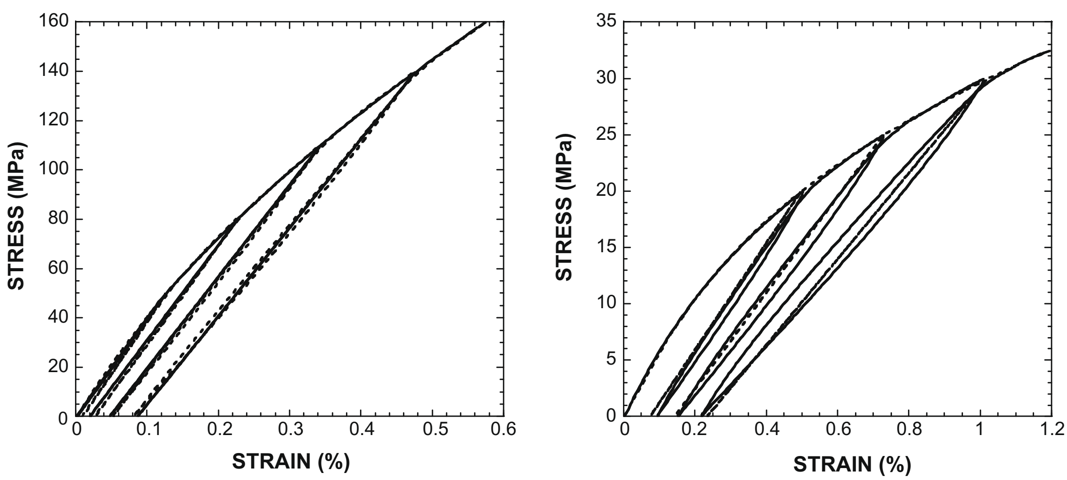

Fig. 2. Identification of the mechanical behaviour of a 3D C/C with ODM (the response of the damage model is in dotted line): (a) loading–unloading cycles in on axis tension and (b) loading–unloading cycles in off axis tension (45°).

$$\sigma = \mathbf{C}^{eff} : \varepsilon^e = \left(\mathbf{S}^0 + \sum_i \eta_i d_i \mathbf{H}_i^0\right)^{-1} : \varepsilon^e, \quad (1)$$

where σ is the stress tensor, ε^e is the elastic stress tensor, $\mathbf{S}^0$ is the initial compliance tensor, $\mathbf{H}_i^0$ is a damage effect tensor. The damage is not active under compression (the microcracks are closed) as taken into account by the deactivation index η_i. The identification of the coefficients of this model only requires two tension tests at 0° on axis and 45° off axis from the fibre direction. Fig. 2 demonstrates good agreement between the model and the experiment in terms of non-linearity, modulus decrease and residual strains. This identification was performed for a C/C similar to N11. The model was then re-scaled (using initial moduli) to fit the mechanical behaviour of N11.

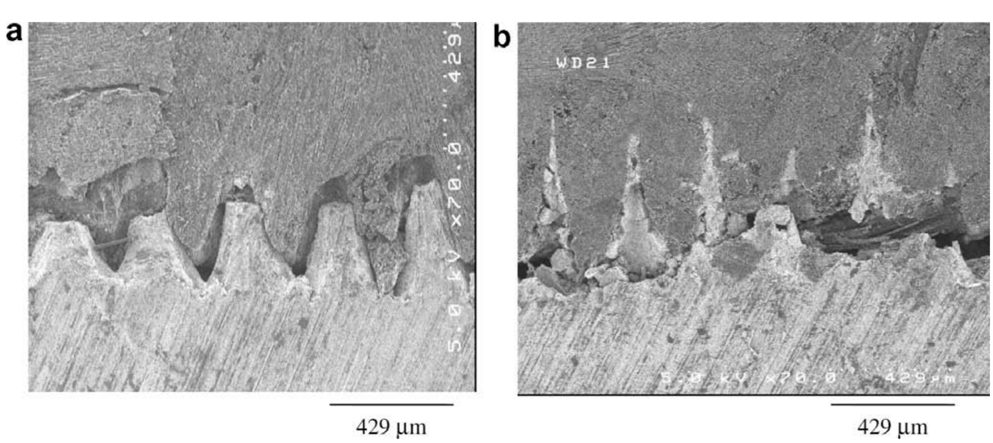

Fig. 3. Damage of the Cu–C/C interfacial zone within a thermally cycled plasma facing component, (a) debonding of the copper spikes and (b) fractured copper spikes.

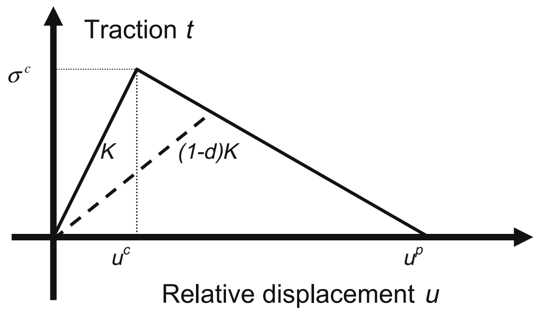

Fig. 4. The interfacial damage law.

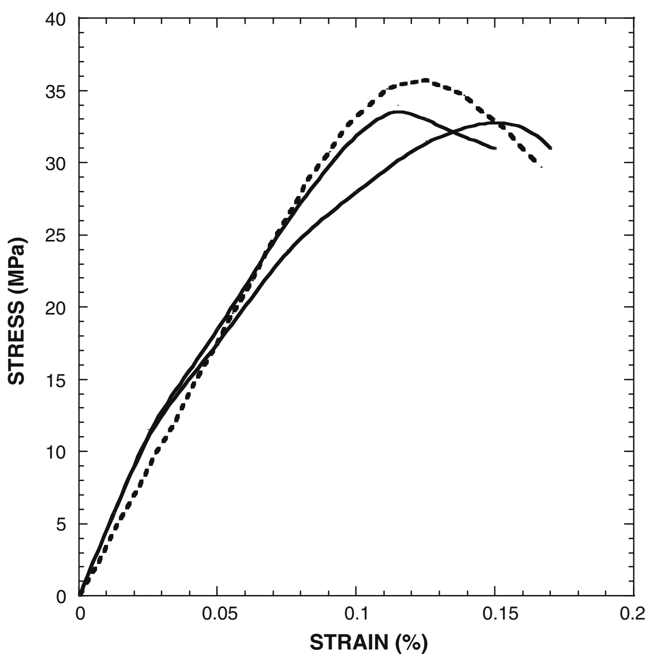

Fig. 5. Tensile behaviour of two Cu/N11 samples (solid line) compared to the model response (dotted line).

3. Modelling the damageable behaviour of the Cu–C/C joint

A reliable joint is required between the C/C tile and the copper alloy. The AMC process combines a laser machining of the C/C surface with an active metal casting process [1]. The formation of copper spikes which infiltrate the composite enhances mechanical bonding. However, microstructural observations of PFC submitted to cyclic thermal loading have revealed the development of interfacial damage which includes debonding and fracture of the copper spikes (Fig. 3). An interface law derived from a damage mechanics theory is used to model this damageable behaviour [6]. The constitutive behaviour is defined with the help of a relation between the relative opening displacement u_i and a corresponding traction t_i (with i being either the local normal (n) or tangential (t) direction in the interfacial plane). The interface traction/displacement law relationship is based on a simple bilinear law (Fig. 4). The traction reaches a peak value σ^c when a critical relative displacement is attained then starts to diminish with the gradual increase of the opening displacement and the interfacial damage d. This will result in the creation of two traction free surfaces corresponding to the nucleation of a crack or the extension of an existing one. This model is related to linear elastic fracture mechanic as the area of the displacement curve is equated to the interfacial toughness G^c. The threshold value σ^c of the traction components must be determined to predict the initiation of the fracture bond and a high initial stiffness K is assumed to ensure a valuable pre-crack behaviour. This interfacial damage law is implemented in the finite element code ZeBuLon with the help of four node element with zero initial thickness.

In order to identify the interfacial damage law, simulation of traction and shear tests performed on Cu–N11 samples were compared to the experimental results [1]. Fig. 5 depicts this comparison for traction tests at room temperature. This procedure leads to the following set of parameters (at room temperature): σ^c = 43 MPa, $G_{\mathrm{I}}^c = 1900\,\mathrm{Jm}^{-2}, G_{\mathrm{II}}^c = 3000\,\mathrm{Jm}^{-2}$. It is worthy of note that $G_{\mathrm{I}}^c < G_{\mathrm{II}}^c$ which illustrates the interest of the presence of the copper spikes to increase the toughness in the sliding mode.

4. Numerical modelling of the PFC under heat flux

The PFC developed for Tore Supra was modelled with the help of bi-dimensional finite element computations. The first step of

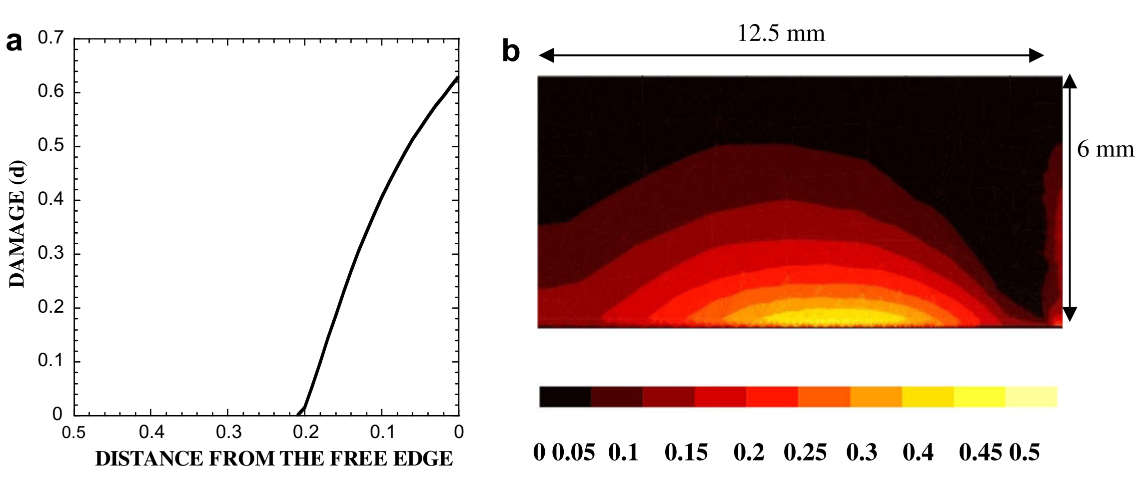

Fig. 6. Numerical modelling of the PFC under heat load: (a) distribution of the interfacial damage d along the interface versus the distance from the free edge and (b) damage indicator d_2 (direction x_2) within the half part of the C/C tile.

the numerical procedure evaluates the temperature field. Residual stresses which result from the processing phase are taken into account by simulating a uniform cooling from 470 °C to room temperature. Then, a constant heat load (10 MW/m^2) is applied on the C/C top surface while a heat transfer is imposed on the internal surface of the cooling hole. Results indicate that the surface temperature of the C/C tile reaches 1000 °C while the temperature at the Cu–C/C interface is about 450 °C. The second step requires the previous temperature field to perform a stress analysis in generalised plain strain. The C/C behaviour law is the non-linear damage model described in Section 2 and interface elements with the appropriate parameters (Section 3) are introduced at the Cu–C/C interface. Elastoplastic behaviour of the copper material is described with a linear cinematic hardening.

The results show that damage develops in the composite near the interface (Fig. 6b) and along a small interfacial distance (Fig. 6a). This is consistent with the experimental observations which have shown that the fracture initiation mode of the C/C tiles is the opening of the Cu–C/C interface from the free edge [1].

5. Conclusion

The constitutive behaviours of the C/C material and the Cu–C/C interface were modelled within the frame of damage mechanics. Using these non-linear models, a thermally loaded PFC was simulated with the help of bi-dimensional finite element computations. The results show the development of limited damage within the composite and along the interface. It is expected that this approach provides more realistic results when compared to a classical linear elastic approach. However, it must be pointed out that dedicated experimental procedures are required in order to identify the coefficients of the constitutive laws. Further modelling efforts are necessary to evaluate the accumulation of damage under repeated heat loads and to apply this approach to various PFC with different geometries.

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