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Fatigue lifetime of repaired high heat flux components for ITER divertor

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ABSTRACT

Thermal fatigue behaviour of repaired monoblocks was assessed from High Heat Flux (HHF) tests up to 20 MW m^{-2} on 11 components. Among these components, 8 monoblocks were repaired (2 CFC and 6 tungsten). These components were manufactured by two EU industries: ANSALDO Ricerche and PLANSEE. Non destructive examination was performed on SATIR thermography test bed before and after HHF tests. SATIR results show that repaired monoblocks have a good thermal exhaust capability before HHF tests. For all monoblocks, no degradation of thermal properties was noticed during cycles at 10 MW m^{-2}. After hundreds of cycles at 20 MW m^{-2}, two W repaired monoblock melted. Post-HHF SATIR examination revealed a degradation of thermal properties which is systematic for W melted monoblocks and non-systematic for W repaired ones. For CFC repaired monoblocks, no damage was observed up to 20 MW m^{-2}. For the first ITER divertor set, specifications for the pre-qualification are that CFC (Resp. W) components have to sustain in steady state 1000 cycles at 10 MW m^{-2} (Resp. 3 MW m^{-2}) followed by 1000 cycles at 20 MW m^{-2} (Resp. 5 MW m^{-2}). For the first ITER divertor set, the repair process is validated for CFC and W monoblocks.

1. Introduction

The ITER divertor system [1] aims to exhaust a significant part of the plasma power (up to 150 MW) and to minimize the helium and impurity content in the plasma. The design consists of 54 cassettes in a circular array. The cassette body supports plasma facing components (PFCs). These consist of the dome, and inner and outer vertical targets. The inner vertical target (IVT), to be delivered by European domestic agency, is composed of 16 units, each one being constituted of about hundred of monoblocks made of carbon fibre composite (CFC) in the lower part and tungsten (W) in the upper part. For the pre-qualification of the first IVT set, ITER specification is that CFC (Resp. W) components have to sustain 1000 cycles at 10 MW m^{-2} (Resp. 3 MW m^{-2}) followed by 1000 cycles at 20 MW m^{-2} (Resp. 5 MW m^{-2}).

In the PFCs, failure of the heat sink to armour bonds inducing water leak could compromise the performance of the divertor and potentially result in its failure and the shut down of ITER operations. There are tens of thousands of such bonds in the divertor assembly, either CFC or W to copper alloy (CuCrZr) bonds. If the armour to CuCrZr tube joint has unacceptable defects, a repair process to avoid the rejection of an entire unit has been developed. The principle is to replace the defected monoblock by a repaired one. The objective of the paper is to report on the fatigue lifetime of repaired high heat flux components.

2. Samples description

Eleven components were procured via industry for the study. There are two kinds of components, the first one is composed of W monoblocks (called W component) and the second one is constituted of CFC and W monoblocks (vertical target prototypal component called VTP component). In each component a CuCrZr swirl tape is inserted (thickness 0.8 mm, twist ratio 2) to enhance the heat exchange coefficient.

For W components, two sets of four components were manufactured both by PLANSEE company (named in the following as PLANSEE) and by ANSALDO Ricerche Company (name in the following as ANSALDO). Each W component is composed of 7 monoblocks. The first set consists of standard components, for which monoblocks were not submitted to repairing process (later called W non-repaired components). For ANSALDO (resp. PLANSEE), those components were called A03 and A05 (resp. P03 and P04). The second set consists of repaired components, for which one monoblock per component was repaired (W repaired components). The place of repaired monoblock was chosen randomly,

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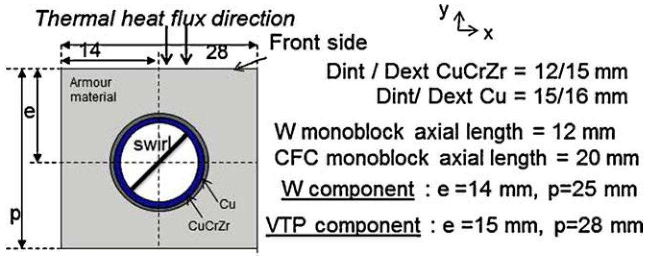

Fig. 1. Monoblock geometries.

however it was not placed at the inlet or at the outlet of the component. For ANSALDO (resp. PLANSEE) those components were called A06 and A07 (resp. P02 and P05).

For the VTP component, one unit was fabricated by ANSALDO and two units were fabricated by PLANSEE. The VTP component has a straight CFC monoblock part of 8 (resp. 11) monoblocks for ANSALDO (resp. PLANSEE) and a curved W monoblock part of 10 (resp. 14) monoblocks for ANSALDO (resp. PLANSEE). Monoblock geometries are presented in Fig. 1.

The joining technologies are different for PLANSEE and ANSALDO [2–4].

For CFC and W monoblocks, the repair process consists in machining the monoblock up to the beginning of the CuCrZr tube. Then the cooling tube is exactly machined to allow the bond of the repaired monoblock. A joining of two half virgin monoblocks with the copper cast layer is then performed on the CuCrZr unit tube (Fig. 2a) by hot isostatic pressure (HIP) for PLANSEE [2] and by hot radial pressing (HRP) for ANSALDO [3,4]. The scheme of repaired monoblock is presented in Fig. 2b. One can notice the remaining of the repair cutting plane.

3. Experimental studies and modelling

3.1. IR examination with SATIR

SATIR is a test bed using infrared thermography [5]. It was developed by CEA and is used as an inspection functional tool in order to assess the thermal exhaust capability of the actively cooled PFCs. This test is based on the comparison of the surface temperature evolution of the inspected component with a reference zone. The reference zone is defined on a monoblock which has globally, on its entire surface, the lowest and the most homogenous thermal time response. When submitted to a hot to cold water flow step, the temperature difference is called DTref. The armour surface temperature on front side (Fig. 1) is observed by means of a digital infrared camera (CEDIP JADE II, $\lambda = 3–5\,\mu$m) facing the tested PFC. Maximum of DTref obtained for each monoblock is called here later DTrefmax.

For the pre-high heat flux (HHF) SATIR inspection, due to the small quantity of components, the evaluation of the component quality was based on conventional statistical techniques (i.e. "normality range with a level of confidence of 95%" corresponding to a range included within two reference standard deviations (σ^{ref}) from the mean value (μ) of tested monoblocks. σ^{ref} was evaluated close to 4 °C for W and CFC monoblock armours [6]. DTrefmax reproducibility is checked performing 2 acquisitions on the same feeder line and is estimated at 2 °C for this study (ΔDTrefmax = 2 °C). A monoblock has a good quality when its DTrefmax is lower than $\mu + \sigma^{\mathrm{ref}} - \Delta$DTref (i.e. $\mu + 2$).

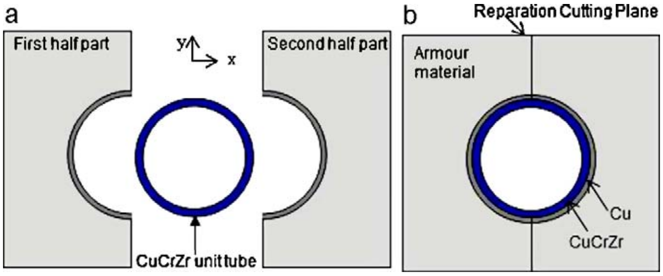

Fig. 2. Scheme of the repair process.

Table 1
Heat loads description (c: cycles).

Thermal flux/MW m^{-2}	10	15	20
W non-repaired component	1000 c	No	1000 c
W repaired component	1000 c	No	500 c
VTP component W part	1000 c	1000 c	300 c
VTP component CFC part	1000 c	No	1000 c

For the post-HHF inspection, no reference component was available. Indeed, all components were HHF tested. Because the thermal characteristics of previously used reference zone have probably changed during the HHF test, for each component the reference is the SATIR IR film of same component recorded before the HHF tests.

3.2. High heat flux tests

Three mock-ups were prepared for HHF testing at FE200 facility [7]: with respectively 4 W non-repaired components, 4 W repaired components and 3 VTP components [8]. Separated areas were defined on each component for dedicated cycle's campaign. Areas were exposed to cycles of 10 s with heating (provided by electron beam sweeping) followed by 10 s without heating. Cycling campaigns are presented in Table 1. In addition, for all components thermal mappings at 5 MW m^{-2} were performed initially and after each cycling campaign. Absorbed thermal heat flux is measured by calorimetry. The cooling water conditions were those of the ITER divertor: inlet pressure at 3.3 MPa, flow at 12 m s^{-1} and inlet temperature at 120 °C. During HHF tests surface temperature is recorded with an IR camera.

3.3. Finite element method (FEM) modelling

No FEM simulations were performed for CFC repaired monoblocks because no damage was noticed during HHF tests. For W repaired monoblocks, damage was noticed during HHF tests. To analyse the effect of repair processes, HHF tests were simulated for non-repaired and repaired W component monoblocks with ANSYS® V12 software. HHF tests were simulated using: a thermal radiation exchange between external surface and FE200 chamber (120 °C), forced convection in the inner tube and homogenous heat flux loading on front side. The mechanical behaviour was calculated using the results of the thermal simulation. Main material parameters used for simulations are presented in Table 2 [9,10].

Table 2
Main mechanical and thermal parameters for FEM simulations [9,10].

	T/°C	Cu	CuCrZr	W	W dummy
E (GPa)	200	120	120	405	304
	400	103	103	399	300
	600	90	90	393	295
	2500	29	29	239	179
λ (W m^{-1} K^{-1})	200	365	351	146	109
	400	338	359	131	98
	600	312	359	124	93
	2500	273	312	84	63