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Examination of W7-X target elements after high heat flux testing

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A B S T R A C T

The reception tests performed on the pre-series high heat flux elements of WENDELSTEIN 7-X (W7-X) divertor by means of infrared thermography inspection and high heat flux thermal cycling tests, exhibited some tiles with thermal inhomogenities, which developed during high heat flux testing. To assess damage detection and to understand the behaviour of pre-series elements under heat loading, post-testing investigations were undertaken to discriminate the tiles with insufficient bonding. Metallographic studies showed a good correlation with the surface temperature rise measured during the thermal cycling tests and the results of non destructive post-examination.

1. Introduction

The target plates of the WENDELSTEIN 7-X (W7-X) divertor [1] are designed to sustain a stationary heat flux of 10 MW/m^2 and to remove a maximum power load up to 100 kW. This highly-loaded surface of 19 m^2 is achieved by the arrangement of 890 individual target elements made of carbon fibre reinforced carbon composite (CFC) Sepcarb® NB31 flat tiles bonded to a CuCrZr copper alloy water-cooled heat sink (Fig. 1). In the frame of the reception tests of this component with a particular focus on the bond between CFC tiles and the heat sink structure, the transient infrared thermography test bed SATIR was used at CEA-Cadarache [2]. Within the framework of the pre-series activities, high heat flux (HHF) thermal cycling tests in the ion beam GLADIS facility at IPP-Garching [3] allowed to assess the performances of full-scale target elements, and to qualify the manufacturing process together with the relevant inspections. The results of HHF tests showed some tiles with thermal inhomogeneities (hot spots) mostly close to the edge, which developed during HHF cycling. SATIR examinations were performed to check the reliability of this method for the prediction (pre-HHF mode) and the confirmation (post-HHF mode) of the detection of flaws that may strongly reduce the lifetime of the component.

This paper will focus on the post-testing investigations performed on the pre-series elements with the relevant metallographic observations in order to assess damage detection and to understand the behaviour during heat loading of the bond between the CFC tiles and the heat sink structure.

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2. Main features of pre-series target elements

The bond between CFC tiles and heat sink is manufactured by PLANSEE SE in two stages. At first, a copper interlayer is cast (Active Metal Casting, AMC®) onto the laser-treated surface of the tile [4]. Subsequently the tiles are joined by hot isostatic pressing (HIP) or by electron beam welding (EBW) to the CuCrZr heat sink. One of the purposes of the pre-series phase is the selection between these two processes. The cooling geometry is formed by four straight channels equipped with twisted tapes as turbulence promoters and connected by U-bends.

The present analysis is related to the third delivered batch of pre-series targets [5,6], on which a full inspection was performed, namely, non-destructive examination (NDE) based on SATIR infrared thermography applied before ('pre-examination') and after ('post-examination') HHF tests, a HHF testing campaign in the GLADIS facility and metallographic observations of some tiles with an aim of correlating the whole results. This additional Batch #3 consists of 22 elements of the same type: 250 mm long, 55-57 mm wide, 10 CFC NB31 tiles.

3. GLADIS high heat flux testing

The capability of components to withstand the heat loads predicted for the divertor of W7-X is checked in the ion beam HHF test facility GLADIS in consecutive steps of power loading. During the acceptance test load pulses of 10 s duration at a flux level of 10 MW/m^2 are applied to the component up to 100 cycles. Assuming a quite flat distribution of the input power, thermal inhomogeneities or hot spots at the CFC surface during the first loading cycle points out an insufficient bonding quality whereas any evolution of the surface temperature (unexpected increase of average

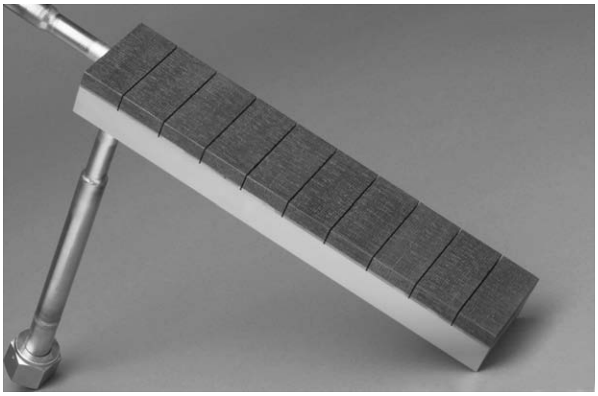

Fig. 1. Target elements of W7-X divertor.

temperature, emergence of progressive hot spots) during cycling loads indicates a degradation of the bond between the tile and the heat sink, which developed during the high heat flux cycling. From there, the results of HHF testing demonstrated the heat removal capability of the pre-series elements from Batch #3 for the nominal heat flux requirements in W7-X. No large detachment or loss of tiles was observed, even after 1000 cycles at 10 MW/m^2 performed on some tiles [6], but growing local surface temperature rise was noticed close to the free edge during the cyclic loading. This behaviour can be attributed to several factors: decrease of CFC thermal conductivity due to degradation of the CFC matrix, corrosion of the inner channels, degradation of CuCrZr thermal conductivity, modification of the behaviour of the defect-free reference element, initiation/propagation of cracks at the interface between the C/C and the AMC copper during the thermal cycling tests. Considering the HHF test results as the reference to judge the quality of the delivered elements, the discrimination of tiles with insufficient bonding quality among several events responsible for evolution of the surface temperature, needs a more comprehensive analysis of these data in order to identify the temperature rise due to progressive damage at the interface.

4. Examination and discussion after high heat flux testing

4.1. SATIR infrared post-examination

The testing protocol of the SATIR test bed is based on a thermal transient induced by an alternative hot/cold water flow in the heat sink structure. The design of the system allows to control several elements in parallel where the surface temperature of each tile of the elements is monitored by an infrared camera. The tile surface temperature transients are compared with those of an assumed 'defect-free' element (so-called reference) and the maximum of the temperature difference (so-called DTref_max) is stored for each tile. A bonding flaw between heat sink and armour will be detected by a high value of DTref_max. This approach gives quantitative information on the global thermal efficiency of the component prior to its installation into the vacuum vessel of a fusion machine. This facility permits, also through an acceptance test based on a reference element, the detection of variability within the produced elements.

The results show a global decrease of the average quality of elements from Batch #3 in terms of thermal efficiency after HHF testing compared with the SATIR pre-examination [7]. Hence, to understand this behaviour on a large number of tested tiles, additional investigations were launched such as metallographic studies using an optical-microscope. The examination was mainly focused on the interface between the C/C tiles and the AMC copper. Two elements (4S-005 and 4S-037) of the Batch #3 have been selected and a metallographic cutting has been undertaken for some tiles of these elements having an interest. The areas of interest were defined by using the IR-images during the HHF tests including temperature evolution as a function of the heat flux cycles and the IR-images during the SATIR post-examination in terms of DTref_max cartography.

4.2. Metallographic observations

Main features of the 13 selected samples (i.e. areas of interest) taken for metallographic observations are summarized in Fig. 2. The acceptance criteria of each test (SATIR non-destructive post-examination and GLADIS HHF tests) are based on the definition of threshold values. Values between the accepted and not accepted range are defined as questionable. This range takes into account the repeatability of the measurement and other factors contributing to the uncertainty of measurement [8].

Fig. 3 shows a comparison between the results of reception tests (GLADIS and SATIR) based on respective acceptance criteria and the metallographic observations for each selected sample (i.e. sectioned tile). A good agreement is observed between the predictions provided by each reception test and the metallographic analysis on most analysed samples.

- The micrographs taken from metallographic cuts of tiles without temperature rise during the GLADIS tests and/or declared conform by the SATIR reception test, revealed an healthy bonding from metallographic observations, excepted for two tiles (4S-005/T8A> and 4S-037/T5A<),[1] where, the cracks exhibited by metallography are in disagreement with SATIR and/or GLADIS results. Concerning SATIR post-examination, the disagreement about the tile 4S-037/T5A< can be explained by a questionable zone located on the reference element in the concerned area which disturbs locally the measurement in terms of DTref_max.
- The micrographs taken from metallographic cuts of tiles with temperature rise (progressing hot spots) during the GLADIS tests and/or declared non-conform by the SATIR reception test, showed systematic failures from metallographic observations, excepted for one tile (4S-005/T4B>) where the defect indication observed by SATIR is not correlated with an evidence of crack by the metallography. However, a misalignment/disorganization of fibres in the CFC material with respect to the normal vector of the bonding interface (Fig. 4) was observed in this area and could explain this behaviour. In addition, this observation confirms PLANSEE SE investigations [9] which showed that due to CFC material characteristics (intrinsically inhomogeneous and anisotropic), some tiles were characterized by a tilting of the ex-pitch fibres with respect to the bonding interface which induced some fibres with no direct connection to the AMC–Cu interface.

Analyses of metallographic cuts of the failed interface have mainly shown that crack propagated on the free lateral edge of damaged tiles with two modes of fractures:

- The tooth structure (i.e. copper cones) cover by the carbide layer is fully detached from the laser structured C/C surface, just above the cones (Fig. 5).
- The tooth structure undergoes a shearing near the interface and cracks are visible through the copper cone and the CFC (Fig. 6).

[1] The symbols < and > are used as a reference mark which inform the flow direction of the cooling water during the tests close to the free edge examined *(namely, upstream < downstream or downstream > upstream).*

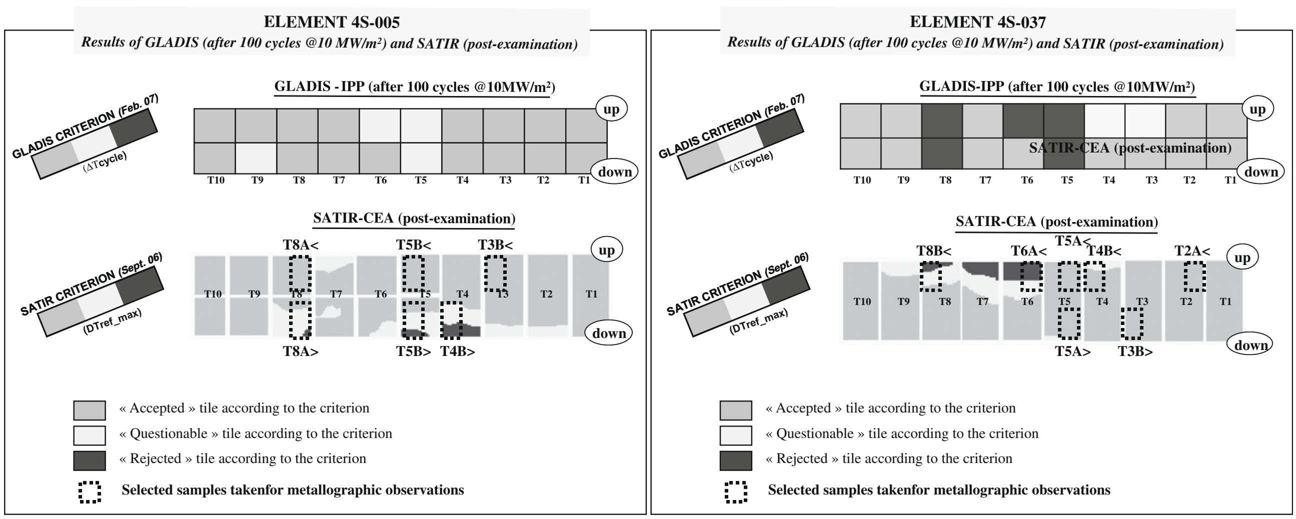

Fig. 2. Mean features of the 13 selected samples from 4S-005 & 4S-037 elements for metallographic observations.

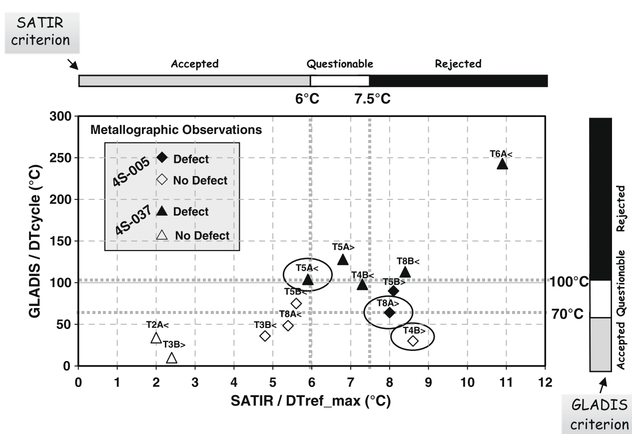

Fig. 3. Comparison between the results of reception tests (SATIR post-examination and HHF test) and metallographic observations.

A crack that had propagated inside the CFC above the interface was also observed on the tile 4S-037/T5A> (Fig. 7), but more often, the cracks within damaged tiles were hybrid and propagate indifferently in the CFC above the copper cones and at the interface through the copper cone and the CFC between two cones.

To evaluate the detection accuracy of two tests (SATIR post-examination and GLADIS tests), the size of cracks observed by metallography was measured. Crack depths were estimated to be extended from the free edge between 3 and 10 mm. The maximum size was observed for a strip defect on the tile 4S-037/T6A<, whereas the minimal size was observed for a corner defect on the tile 4S-005/T8A>. By comparison with these results, the results of HHF testing indicated a surface temperature rise range from 65 °C to 240 °C and the NDE using infrared thermography predicted values ranging from 8 °C to 11 °C in terms of DTref_max.

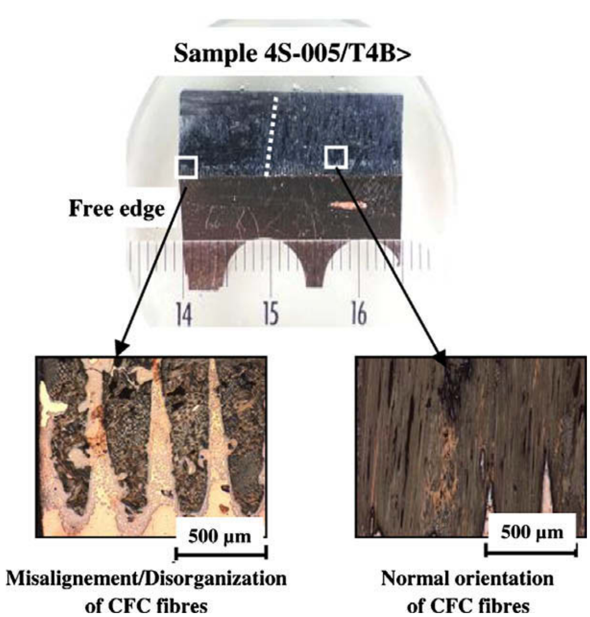

Fig. 4. Sample 4S-005/T4B>: misalignment/disorganization of fibres in the CFC material.

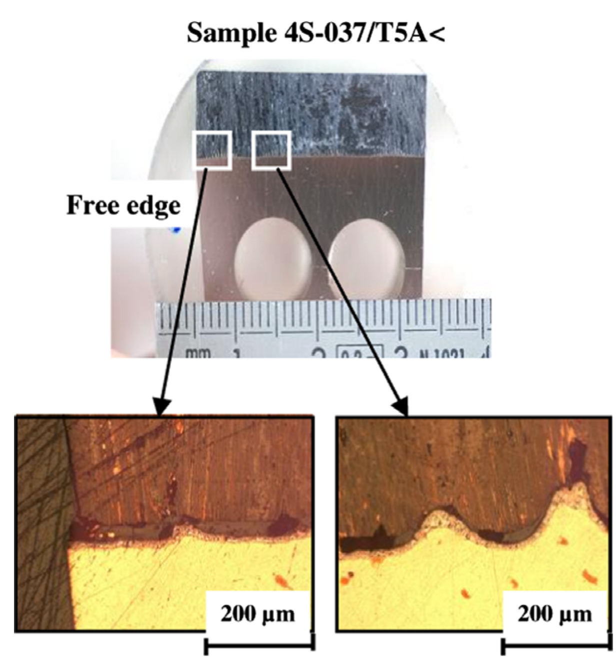

Fig. 5. Typical crack by detachment above the copper cones (observed on the samples: 4S-005/T5B>, 4S-037/T5A<, 4S-037/T8B<).

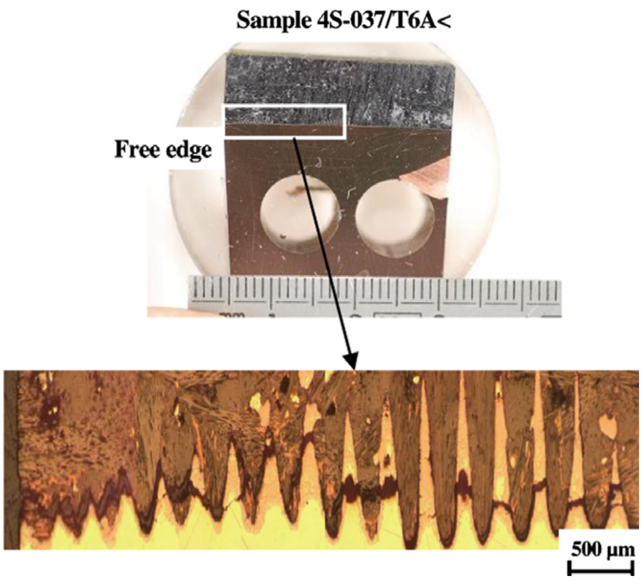

Fig. 6. Typical crack by shearing of copper cones (observed on the samples: 4S-005/T8A>, 4S-037/T4B<, 4S-037/T6A<).

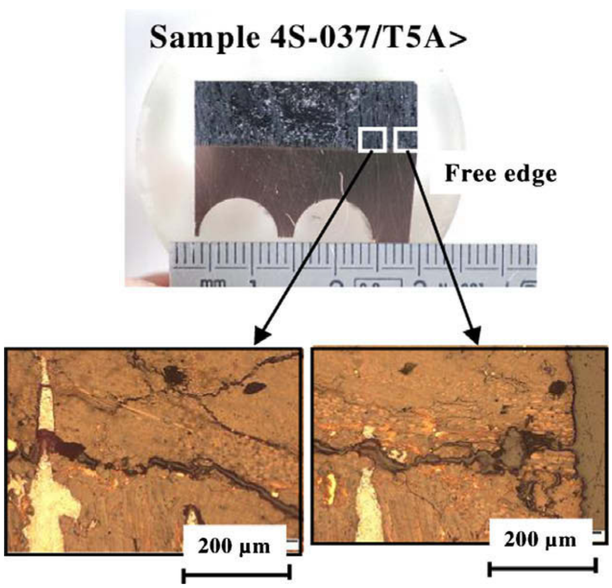

Fig. 7. Typical crack initiated inside the CFC observed on the 4S-037/T5A> sample.

5. Conclusion

The reception tests performed on the W7-X target pre-series elements by means of infrared thermography inspection in SATIR and HHF thermal cycling tests in GLADIS, exhibited some tiles with thermal inhomogenities, which developed during high heat flux testing.

Metallographic studies were performed in attempt to correlate the surface temperature rise during the high heat flux tests in GLADIS and/or the poor thermal response measured during SATIR post-examination to defects. The results obtained from some representative selected samples are significantly correlated with the acceptance criteria from GLADIS and SATIR tests. Considering the metallographic results, the criteria of acceptance associated with SATIR inspection and HHF testing are reliable and validated (100% of selected samples declared like acceptable were also detected as healthy from metallographic observations). On the other hand, the criteria of rejection of the two reception tests require careful interpretation due to the features of CFC material. Intrinsically inhomogeneous and anisotropic, the CFC material might be responsible of an inaccurate interpretation inducing an incorrect diagnostic in terms of acceptance.

Finally, the post-testing investigations confirms the necessity to improve the design at the interface between C/C tiles and the AMC copper with respect to a further reduction of stress in this zone under heat loading. The manufacturing of additional W7-X target pre-series elements, including these improvements, has been launched and will be tested in GLADIS [10], to select the most favourable bonding technique for the serial fabrication.

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