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Marc Missirlian, H. Greuner, T. Höschel, Ch. Linsmeier, M. Richou, et al.. Influence of CFC quality on the performance of TS limiter elements under cyclic heat loading. *Fusion Engineering and Design*, 2011, 86 (9-11), pp.1579-1582. <10.1016/j.fusengdes.2011.03.113>. <hal-04620308>

HAL Id: hal-04620308

<https://hal.science/hal-04620308v1>

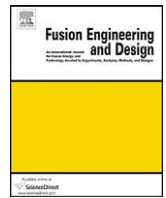
Submitted on 9 Jul 2024

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Influence of CFC quality on the performance of TS limiter elements under cyclic heat loading

M. Missirlian^{a,*}, H. Greuner^b, T. Höschel^b, Ch. Linsmeier^b, M. Richou^a, M. Lipa^a,
B. Boeswirth^b, J. Boscary^b

^a CEA, IRFM, F-13108 Saint-Paul-Lez-Durance, France

^b Max-Planck-Institut für Plasmaphysik, EURATOM Association, Boltzmannstrasse 2, D-85748 Garching b. München, Germany

ARTICLE INFO

Article history:

Available online 8 May 2011

Keywords:

Tore Supra
Plasma-facing components
CFC
High heat flux testing

ABSTRACT

For the fabrication of 600 actively cooled finger elements for the Tore Supra pump limiter in operation since 2001 it was necessary to rely on two different batches of the CFC N11 grade (Carbon Fibre reinforced Composite) namely so-called SEP N11-92 (fabricated in 1992) and N11-98 (fabricated in 1998). It came out during the incoming inspection of the fingers that the bonding quality was degraded for the 98-batch so that an important number of tiles had to be repaired. Due to the coming upgrade of the Tore Supra heating system, two high heat flux test campaigns were performed on the neutral beam GLADIS facility (IPP Garching, Germany) including micro-structural analyses in order to evaluate, compare and understand the fatigue behaviour of 92- and 98-batch finger elements.

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1. Introduction

For the roughly 12000 tiles of the Tore Supra (TS) pump limiter structure [1,2] it was necessary to rely on two different elaboration batches of the same CFC N11 grade (Carbon Fibre reinforced Composite) namely so-called SEP N11-92 (fabricated in 1992, delivered in individual blocks of size $27 \times 35 \times 270 \text{ mm}^3$) and N11-98 (fabricated in 1998). The latter, ordered in 8 mm thick plates, suffered an accidental overheating during the graphitisation process at SNECMA. While this led to a slight modification of CFC properties compared to the specifications, the material was finally accepted [3]. From statistic analysis, it was deduced, that mainly the density and the stiffness (ultimate bending angle) were higher than for the N11-92 material. The Active Metal Casting (AMC[®]) bonding process was optimised for this material batch by the manufacturer PLANSEE and qualified through mock-ups, prototypes and short antenna fingers. During fabrication and a subsequent very limited high heat flux (HHF) test campaign (sampling rate of standard elements $\sim 1.4\%$) at TS design value (10 MW/m^2 , 1000 cycles [4]), finger elements equipped with N11-98 tiles showed a much higher failure rate and degraded performances. Following the reception of series elements based on visual inspection (detection of cracks at the interface) and on SATIR thermography [5], an important number of tiles had to be repaired during fabrication.

Due to a tight time schedule, this degradation of performance has never been investigated in details. With the recent upgrade of heating power in TS, it is expected to reach the design heat flux in the range of $8\text{--}10 \text{ MW/m}^2$. Therefore additional HHF tests were undertaken also at lower heat loads, as well as micro-structural analysis in order to evaluate, compare and understand the fatigue behaviour of 92- and 98-batch finger elements in view to operate the pump limiter safely.

2. High heat flux tests campaign at GLADIS

Two HHF test campaigns in 2009/2010 were performed on the neutral beam GLADIS facility (IPP-Garching, Germany) [6].

During the *first campaign* (2009) a “virgin” (never loaded finger element) 92-batch element (N° S703) has been compared with a “plasma exposed” 98-batch element (N° S494) which has been removed from the Tore Supra limiter for dedicated analyses. It should be noticed that such an element has been subjected so far to maximum in-situ heat fluxes up to $1\text{--}2 \text{ MW/m}^2$ during roughly several hundreds plasma discharges. After removal from TS, infrared SATIR inspection [4] suggested no tile damage on these finger elements.

The *second campaign* (2010) included the same 92-batch element (N° S703) and a “virgin” 98-batch finger element (N° S390). Infrared SATIR inspection before testing suggested also no tile damage on this finger element.

Two finger elements were installed hydraulically in parallel and mounted perpendicular to the neutral beam axis in the GLADIS facility so that the beam loaded respectively two elements at the

* Corresponding author. Tel.: +33 4 42252598; fax: +33 4 42254990.
E-mail address: marc.missirlian@cea.fr (M. Missirlian).

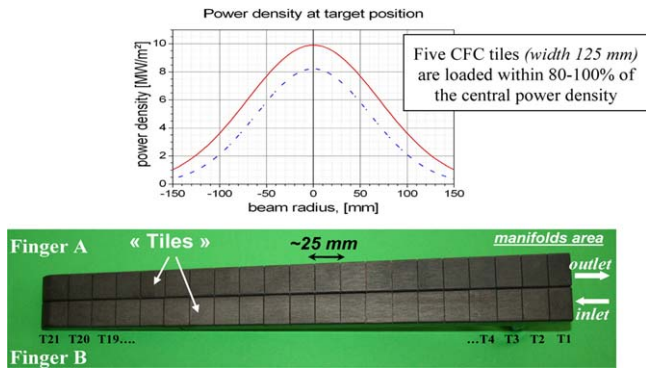


Fig. 1. Assembly of two finger elements for the HHF tests and the applied power density profiles of the GLADIS facility.

same time (Fig. 1). Due to the Gaussian profile of the hydrogen beam inducing a non uniform heat load on the finger elements, a relevant tile position was chosen to place the central heat flux (i.e. maximal heat flux) on a dedicated area. During the test campaigns the finger elements could be shifted if necessary, giving the possibility to load different CFC areas. A typical pulse length of 10 s per cycle was applied, because the finger achieved the thermal equilibrium after 5 s of loading (hydraulic test parameters see §2.3). For the surface temperature measurements an IR camera and one- and two-colour pyrometers were used. The component temperature was measured with thermocouples (type K) positioned within the cooling structure and the CFC tiles. A detailed description of the beam profiles and the used diagnostics is given in [6,7].

2.1. Results and discussion of first experimental campaign (2009)

The beam profile was centred on tile T8, loading tiles T6-T10 between 8 and 10 MW/m². At the mentioned beam location, the “virgin” 92-batch element (S703) survived without notable degradation of the CFC/Cu bonding or growing hot spots 3190 cycles at 10 MW/m² at a surface temperature (measured by IR camera) of about 900 °C. A temperature increase of ~60 °C (based on thermocouple measurements) between cooling structure and CFC tile T8 during the whole cycling campaign confirmed the good bonding quality of 92-batch finger and the promising behaviour in terms of fatigue lifetime up to 10 MW/m² in agreement with the full power operating requirements.

The cycling of the “plasma exposed” 98-batch element (S494) generated a relatively fast debonding of 3 tiles (Fig. 2):

- Tile T9: ~10 MW/m², first indication of delamination after approximately 90 pulses. T_{surf}>2000 °C after approximately 200 pulses. Tile removed after 777 pulses.
- Tile T8: ~10 MW/m², first indication of delamination after approximately 1700 pulses. T_{surf}>2000 °C after approximately 2000 pulses. Tile removed after 2146 pulses.
- Tile T6: ~8 MW/m², first indication of delamination after approximately 2300 pulses. T_{surf}>2000 °C after approximately 2400 pulses. Tile removed after 2742 pulses.

Delamination at the CFC/AMC interface propagated on tiles T6 and T8 parallel to the cooling channel direction and on tile T9 perpendicular to the cooling channel direction.

These results confirmed the degraded performance of the CFC/AMC interface for the 98-batch fingers showing several growing CFC surface hot spots after roughly a few hundreds of load cycles. They are followed by a fast increase of surface temperature due to a progressive delamination of armour tiles. The initial average CFC surface temperature of 800-900 °C measured for a heat load

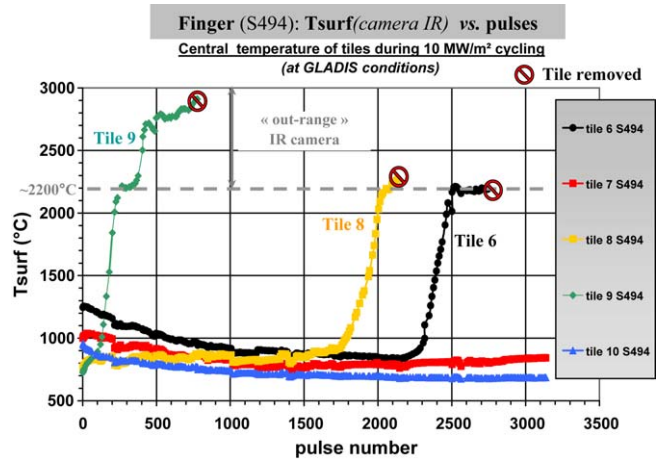


Fig. 2. Test campaign 2009: Surface temperature vs. pulse number of finger element S494 (N11-98).

of 10 MW/m² at the beginning of cycling tests, increased by 50% to 100% after ~100-150 and ~200-250 cycles, respectively, once the first indication of delamination was observed.

Finite elements calculations show that doubling of tile (central) surface temperature is reached for a delamination fraction (parallel to the cooling channel direction) of 40% at the CFC/AMC interface. Experimental damaged tiles were removed after a delamination fraction of about 60% in order to avoid excessive carbon pollution (surface temperature >2000 °C) in the vacuum chamber of GLADIS facility. In addition both results (experimental and calculations) demonstrate the “tolerance” of critical heat flux behaviour of the flat tile design (the transferred tile heat load to the heat sink is spread over the entire copper compliant layer) under such CFC/Copper interface failures.

2.2. Results and discussion of second experimental campaign (2010)

The beam profile on experimental assembly S703 (N11-92) and S390 (N11-98) was first centred on tile T16 then on T13 and finally on T14/T15 (Fig. 3). At the mentioned beam locations, the “virgin” 92-batch element (S703), already tested locally around T8 during the 2009 campaign, survived again without defects indication.

As shown in Fig. 4, the “virgin” 98-batch element (S390) generated rapidly defects:

- Tile T17: ~10 MW/m², a large defect occurred after roughly 200 pulses.

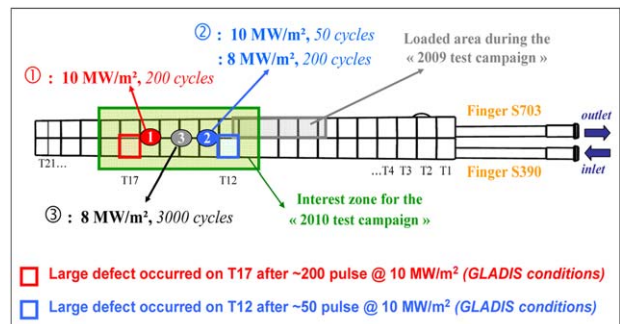


Fig. 3. Heat loading protocol of test campaign 2010.

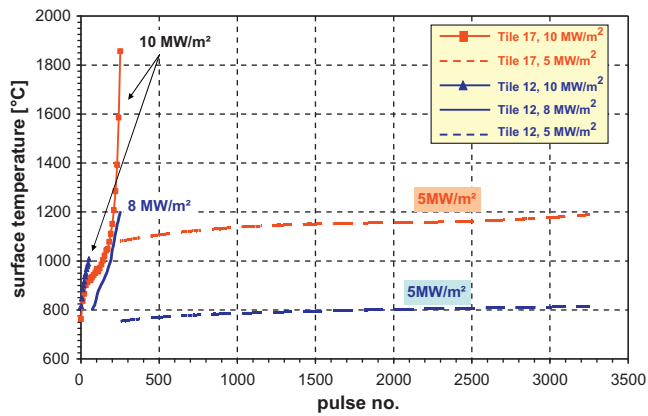


Fig. 4. Test campaign 2010: Surface temperature evolution as function of power density and pulse number - Central temperatures of the defect tiles T12 and T17 of element S390 for heat fluxes ranging from 5 to 10 MW/m².

- Tile T12: ~ 10 MW/m², a large defect occurred after 50 pulses, while after additional 200 pulses at ~ 8 MW/m² only a slowly growing defect was observed.

The 8 MW/m² beam was finally centred on tile T14/T15 to continue the cycling. Corresponding to the beam profile, tiles T12 and T17 were loaded with 5 MW/m². 3000 pulses were sustained at an average surface temperature of 1150°C and 800°C, respectively. The pre-damaged tiles T12 and T17 survived the whole test campaign without indication of evolution of tile delamination at the CFC/AMC interface.

The results of this second campaign, comparing plasma unexposed elements, confirmed the degraded bonding quality for the 98-batch finger element in terms of fatigue lifetime under heat flux beyond 8 MW/m². In spite of no water leakage affecting directly the thermo-mechanical integrity of elements, a growing CFC surface overheating can induce dramatic surface erosion which is obviously incompatible with LPT long pulse scenarios. However, a stabilisation or drastic slow down of damage evolution at lower heat load levels, typically lower than 6 MW/m² can be expected from these experimental results.

2.3. GLADIS tests-Tore Supra operation comparison

Based on the assumption that the fatigue mechanism of the fingers during fatigue lifetime is mainly driven by the CFC/Cu joining interface temperature, comparative thermohydraulic and thermomechanical calculations by finite element method, showed that the equivalent heat flux to e.g. 10 MW/m² in GLADIS (8.5 m/s cooling water velocity, ~ 20 °C inlet temperature and 1 MPa static pressure) corresponds to about 8 MW/m² at TS operating requirements with a pressurized hot water circuit (namely, 9 m/s cooling water velocity, ~ 130 °C outlet temperature and 3 MPa outlet pressure).

Consequently, this led to following results in TS cooling conditions which are finally of interest: the element bonded with N11-92 tiles survived without notable degradation of the CFC/Cu interface and growing hot spots 3190 cycles at 8 MW/m², while the 98-batch elements were damaged (growing hot spots, delamination of several tiles) after roughly a few hundreds of load cycles at 6-8 MW/m² in steady state conditions. From experimental results with N11-98 tiles, a stabilisation or drastic slow down of damage evolution can be expected at lower heat load levels, typically lower than ~ 5 MW/m². This outcome can hence enable in spite of interface failures, to perform tolerable operational con-

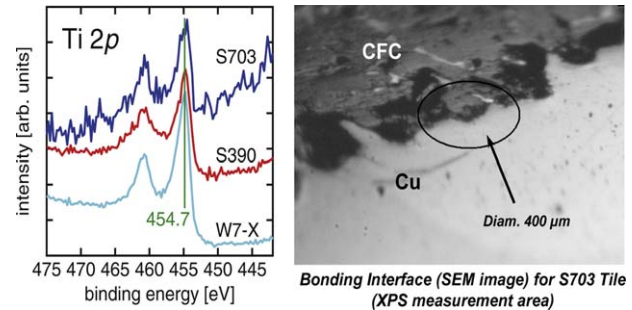


Fig. 5. XPS spectra in the binding energy region of Ti 2p, comparing the tiles S703 and S390 after HHF testing as well as for a W7-X divertor tile element (for comparison).

ditions once a relevant power handling of plasma scenarios is achieved.

3. Post mortem analyses

Optical microscopy imaging of the CFC/AMC interface at different tile locations revealed a lower AMC copper infiltration depth on N11-98 tiles compared to the N11-92 elements with average values of respectively 1.4 mm and 1.9 mm.

In addition, the bonding layer is investigated by X-ray photoelectron spectroscopy (XPS) in order to investigate the presence of the AMC bonding layer and the chemistry at the interface. The bonding interface is compared for the tile element S703 (surviving the HHF tests) and the tile element S390 (failed the HHF tests). The XPS spectra are measured with Al K α radiation in order to avoid the Cu Auger peaks to overlap with the Ti 2p binding energy, despite the lower resolution compared to Mg K α . The XPS analysis detects Ti on all measured interfaces (Fig. 5). The AMC bonding layer therefore is present in both S703 and S390. Moreover, the position of the Ti 2p_{3/2} peaks is in all cases at a binding energy at 454.6 eV. This binding energy is characteristic for Ti in TiC [8] and confirms that during the bonding process the Ti reacts with the carbon from the graphite. This is the case for both the failing S390 and the S703 elements. As seen in Fig. 5, also a comparable W7-X divertor component shows this interface reaction. The formation of the TiC is also detected in the C 1s binding energy region. From these XPS chemical analyses it can be concluded that the bonding failure of tile S390 cannot be attributed to a missing bonding layer between copper and the graphite tiles, in particular to a missing reactive Ti component.

4. Conclusion

Two high heat flux test campaigns in the GLADIS test facility confirmed the degraded bonding behaviour of the CFC/Copper interface on finger elements armoured with the so-called CFC N11-98 from SEP in terms of fatigue life time. A stabilisation or drastic slow down of damage evolution can be expected at lower heat load levels.

The different analyses show that the cause of the degraded bonding behaviour of CFC N11-98 tiles, may be “multi-factorial” such as: modified material properties during the elaboration process as already mentioned, a not optimized AMC bonding technique (CFC/AMC wettability problems) and a reduced laser treatment depth of the CFC tiles for copper infiltration. Post mortem analysis of the bonding interface confirms the presence of Ti and the TiC formed during the AMC bonding process. Finally, main technical lessons learned by this study for a successful manufacture series and a reliable behaviour in terms of fatigue lifetime in-service is that, prior to the launching of manufacture series; each delivered batch material has to be fully qualified through pre-material analysis and relevant samples. Furthermore, even if manufacture process

must offer margins in order to be compliant in regards to materials properties, any non-conformity of materials must imply a new qualification through a full characterization program.

Acknowledgments

This work, supported by the European Communities under the contract of Association between EURATOM and CEA, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission. Furthermore, the HHF tests carried out in the GLADIS facility of the IPP-Garching were performed under the grant N° 03FUS0014A from the Federal Ministry of Education and Research. The authors are sole responsible for the content of this document.

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