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Fracture modes of ITER tungsten divertor monoblock under stationary thermal loads

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ABSTRACT

During the qualification program of the tungsten divertor vertical targets, the tested mock-ups (250 tested tungsten monoblocks in total) successfully demonstrate their thermal performances and structural integrity. However, some of the tested monoblocks, in average 30%, showed macro-cracks in the tungsten.

This paper presents the results of 3D elastic-plastic thermo-mechanical analysis of the tungsten monoblock under stationary thermal loads for two cases of tungsten material properties: (1) stress-relieved and (2) recrystallized. The comparison pointed out that the recrystallized tungsten monoblock accumulated more damages at the loaded than stress-relieved tungsten. In addition, recrystallization may lead to early development of cracks on the monoblock either due to progressive deformation or fatigue while the non-recrystallized monoblock has a much smaller probability to develop cracks, as long as the exposed surfaces are free from defects.

1. Introduction

The ITER tungsten divertor is one of the main interface between the plasma facing components and plasma. It is designed to extract the heat and particles, and to protect the surrounding components from the heat and neutron loads. Among all the components constituting the ITER divertor, the vertical targets are designed to withstand the highest surface heat fluxes, up to 10 MW/m^2 during steady state operation and 20 MW/m^2 during slow transients [1,2]. To meet these requirements, the ITER divertor vertical targets use the monoblock technology, which consists of pure tungsten armour joined to the copper alloy pipe via a pure copper interlayer [3–6]. The monoblocks are water cooled, the coolant being at a temperature between 70 °C and 120 °C and at an inlet pressure of 4 MPa.

In the frame of the full-tungsten divertor qualification program [3], small scale mock-ups, made of 5–7 monoblocks, and full scale prototype plasma-facing units (PFUs) were tested under high heat fluxes to demonstrate and validate the thermal performances and the structural integrity requirements of the tungsten to copper interface. All the tested mock-ups containing 250 tested monoblocks in total – were successfully passed the qualification program in terms of thermal performances and structural integrity. However, some of the tested monoblock, in average 30%, showed macro-cracks sometime denoted as “self-castellation”. These macro-cracks were never observed during the cycling at 10 MW/m^2 but exclusively on some monoblocks after a few tens (up to a few hundreds) of cycles at 20 MW/m^2 [7]. From a phenomenological standpoint, metallographic examinations confirmed that the crack was initiated at the heated surface of the monoblock (see incomplete propagation of cracks as shown on Fig. 1).

Although the macro-cracks did not impair the thermal performance, it is preferable to avoid them not to cause any impact on plasma operation such as potential melting of tungsten due to leading edges at the crack edges. This is why an extensive study, including modelling and tungsten material characterization [4,8], was launched to understand the fracture modes implied and be able to prevent the crack to appear. In this paper, the results of the analysis of the tungsten monoblock under stationary thermal loads are presented, following the method used in RCC-MR [9] and using available tungsten material properties. The study focuses on the crack initiation at the loaded surface, and discussed results are limited to the loaded surface of the monoblock.

2. Thermo-mechanical analysis

2.1. Geometry and mesh

The Finite Element (FE) modelling presented in this paper used the ANSYS V15 software. The 3D model of tungsten monoblock is presented in Fig. 2. The monoblock dimensions are 28 mm × 28 mm × 12 mm.

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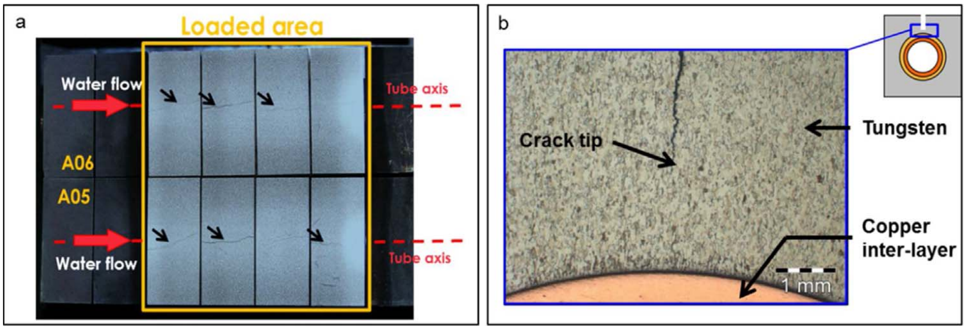

Fig. 1. (a) 2 mockups tested for 5000 cycles at 10 MW/m^2 and 300 cycles at 20 MW/m^2. macro-cracks were observed in 6 out of 8 monoblocks [4]. (b) Macro-crack at cross section of tungsten monoblock around copper interlayer [4].

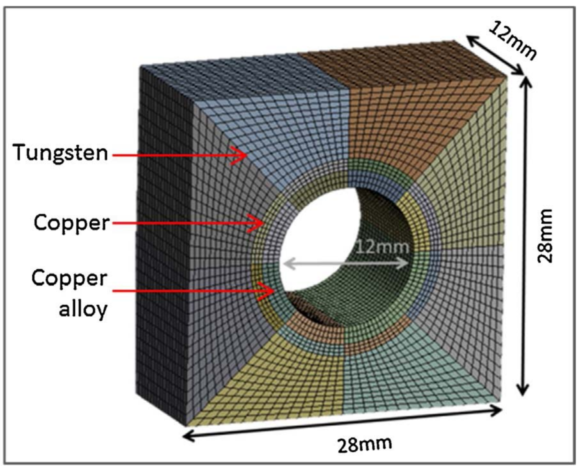

Fig. 2. Monoblock model (tungsten armour thickness is 6 mm), meshed with tetrahedrons elements.

The tungsten armour thickness is set to 6 mm above the copper interlayer. The copper alloy tube inner and outer diameters are 12 mm and 15 mm respectively. The copper interlayer, located between the tungsten armour and the interlayer tube has an outer diameter of 17 mm. The model is meshed with tetrahedron elements (36,288 elements and 157,472 nodes using mid-side nodes) as a result of a mesh sensitivity study.

2.2. Material properties

The materials, pure tungsten, pure copper and Copper-Chromium-Zirconium alloy were assumed to behave elastic-plastically and modelled with a Kinetic-hardening (kin-H) model. The kin-H material law was chosen in agreement with the recommendations made by the RCC-MR (Tome 1 – Volume Z – Annexe technique AT A10.7200) to assess progressive deformation and fatigue. Two cases are assessed: (1) tungsten monoblock made of stress-relieved tungsten; (2) tungsten monoblock made of recrystallized tungsten. The material properties of stress-relieved and recrystallized tungsten are given in Table 1 for 800 °C and 1800 °C.

It should be noted that the material properties are coming from [10,11], a collection of tungsten material properties extracted from the literature. As a consequence, the scatter of the data is significant (i.e. ± 15% for yield strength and ± 25% for Ultimate Tensile Strength) and has to be considered in the reliability of the results presented below. Material properties are assumed isotropic in the following calculations.

2.3. Boundary conditions

The boundary conditions for the thermal analysis are the following:

Table 1
Material properties of stress-relieved tungsten and recrystallized tungsten at 800 °C and 1800 °C [10,11].

	800 °C		1800 °C	
	Stress-relieved	Recrystallized	Stress-relieved	Recrystallized
Thermal conductivity (W/m K)	118		100	
Coefficient of thermal expansion (10^6 K^{-1})	4.81		5.30	
Specific heat (J/kg K)	152		176	
Young's Modulus E (GPa)	379		306	
Yield strength Ys (MPa)	609	76	103	53
Ultimate tensile strength UTS (MPa)	714	305	141	101
Total uniform elongation	0.02	0.50	0.25	0.46

- Water cooling is modelled using convection accounting for water boiling. The heat transfer coefficient is determined from [12] and is a function of the surface temperature: it ranges between 8 kW/m^2 at 50 °C and 226 kW/m^2 at 300 °C;
- The top surface of the monoblock is loaded by a surface heat flux set at 20 MW/m^2 during 10 s for each heating cycle;
- For Stephan-Bolzman radiation conditions, ambient temperature at 200 °C and tungsten emissivity of 0.3 were applied at the loaded surface. The tungsten monoblock was assumed to be stand-alone.

The bottom part of the tungsten monoblock, which is opposite side of the loaded surface, was fixed simulating the bonding to a support (by fixing all Ux, Uy and Uz displacements).

The water pressure, 4 MPa inside the tube was included in the study. Please note that a preliminary analysis shows that primary stresses induced by the water pressure are negligible compared to the secondary stresses induced by the thermal loads.

The time evolutions were calculated during 5 heating cycles, each being 10 s of heating followed by 10 s of cooling.

The main results of calculations were received for the tungsten loaded surface where the cracks were initiated. The results at the interfaces of tungsten with the copper interlayer and for the interface between the copper interlayer and the tube are indicative. These joins shall be assessed by “design-by-experiment” [13].

The stress free temperature of the monoblock is set at 70 °C. This temperature depends on the manufacturing routes, and is responsible for residual stress inside the component. Depending on the manufacturing route, temperature at the joint varies between room temperature up to 980 °C. Nevertheless, the impact was found to be negligible in terms of thermo-mechanical response at the loaded surface. Furthermore, the stress free temperature has no impact on the cyclic