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Heat Removal Capability of Actively Cooled Plasma-facing Components for the ITER Divertor

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Abstract

Non destructive examination followed by high heat flux testing has been performed for different small and medium-scale mock-ups which included the most recent developments related to actively cooled W/CFC-armoured plasma-facing components. In particular, the heat removal capability of these mock-ups manufactured by European companies with all the main features of the ITER divertor design was investigated both after manufacturing and after thermal cycling up to 20 MW/m². The compliance with ITER requirements was explored in terms of bonding quality, heat flux performances and operational compatibility.

Main results showed an overall good heat removal capability after the manufacturing process independent of the armour to heat sink bonding technology and promising behaviour with respect to thermal fatigue lifetime under heat flux up to 20 MW/m² for the CFC armoured tiles and 15 MW/m² for the W armoured tiles, respectively.

1. Introduction

Some of the most technically challenging components of ITER are the ones directly facing the thermonuclear plasma. Within this framework, extensive R&D programmes have been performed in Europe to develop suitable technologies for high performance actively cooled plasma-facing components (PFCs) for the ITER divertor. These activities focus on the development and fabrication of relevant plasma-facing materials and components compatible with plasma operations and associated plasma wall interaction to consolidate the thermal fatigue data base.

In this paper, recent results are presented and discussed for various types of actively cooled small and medium-scale mock-ups with W/CFC armour having all the main features of the ITER divertor design. In particular, the heat removal capability after manufacturing and the damage evaluation after thermal fatigue up to 20 MW/m^2 are assessed by an active infrared thermography method. The performance of repairing methods, whose objectives are to maximize the acceptance rate of the divertor high heat flux components and to reduce the fabrication costs during the series production for ITER, are also investigated.

2. Main features of the tested components

A total of sixteen *small-scale* components (so-called CFC or W components according to the armoured material, see **Fig. 1a**) and three *medium-scale* Vertical Target Prototypical components (so-called VTP components, see **Fig. 1b**) were manufactured by Ansaldo Ricerche (four CFC components, four W components and one VTP component) and Plansee SE (four CFC components, four W components and two VTP components). The bonding technologies are different for both manufacturers: based on Pre-Brazed Casting (PBC[®]) (*resp. Cu casting*) and Hot Radial Pressing (HRP[®]) for CFC (*resp. W*) armoured

components of Ansaldo Ricerche [1] and on Active Metal Casting (AMC[®]) (*resp. Cu casting*) and Hot Isostatic Pressing (HIP) for CFC (*resp. W*) armoured components of Plansee SE [2].

All PFCs include all the main features of ITER divertor Vertical Targets design and are made of monoblock tiles having a width of 28 mm and an axial length of about 20 mm (*resp. 12 mm*) for CFC tiles (*resp. for W tiles*). With a total height ranging between 25 and 30 mm, these PFCs have an armour thickness of 6-7 mm. To reduce the joint interface stress, a pure Cu interlayer (0.5-1 mm thick) was provided between the armour and the cooling tube. The cooling tube (12/15 mm inner/outer diameter) is made of CuCrZr. A twisted tape, 0.8 mm thick, with a twist ratio of 2, was inserted into the cooling tube as turbulence promoter to enhance heat transfer and to increase the critical heat flux margin.

For each manufacturer, two CFC (*resp. two W*) components included one repaired monoblock tile. For the VTP components, Ansaldo Ricerche unit is provided with two repaired monoblocks in both the CFC and W parts and the two Plansee SE units are each provided with one repaired monoblock, one in the CFC part, the other one in the W part. The repairing process [3] on a component requires the execution of a second bonding step between the armour and the heat sink structure during the manufacturing phase, in addition to the one performed initially.

3. Experimental Campaign

3.1. Testing sequence and procedure

The qualification of actively cooled components includes several tests. The HHF fatigue testing is the leading part of the qualification. This testing enables to check the robustness of the PFC in thermal conditions as close as possible to those foreseen during plasma exposure, to evaluate the limit of design and to draw information on the components thermal fatigue lifetime. In addition, the HHF fatigue testing is preceded and then followed by a dedicated

non destructive examination. Based on a visual control and an active infrared thermography inspection, the non destructive examination enables to check the manufacturing quality prior to thermal fatigue testing (pre-examination) and to assess the damage evolution (post-examination) which is helpful for a better understanding of the thermal behaviour.

3.2. Tools for testing

3.2.1. Non Destructive Examination

Since the Tore Supra's first generation of actively cooled PFCs, a dedicated facility named SATIR (French acronym for Infra Red Acquisition and Data Processing device) is running in Cadarache (France) and has proved to be very efficient in terms of defect detection for CFC armoured components [4]. Recently, the SATIR facility has also been used successfully for W armoured actively cooled components in the frame of studies dedicated to ITER prototype components [5]. This integrated method appeared hence to be relevant for qualifying potential imperfections in terms of heat removal capability of CFC or W armoured actively cooled components.

a. Principle of SATIR

SATIR technique [6] is based on the detection of a time delay of the surfaces temperature evolution measured by infrared thermography during a fast decreasing of the water temperature flowing in the cooling tube. An imperfection at one of the joints or into a material may create a thermal resistance so that the delay increases during the transient thermal regime. This delay is measured by comparison with the thermal behaviour of a "defect-free" reference component. The maximum value of this delay in terms of temperature –called DT_{ref_max} (°C)– is calculated for each pixel on the infrared images. The emissivity variations in surface are corrected by a processing based on a pixel normalization algorithm during the hot thermalization (hot water flow at $\sim 100^\circ\text{C}$ into the cooling tube) for steady state conditions at

the beginning of test. This technique was applied on three sides (the plasma faced and lateral sides) of each monoblock of each CFC/W armoured component.

b. Quality criteria

The SATIR quality criterion is based on previous results [7] related to a comprehensive study to define acceptance criteria for the divertor PFCs with regards to thermomechanical fatigue. This study confirmed that the most critical part of a PFC is the armour to heat sink joint and proved that the dimension of defect extension at the interfaces of bonding was a relevant criterion. It was finally stated that the maximum acceptable defect extension, whatever the location, is 45° for the monoblock geometry. Thereafter, based on finite element calculations, the extrapolation to the components considered in this study leads to a “faulty tile” threshold in terms of DTR_{ref_max} on SATIR of 9°C (resp. 12°C) for CFC (resp. W) monoblock component, the “detectability” threshold of the SATIR facility being 5°C .

3.2.2. Thermal Fatigue Testing

Fatigue testing campaign was performed in the high heat flux AREVA FE200 electron beam facility at Le Creusot in France [8]. The monitoring of the shots was provided by means of a CCD camera, two optical pyrometers, a pyro-reflectometer and an infrared camera. The absorbed heat flux is obtained by global calorimetry from the measurement of two thermocouples installed at the inlet and at the outlet of the tested components. The experimental campaign was devoted to several steps of fatigue cycle tests (see **Table 1**).

The thermal cycle was 10s power on (provided by electron beam sweeping at 14 kHz), then 10s dwell time. Initial, intermediate and final screenings (thermal mapping) were performed at 5 MW/m^2 between the cycling phases. The hydraulic conditions were set at nominal ITER conditions, namely at a pressure of 33 bar, an inlet temperature of 120°C and a water velocity inside the tube of 12 m/s.

4. Experimental results and discussion

4.1. Qualification after manufacturing for consolidated and repaired technologies

4.1.1. CFC armoured monoblock tiles

SATIR pre-examination on CFC armoured monoblock tiles revealed globally a good bonding quality after the manufacturing phase with regard to tested components whatever the bonding technology. Only two monoblock tiles showed a thermal behaviour exceeding slightly the "faulty tile" threshold for VTP component with HRP process (10°C compared to 9°C of threshold value, see **Fig. 2a**). Thereafter, initial screening (thermal mapping at 5 MW/m²) performed before HHF fatigue testing in the FE200 facility showed a good thermal behaviour for each monoblock of each component (**Fig. 2b**) and confirmed the good quality of CFC components after manufacturing.

Based on DTref cartography obtained from SATIR measurements (**Fig. 3**), a finite element simulation of SATIR test was performed on the two tiles (namely, #4 and #5) indicating a poor thermal response, to assess the size of probable manufacturing defects. The simulations showed that this low heat transfer could be due to defects localized at the armour/heat sink interface enough far from the front side (typically, $\theta_0 \sim 30^\circ$, $\Delta\theta \sim 50^\circ\text{C}$ for #4 and $\theta_0 \sim 60^\circ$, $\Delta\theta \sim 60^\circ\text{C}$ for #5). Previous studies [9] for similar manufacturing defects (namely, located far from the loaded surface with a circular extension not exceeding 60°), did not show evidence of critical failure for heat fluxes close to 20 MW/m². However, these defects can sometimes favour slight erosion at surface due to sublimation phenomenon which is induced by higher temperatures (typically, exceeding 2000°C at 20 MW/m²).

4.1.2. W armoured monoblock tiles

SATIR pre-examination on W armoured monoblock tiles revealed also an overall good bonding quality after the manufacturing phase with regard to tested components whatever the bonding technology. Only one monoblock tile showed a thermal response close to the "faulty

tile" threshold (**Fig. 4a**). Finally, additional investigation proved that the SATIR signal was locally disturbed (namely, close to the outlet area) by a reflexion phenomenon due to the surrounding water manifolds which induced an infrared artefact.

In the same way, the initial screening (thermal mapping at 5 MW/m^2) performed before HHF fatigue testing in the FE200 facility showed a good thermal behaviour for each monoblock of each component (**Fig. 4b**) and confirmed the good quality of W components after manufacturing phase.

4.2. Damage evaluation after thermal fatigue testing

Main experimental HHF results were recently reported [3, 10] and pointed out that all tested components including 'not-repaired' and 'repaired' monoblocks endured correctly the cycling at 10 MW/m^2 without any visible damage. This first step of thermal cycling did not show hot spots or evolution of surface temperature, and confirmed the promising behaviour already observed in the past. While no water leakage occurred during the thermal fatigue tests above 10 MW/m^2 , visual surface damage was observed during and after the thermal cycling at higher heat fluxes (see **Table 1**). Thereafter, the post-examination (visual control and infrared thermography inspection by SATIR) showed clear evidence of heat transfer degradation for the CFC monoblock tile which appeared significantly eroded in surface (**Fig. 5**) and for the W monoblock tiles which exhibited a partial or complete surface melting after the HHF fatigue testing (**Fig. 6**).

Correlated with visual control, the SATIR outcome lead to factual observations and comments reported hereinafter.

4.2.1. CFC armoured monoblock tiles

- No significant thermal degradation in terms of heat flux removal capabilities has been measured by SATIR post-testing after a thermal cycling (up to 1000 cycles) at 20 MW/m^2 .

This promising result is observed whatever the bonding technology for the '*not-repaired*' and '*repaired*' monoblock tiles related to components armoured with CFC-NB41 grade (i.e. *medium-scale* VTP components by Ansaldo and Plansee, and *small-scale* CFC components manufactured by Plansee). However, one of two tiles with a poor thermal response detected during the SATIR pre-examination (see §4.1.1) pointed out an abnormal temperature evolution during the last step of cycling at 20 MW/m² (typically, an increase of surface temperature of about 30% between the beginning and the end of the cycling was measured by IR thermography for this tile). This thermal behaviour is confirmed by the final thermal mapping at 5 MW/m² as well as the SATIR post-examination. Associated to finite element simulation, the SATIR measurement by IR thermography exhibits a low propagation of initial manufacturing defect which could lead to progressive heat transfer degradation and also the slight erosion by sublimation observed at the loaded surface.

- Large surface alteration (erosion phenomenon) is observed by visual control of loaded surface after a thermal cycling at 20 MW/m² for one '*repaired*' monoblock tile related to components armoured with CFC-NB31 grade (i.e. *small-scale* CFC components manufactured by Ansaldo with a repairing process based on HRP technology, see **Fig. 7**). Thereafter, SATIR post-examination showed a significant thermal degradation in terms of heat removal capability as a result of a debonding at the armour/heat sink interface mainly localized on one half part of the '*repaired*' tile. This result is fully in agreement with the high surface temperature evolution measured by IR thermography during the final thermal mapping at 5 MW/m² with an increase in temperature exceeding 100% (i.e. an average surface temperature close to 1000°C to be compared with an average surface temperature of about 450°C for a healthy monoblock) for the '*repaired*' monoblock tile

which is largely altered in surface (i.e. eroded by sublimation) after thermal cycling at 20 MW/m².

4.2.2. W armoured monoblock tiles

- No significant thermal degradation in terms of heat flux capabilities is noticed after 1000 cycles at 15 MW/m², but longitudinal primary millimeter-length cracks (**Fig. 8/①**) oriented perpendicularly to the loaded surface, are observed on some 'not repaired' tiles.
- Progressive spread of the previous primary cracks is noticed on a majority of 'not repaired' monoblock tiles after a few hundreds of cycles at 20 MW/m². In addition, a dense network of secondary micro-cracks (**Fig. 8/②**) is observed after a few tens of cycles at 20 MW/m² inducing an overall alteration of the surface (rough aspect).
- Presence of molten W droplets (**Fig. 8/③**) at the surface of altered monoblocks by secondary micro-cracks is noticed after several hundreds of cycles (typically more than 500 cycles) at 20 MW/m². However, despite this structural damage, no significant increase of surface temperature was observed during the thermal cycling (e.g. the maximum increase of surface temperature which has been measured by IR thermography between the beginning and the end of cycling did not exceed 20%, excepted for a few monoblocks having exhibited a complete melting as discussed later on).

SATIR post-testing performed after thermal fatigue testing up to 20 MW/m² shows that the W armour material embrittlement leading to crack formation at the surface and located surface melting (molten W droplets), does not impair the heat removal capability between the surface and the coolant (see **Fig. 6**). In agreement with the final thermal mapping at 5 MW/m², the post-testing results confirm that the high surface temperature leading to the located surface melting cannot be explained neither by a global deterioration of heat transfer between the surface and the coolant nor by the propagation of defects at the W/Cu interface. Therefore, it appears that the surface melting described here above mainly depends on

structural changes in the material rather than on the manufacturing technique. Those interpretations are preliminary conclusions which will have to be confirmed in a near future by the metallographic examination of the monoblocks.

In addition, a complete melting (with a collapse of armour material) was noticed during the cycling at 20 MW/m^2 on two '*not-repaired*' monoblocks (i.e. less than 3% of tested monoblocks with W armour) after hundreds of cycles (namely, after 450 and 520 cycles, respectively) [10], as well as on two '*repaired*' monoblocks (among the six W '*repaired*' tiles in total, distributed out on six components) after 50 and 250 cycles, respectively [3]. However, the thermal cycling pursued as planned in the testing plan without occurrence of a water leak despite a very significant degradation in terms of heat flux capability noticed by SATIR post-testing (see **Fig. 6**). Complete melting events were only observed for W components and VTP components with a manufacturing process based on HRP technology. The SATIR post-testing results suggest that this complete melting is probably caused by the propagation of a defect at the W/Cu interface combined with a creep deformation of the pure copper interlayer.

5. Summary and Conclusion

Tests have been performed for different mock-ups including most recent developments related to actively cooled W/CFC-armoured plasma-facing components. In particular, the heat removal capability of these mock-ups manufactured by European companies with all the main features of the ITER divertor design was investigated after manufacturing and after thermal cycling up to 20 MW/m^2 .

Main results showed an overall good bonding quality in terms of heat transfer capability after the manufacturing process whatever the armour to heat sink bonding technology. Thereafter, all the tested components endured correctly the thermal cycling (1000 cycles) at 10 MW/m^2

without any degradation of the heat removal capability of the component. Beyond, the following factual observations were noticed:

- **CFC-NB41 armoured tiles** (including the repaired ones) showed a promising behaviour with respect to thermal fatigue lifetime under heat flux up to 20 MW/m^2 , despite a possible erosion phenomenon in surface which is correlated with a slight thermal degradation in terms of heat capacity.
- **W armoured tiles** (including the repaired ones) showed a promising behaviour with respect to thermal fatigue lifetime (up to 1000 cycles) under heat flux at 15 MW/m^2 , despite a start of structural damage after several hundreds of cycles. In addition, power handling capability seems to be well preserved with no significant increase of surface temperature during the thermal cycling, confirmed later with the SATIR thermography post-examination. Beyond, and after a limited number of cycles at 20 MW/m^2 , the recrystallization of W armour is still considered unfavourable for high temperature structural integrity and cyclic thermal fatigue, and can lead after a limited number of cycles at 20 MW/m^2 to local surface melting (droplets formation) at the loaded surface.

These results confirm that both manufacturing technologies are pre-qualified for the manufacturing of full scale CFC/W armoured components. In addition, the recent consolidated technologies and the repairing process developed by European industries are validated up to 1000 cycles at 20 MW/m^2 (*resp. 10 MW/m²*) for components armoured with CFC-NB41 grade (*resp. pure W grade*), which is beyond the current design target qualification required for the ITER divertor.

While a mixed-CFC/W divertor is considered to be suitable for the ‘exploratory’ stage of operation in H and He, the deployment of an all-tungsten divertor in ITER foreseen for the following deuterium-tritium (D-T) phase still needs additional R&D. The outcome of this study underlines the concerns regarding prolonged use of W above recrystallization

temperatures (high temperature usage) and below DBTT. Thus, the compatibility with subsequent plasma operations of surface damages (like high roughening, brittle destruction and melting) occurring under strike-point load conditions in ITER will have to be investigated. Dedicated experiments in machines with ITER relevant W-armoured PFCs will be of interest (e.g. metallic environment with actively cooled components). In particular, to explore the long pulse high heat flux exposition with repetitive high heat flux cycling as well as the effects of combined transient heat loads (e.g. short pulse loads to simulate ELMs-like transient loads, thermal fatigue in steady-state conditions and neutron irradiation).

Acknowledgement

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Table Captions

Table 1: Summary of Heat Loads on each small/medium scale component
(* 1000 cycles for the “not-repaired” components and 500 cycles for the “repaired” ones)

Figure Captions

Figure 1: ‘Small-scale’ components (a) and ‘Medium-scale’ Vertical Target Prototypical components (b)

Figure 2: SATIR pre-examination (a) and FE200 Initial Screening (b) for each CFC monoblock of each component

Figure 3: SATIR pre-examination results for CFC part of VTP component manufactured by Ansaldo
(*low heat transfer detected on monoblock tiles #4 and #5*)

Figure 4: SATIR pre-examination (a) and FE200 Initial Screening (b) for each W monoblock of each component

Figure 5: SATIR post-testing: Comparison of DTrefmax before and after HHF thermal fatigue testing for **CFC components** manufactured by Ansaldo (*left*) and by Plansee SE (*right*)

Figure 6: SATIR post-testing: Comparison of DTrefmax before and after HHF thermal fatigue testing for **W components** manufactured by Ansaldo (*left*) and by Plansee SE (*right*)

Figure 7: Surface view after 1000cycles x 20MW/m² on the CFC component manufactured by Ansaldo
(*large erosion of the ‘repaired’ tile damaged under thermal fatigue*)

Figure 8: Surface view after thermal fatigue at 10 MW/m² (a), then 20 MW/m² (b) on W components
(*① Longitudinal primary cracks; ② network of secondary micro-cracks; ③ molten W droplets*)

	SMALL-SCALE		MEDIUM-SCALE	
	W Components	CFC Components	W Part	CFC Part
<i>Thermal Mapping</i>	YES	YES	YES	YES
10 MW/m²	1000 cycles		1000 cycles	1000 cycles
<i>Thermal Mapping</i>			YES	
15 MW/m²			1000 cycles	
<i>Thermal Mapping</i>	YES		YES	YES
20 MW/m²	1000 / 500* cycles	1000 cycles	300 cycles	1000 cycles
<i>Thermal Mapping</i>	YES	YES	YES	YES

Table 1: Summary of Heat Loads on each small/medium scale component
 (* 1000 cycles for the “not-repaired” components and 500 cycles for the “repaired” ones)

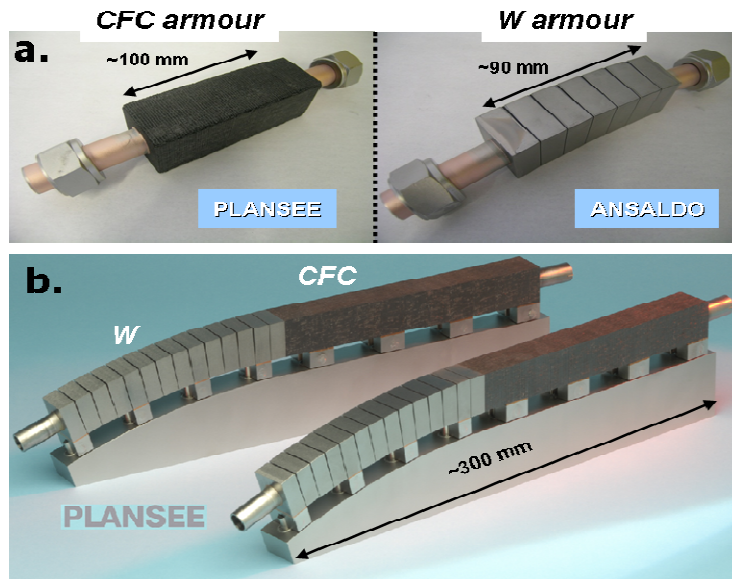


Figure 1: 'Small-scale' components (a) and 'Medium-scale' Vertical Target Prototypical components (b)

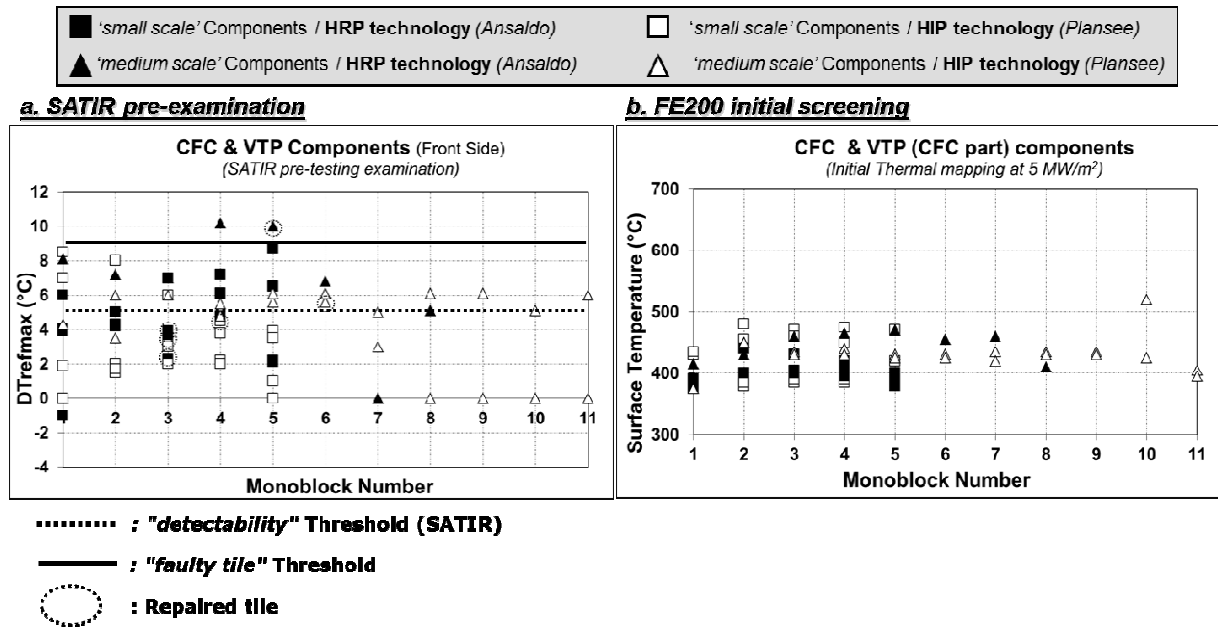


Figure 2: SATIR pre-examination (a) and FE200 Initial Screening (b) for each CFC monoblock of each component

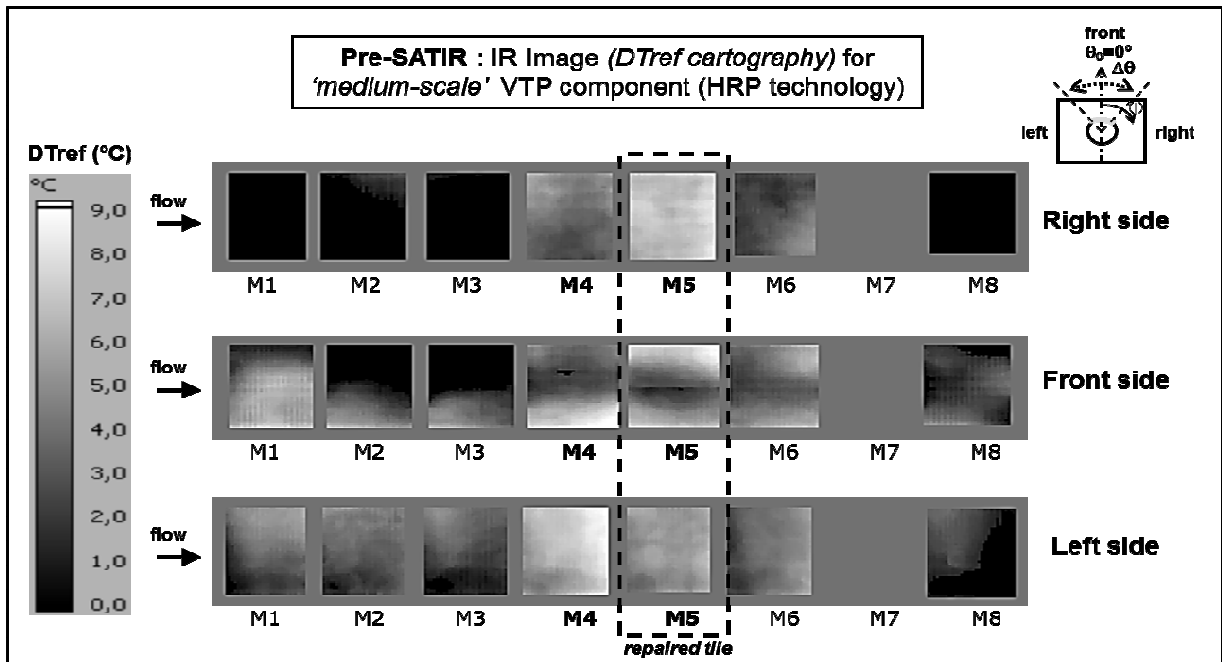


Figure 3: SATIR pre-examination results for CFC part of VTP component manufactured by Ansaldo (low heat transfer detected on monoblock tiles #4 and #5)

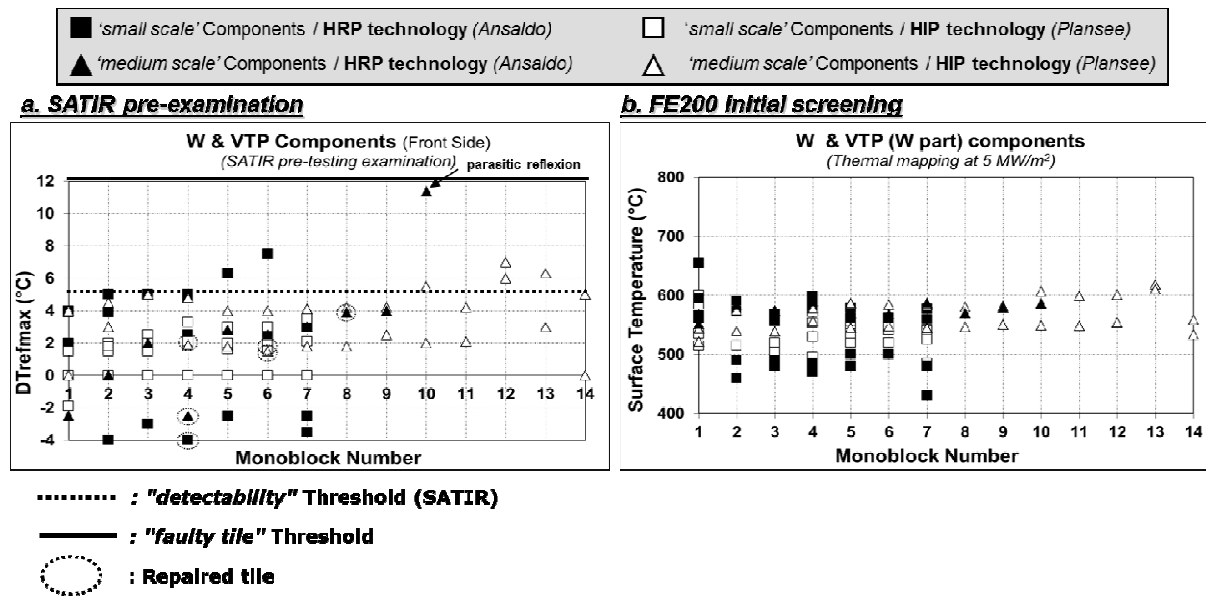


Figure 4: SATIR pre-examination (a) and FE200 Initial Screening (b) for each W monoblock of each component

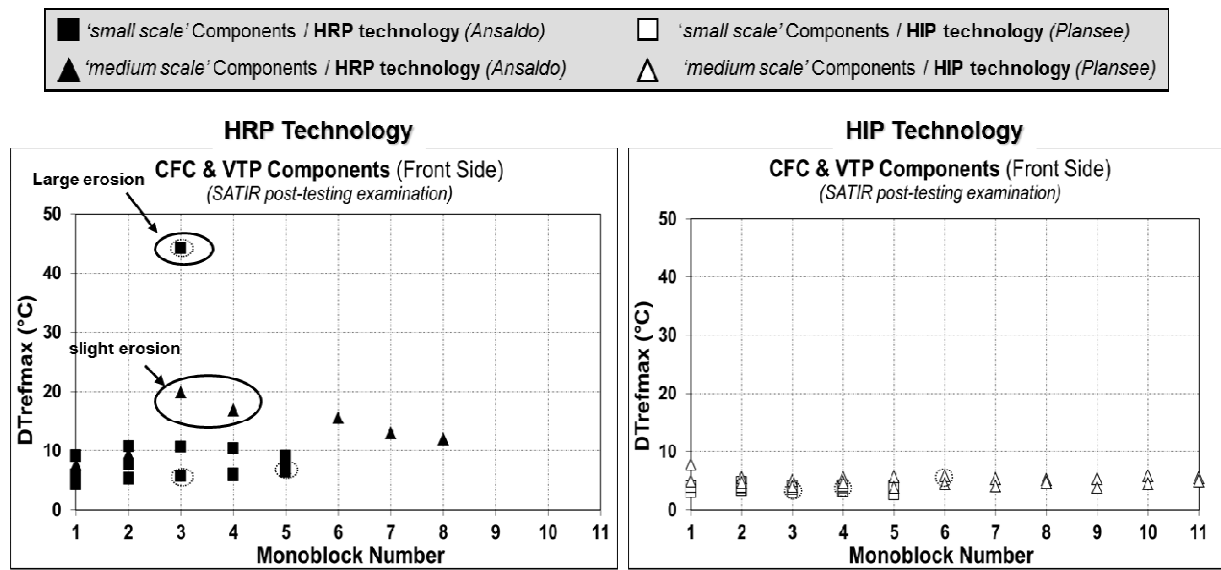


Figure 5: SATIR post-testing: Comparison of DTrefmax before and after HHF thermal fatigue testing for CFC components manufactured by Ansaldo (*left*) and by Plansee SE (*right*)

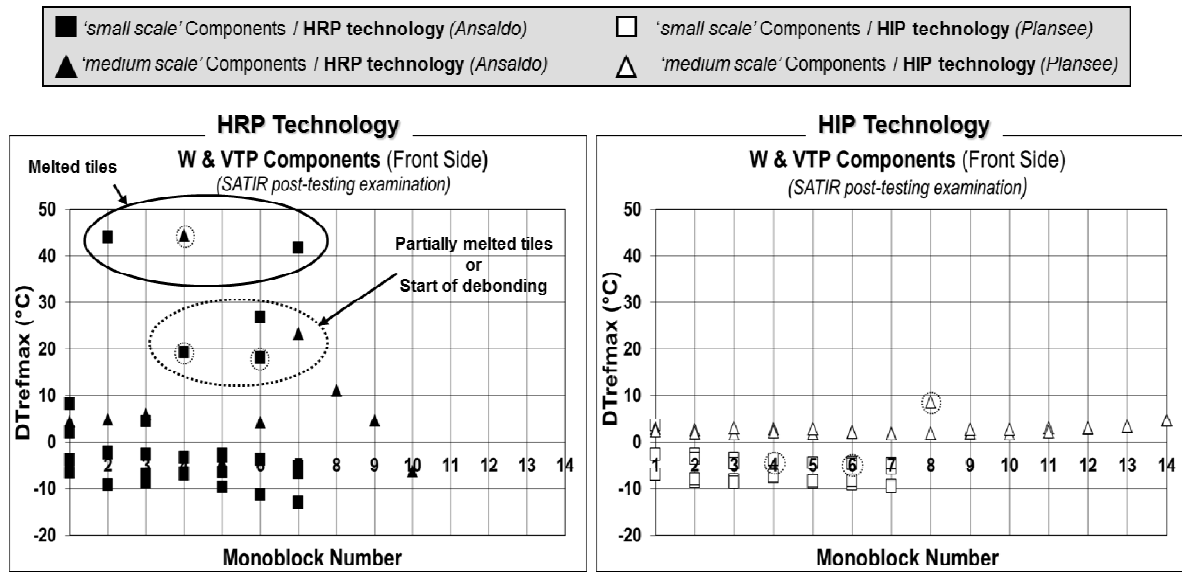


Figure 6: SATIR post-testing: Comparison of DTrefmax before and after HHF thermal fatigue testing for **W** components manufactured by Ansaldo (*left*) and by Plansee SE (*right*)

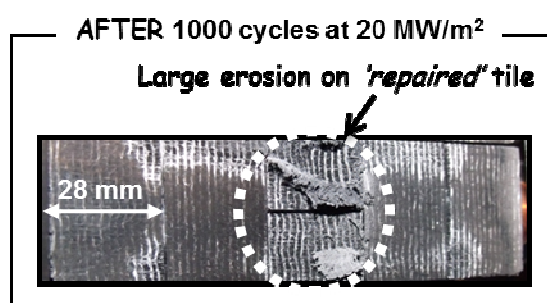


Figure 7: Surface view after 1000cycles x 20MW/m² on the CFC component manufactured by Ansaldo
(large erosion of the 'repaired' tile damaged under thermal fatigue)

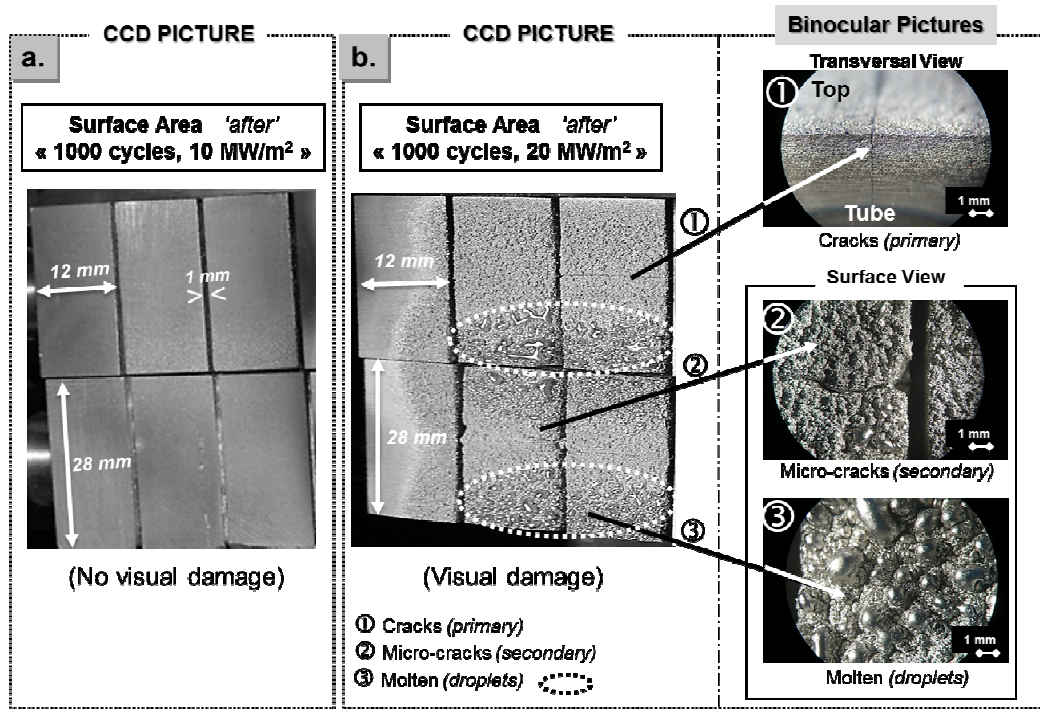


Figure 8: Surface view after thermal fatigue at 10 MW/m² (a), then 20 MW/m² (b) on W components (① Longitudinal primary cracks; ② network of secondary micro-cracks; ③ molten W droplets)