Damage in Carbon Fibre Composite Armours of Actively Cooled Plasma Facing Components

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TORE SUPRA

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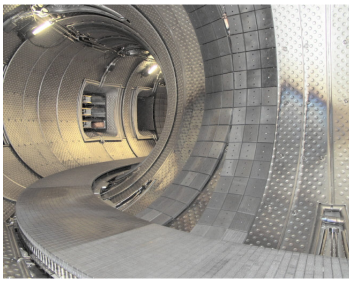
INTRODUCTION: The understanding of damage mechanisms of carbon fibre composite (CFC) armours for actively cooled plasma facing components (PFC's) is an important challenge for controlled fusion devices. A reliable mechanical and thermal bond must be achieved despite the thermal expansion mismatch between the composite tile and the metallic heat sink.

Flat tile water cooled concepts, designed for heat flux up to 10 MW/m^2, were studied, developed, and finally successfully tested in the Tore Supra (TS) tokamak. The bond is obtained thanks to a structuring of the CFC surface and a casting of copper, which allows a gradient layer to be built. During the validation phase, prototypes were fatigue tested in a high heat flux (HHF) facility and observations show some initiation of damage within the CFC in the vicinity of the bond. For the ITER machine a different tube-in-tile concept was developed. This new component was designed to sustain a heat flux of 20 MW/m^2.

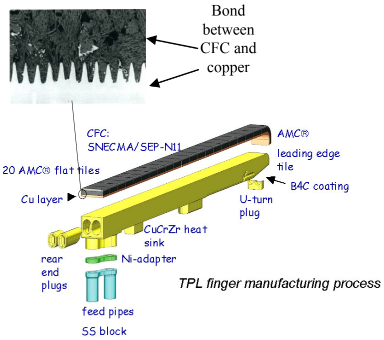
In order to predict the lifetime of a PFC, it is necessary to analyse the damage mechanisms and to model the damage propagation when the component is submitted to cyclic operative conditions (taking into account the stress field existing in the component after manufacture).

High heat flux limiter in Tore Supra

The Active Metal Casting (AMC®) technique : laser treatment and Ti deposition



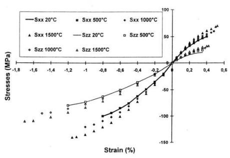
The installation of this component in 2002 allowed a 6 minute plasma to be performed (1 GJ)

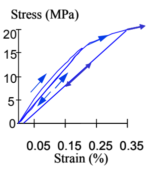


TPL finger manufacturing process

Characterisation of the carbon fibre composite (CFC material)

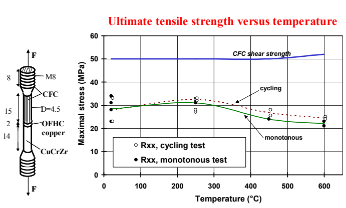
Example en N11 material

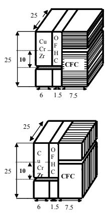


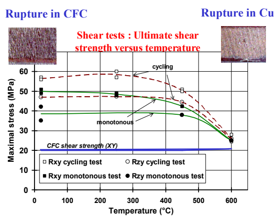


- -Temperature dependent
- -Anisotropic
- -Low strength: Sxx 50 MPa, Szz 20 MPa
  Sxy 20 MPa, Sxz 15 MPa
- -Damaging behaviour (redistribution of the stresses from the matrix to the fibres)
- -Constitutive law for such a material needs to evaluate 22 values and 4 functions (tests in the axes but also at 22.5 and 45°)
- -Rupture, fibre direction: critical stress
  shear direction: critical damaging
  compression: critical elastic energy

Characterisation of the AMC bond

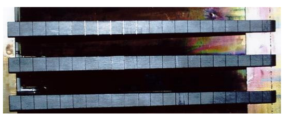


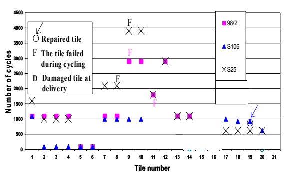


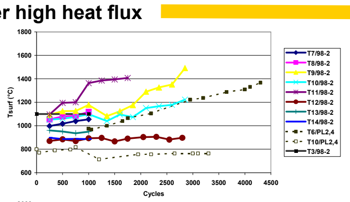


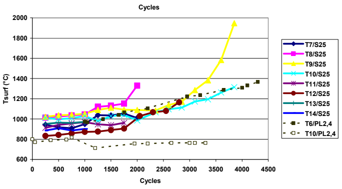
The tensile strenght of the bond is lower than the CFC one whereas the shear strenght is higher than the CFC one

Thermal fatigue tests of the bond under high heat flux









Damage mechanism study

At the macroscopic scale, the composite is mainly submitted to compression, as a result of the residual stress field that is induced by the fabrication phase (Figure a). However, a very localised traction singularity is observed near the tile edge (Figure b) and could lead to crack initiation in the composite.

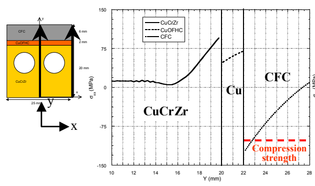


Fig. a: σ_{xx} at middle

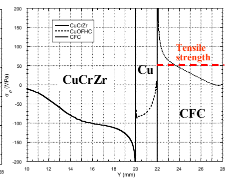


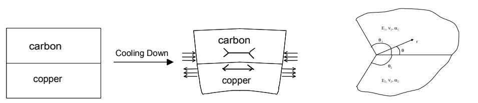
Fig. b: σ_{yy} at tile edge

Generalized Plane Strain calculations:

- Temperature dependent materials
- Elasto-plastic behaviour of CuCrZr and Cu
- Orthotropic characteristics of CFC
- Non linear behaviour of CFC
- Singularity at the tile edge

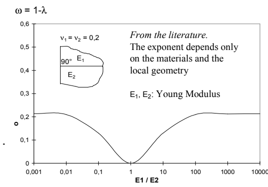
Fabrication phase: cooling down from 470°C down to 20°C

Crack initiation



The generalized intensity factor **k** depends on the loading and on the global geometry, whereas **λ** depends only on local geometry (i.e. the angles made by the two materials)

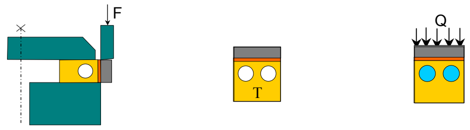
$$\sigma_{ij}(r,\theta) = k.r^{\lambda-1}.s_{ij}(\theta) + \sigma_0 \ldots$$



The fracture analysis is governed by plastic (copper) and thermal stresses due to the presence of two materials, calculations are in progress.

The failure criterion writes: $k > k_c$ where the critical value k_c of k depends both on the tensile strength σ_c (stress criterion) and on the toughness G_c (energy criterion, "Griffith") of the bonding.

Possible qualification tests of crack propagation model

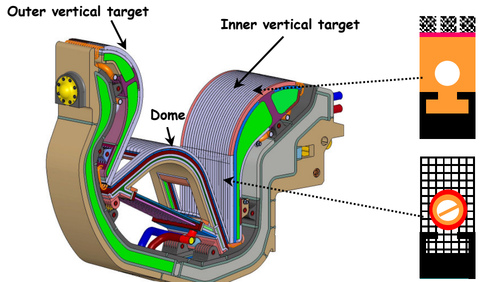


Monotonous and cycling shear tests F = ~2.10^5 – 0 N/m

Heating and cooling cycling tests T = 650 – 20°C

High heat flux cycling Q= 10 – 0 MW/m^2

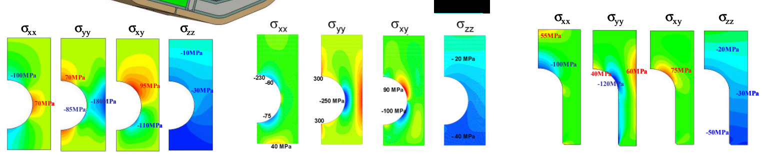
High heat flux elements in ITER divertor



Flat tile W
5 MW/m^2, 3000 cycles, 400s

- CFC
- W (tungsten)
- Cu
- CuCrZr
- Stainless steel

Monobloc CFC NB31
10 MW/m^2, 3000 cycles, 400s
20 MW/m^2, 300 cycles, 10s



Standard monoblock	Two half tiles option	Saddle tile option
High shear stresses at the bond	High shear and compressive stresses Singularity in σ_{yy}	More acceptable stresses at the bond

Fabrication phase: cooling down from 470°C down to 20°C

CONCLUSION: Partial characterisations of CFC material and of its bonding to copper through the AMC technique have been done, this work is still to be pursued in order to determine constitutive laws for N11 and NB31as well as tensile strength and tenacity of the CFC/Cu bond. Special finite element calculations have been performed: i) at a macroscopic scale taking into account the non linearity of the materials and the damaging of the anisotropic CFC to determine the global values of the stresses, ii) at a microscopic scale to determine the stress intensification factor k.

These analysis methods and test programs are essential for the concept qualification of ITER divertor high heat flux elements and for the prediction of the element damage versus the heat load history.