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High heat flux components in fusion devices: from current experience in Tore Supra towards the ITER challenge

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Abstract

A pioneering activity has been developed by CEA and the European industry in the field of actively cooled high heat flux plasma facing components in Tore Supra operation, which is today culminating with the routine operation of an actively cooled toroidal pumped limiter (TPL) capable of sustaining up to 10 MW/m^2 of nominal convected heat flux. This success is the result of a long lead development and industrialization program (about 10 years) marked out with a number of technical and managerial challenges that were taken up and has allowed us to build up a unique experience feedback database, which is displayed in the paper.

1. Introduction

The future progress of acceptable plasma wall interaction conditions depends on integrated physics and technology solutions. The full integration is a very demanding process, involving complex R&D, an industrial manufacturing route and complex implementation requirements for the system to be installed inside the plasma vessel. Tore Supra is the first large tokamak ($R = 2.36$ m, $a = 0.72$ m) designed for long pulse operation with a high level of additional power (~20 MW, 30 s then 1000 s) [1]. From the very beginning of the project, this required the implementation of actively cooled plasma facing components. The first generation of components exhibited some weaknesses that were due essentially to the difficulties encountered in joining carbon to a metallic substrate [2]; this was even more difficult when too complex designs have to be implemented [3]. A new project (so-called CIEL for Internal Components and Limiters in French) was launched to install a new generation of reliable high heat flux (HHF) Plasma Facing Components (PFCs), based on hardened copper alloy heat sink structures covered by a CFC armour. These have been developed in order to enable a large enough power exhaust capability. This resulted in a state of the art actively cooled high heat flux component, the so called finger element, which is able to remove up to 10 MW/m^2. A schematic representation is displayed in Fig. 1. In the frame of CIEL project, about 600 of such high performance parts have been manufactured to build the 7.6 m^2 Toroidal Pump Limiter (TPL) [4]. This assembly has been operated in Tore Supra since Spring 2002, participating to a new world record with the achievement of a 4.2 min long discharge, involving the injection of about 0.75 GJ [5].

In spite of a well defined R&D programme, and a robust design [6], some difficulties occurred during the manufacturing phase, resulting in delivery delay. The experience gained is extremely important and consequently, the achievement of the fully integrated programme, enables us to stress the major requirements for HHF PFCs in fusion devices:

- a well developed R&D effort focused towards the major technological issues (here, mainly the quality

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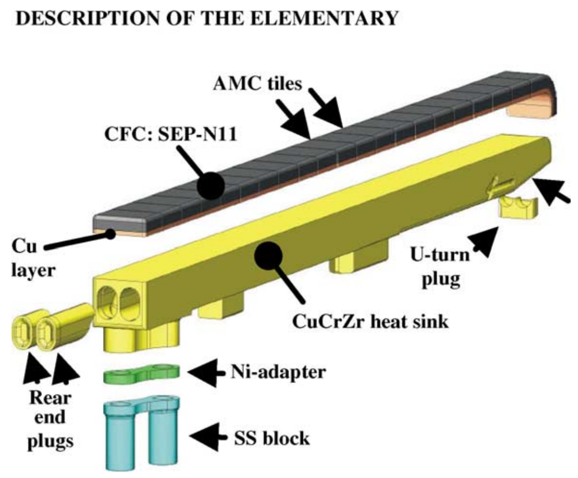

Fig. 1. Break up view of the 'finger' element of the Tore Supra toroidal pump limiter stressing the material assembly.

of the bond between heterogeneous materials: CFC and metals);

- a procedure to integrate in the design the experience gained from R&D, and the constraints of industrialisation processes;
- the development of reliable and benchmarked qualification and acceptance tests leading to an efficient industrial manufacturing qualification;
- the implementation of the foreseen operating conditions with in situ monitoring capabilities.

These points will be summarized in the three following subsections, based on the experience gained in Tore Supra and discussed in view of the ITER construction.

2. Major technical issues

2.1. Bonding techniques

The major technical issue that has to be solved is the assembly of a substrate which is acceptable next to the plasma to a heat sink which could provide both the heat exhaust into pressurized water and mechanical integrity. In Tore Supra, as in ITER, the former is carbon while the latter is a hardened copper alloy. It is important to also notice that this metal has to be linked to stainless steel which is the metal used for the cooling pipes.

The carbon material is a carbon–carbon fibre composite (CFC). A homogeneous CFC with good mechanical and thermal properties was chosen (N11 from SEP-SNECMA) [7]. The major difficulties for this kind of materials arise from the variability of the production from one batch to another and even during a single batch, since the production process is unable to achieve completely similar results. To give a sole example, the density of the material varied from 1.76 to 1.81 in one batch and from an average of 1.79 to an average of 1.85 from one batch to another. This implied obviously significantly modified mechanical and physical (e.g. thermal conductivity λ) properties.

The hardened copper alloy CuCrZr was rapidly preferred to the dispersion strengthened Glidcop essentially because its extremely low ductility preventing any welding. However, different companies producing CuCrZr do not elaborate the material in a similar way and the composition may differ from one to another. Welding tests were done, so as to assess the ability to minimize cracks within the seam weld. The scientific output of these investigations is still not completely clear and a significant R&D programme is thus still required [8].

As far as the carbon copper joining is concerned, OFHC copper has already been used as an intermediate compliant layer in the first generation of Tore Supra PFCs. However, in spite of optimisation, the brazing techniques which were used at that time, appeared still insufficient in view of the requirements for brazing temperature cycling. This required a further procedure to restore the material mechanical properties of the whole element, while making element repair difficult. This is the reason why the active metal casting technique (AMC®), developed by the Plansee company, was finally chosen. This ensures a very strong CFC–Cu mechanical attachment. The complete joining is a two phase process, creating the C/C–OFHC and the OFHC–CuCrZr interfaces in two successive separate steps.

The first step consists of a laser treatment of the CFC tile surface to be bonded (machining of micro cone shaped holes), followed by Active Metal Casting (AMC®) of a 2 mm thick, soft copper compliant layer, onto the rear side of each CFC tile. The quality of the CFC/soft-copper joint homogeneity is then checked by X-ray radiography perpendicular to the tile surface, while the occurrence of eventual thin cracks in the CFC is detected by lock-in thermography, a new developed process. The second step consists of EB (electron beam) welding of the AMC tiles in order to create a thermally conductive interface between the OFHC layer and the CuCrZr heat sink. The heat affected zone depends strongly on EB welding parameters. However the material properties change locally (while the bulk material remains unchanged) and therefore are restored (e.g. thermal conductivity), as far as possible, by an adequate heat treatment. In addition, CuCrZr may retain its original strength as there is no uniform heating of the whole component as it would be the case with brazing procedures.

2.2. Other issues

Other unexpected difficulties were recorded such as the welding of the stainless tubes to the CuCrZr heat sink but they will not be described here as essentially the design could be easily improved to avoid such problems [9]. However, the production of the cooling channels within the heat sink also proved to be a little more difficult than expected. First, the two cooling channels were produced by deep drilling, a mastered technique which was not always successful (rejection rate up to 9% in the first batch due to out of specification deviation of more than 0.5 mm along the 500 mm drilling, decreasing to less than 2% as the process was improved through experience gained). Note that thermomechanical modifications of the material due to EB tile welding could be invoked. At the same time, the EB welding of the rear and front plugs, closing the channels, was achieved rather satisfactorily. This required some effort on the welding procedure during the R&D phase (including, mechanically tight adjustment of the pieces and, more recently fast cooling during the welding i.e. a shrinking treatment).

A final heat treatment has been performed for component outgassing and to restore, as far as possible, affected material properties. In the case of CuCrZr, the heat treatment is performed taking into account a well-defined relationship between temperature and holding time which has to be carefully monitored during the industrial process [10].

3. Technical feedback from the industrialisation process and monitoring

A major technical lesson from the experience gained with producing the limiter fingers is that the 5-year-long R&D programme carried out before manufacturing allowed us to gain confidence with in the validity of the various processes. Nevertheless, the production conditions for such elements do not allow us to draw quantitative conclusions about the risks of defects in each involved process. This is extremely problematic for systems which cannot be designed with wide enough margins and that rely on specific and not easily available materials, plus numerous and complex processes. Obviously, the number of processes should be minimised at least for those involving a non-negligible or non-assessed risk while a production involving many subcontractors will introduce additional risks linked with possible cumulative delays.

The industrialisation remains of course under the responsibility of the supplier. However, in such complex fabrication, an adequate relationship has to be developed with him so as to keep the production under control. The key to obtain this relationship relies at first on the quality of the technical specifications and on the capability of designing acceptance tests with well defined criteria. Good development of the tests was thus extremely important. Many tests were achieved by the supplier during the manufacturing process. The X-ray test on every AMC tile was essential before welding. Nevertheless, the difficulties encountered during the manufacturing again question the ultimate quality of the AMC bond. Lock-in thermography would permit ascertaining both the thermal and mechanical integrity of the bond before and after welding of tiles.

This possible improvement refers to the importance of the so called SATIR test. The method is based on IR measurements of tile surface temperatures during a thermal transient produced by hot/cold water flowing in the heat sink cooling channel. This inspection method was introduced during former improvements to inner first wall components [11] and is the subject of continuous improvement [12,13]. The definition of an acceptance criterion was the subject of extensive studies including the realisation of measurement on fingers with well defined defects.

The SATIR tests permitted detecting variability of the produced elements during the manufacturing; decreased quality (measured from the production rejection rate by both the supplier and us) after the first batch production was unexpected. However, the acceptance test permitted quantitatively monitoring of the production. Good acceptance rate for single tiles resulted in some case to a rejection rate approaching 50% [14], due to the number of tiles (21) on each element. This could have impaired the whole production: the production of additional elements being in any case affected by the severe delays related to providing materials (especially for CFC). Consequently two lines were investigated to reconcile the manufacturing aims. One was to understand the reasons for production variability and the other relied on the capability to develop a repair procedure. For both, a close collaboration between the suppliers and the laboratory proved to be a strong prerequisite. The repair process proved to be a required development during manufacturing. The principle involved exchanging a faulty tile for a new one without affecting the other acceptable tiles. A specific welding procedure was found to be effective [14]. It could be firmly validated by means of a HHF test [15], in good correlation with the SATIR test. The analysis of the problem proved to be less straightforward, as a consequence of the complex multi process procedure involved in the manufacturing route. However, the tile welding process, the thermal treatment procedure after welding and the CFC characteristics were questioned. If the second finding resulted in a direct correction, the first one was certainly more difficult to assess and consequently to correct. Finally, this allowed controlling both the delay and the quality of the production, albeit with some relaxation of the acceptance criteria.

The HHF tests were very efficient in the selection process of the ‘best’ technology for such PFCs. Afterwards, in 1996, 2 scale one elements were manufactured with the leading edges designed at 45° angle. Fatigue cycling performed in FE200 showed that the flat part of the components was able to sustain 1000 cycles at 14.5 MW/m^2 (nominal design: 10 MW/m^2), the limit being around 18 MW/m^2. However, the leading edges failed as soon as 9 MW/m^2 was reached (nominal design 8 MW/m^2). This last result led to a revision of the leading edge design. Two pre-serial prototypes with the current rounded leading edge were manufactured and successfully tested at FE200.

Eight standard fingers from industrial series manufacture were HHF tested at FE200 during the year 2000 and 2001 in two testing campaigns. It represents a sampling rate of only 1.4%. The first series gave evidence of manufacturing defects, confirming the overall SATIR detected defects (despite a non-absolute correlation). The second series allowed validating the repair process which proved to be efficient on the repaired tiles. Unfortunately, other tiles did not completely reach the specifications during cycling. This last observation stressed the difficulty of reaching the specifications on all the tiles. It led to accepting some relaxing (from SATIR acceptance criteria point of view) on a limited number (80) of elements, to keep the delivery delay acceptable. Such elements, which should likely sustain 5 MW/m^2 (more than 1000 cycles) could be installed in limiter shadowed zones where such fluxes are far from expectations.

The correlation between HHF tests and SATIR deserves some discussion. Ninety-one tiles of CFC-N11 dispatched on 8 standard fingers were pre-examined on the SATIR test bed, screened at 5 MW/m^2 on FE200, then fatigued at various heat fluxes (range from 5 to 10 MW/m^2) during more than 1000 cycles. Correlation between the thermographic examination and the initial screening at FE200 under 5 MW/m^2 is not completely systematic. Furthermore, as it is shown in Fig. 2, the correlation between failure under fatigue and initial screening is not systematic. However, it appears very clearly that all strong SATIR detected defects reveal tiles to be strongly damaged under heat flux, whereas for tiles obeying the acceptance criteria, 8% failed during fatigue.

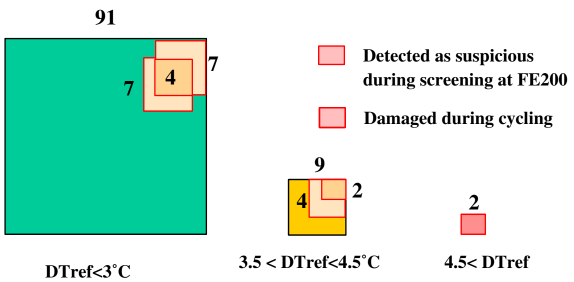

Fig. 2. Correlation between SATIR tests acceptance criteria and results from high heat flux tests.

Among these, only 57% were detected during FE200 screening. Furthermore, 43% of the tiles detected during FE200 screening did not fail after fatigue. The SATIR test has thus to be improved while some studies are also needed to better understand the detailed failure processes. This stresses the difficulty related to various defect typology. There are two possible explanations [15] for the loss of cohesion between CFC and copper; it could either be due to a crack within the CFC itself which appears suddenly at a rather high heat flux or to a bad adherence at the AMC interface in-between Cu–OFHC and CFC. This defect type displays a thermal resistance and may be detected by FE200 screening and SATIR through further improvements of both test facilities. This defect may however also be stable before developing slowly during fatigue testing.

4. Tore Supra operation with the Toroidal pump limiter

The monitoring of high heat flux elements is mandatory, to serve the two aims of immediate safety (in view of the few seconds thermal time constant involved) as well as of in situ behaviour assessment. It is based on the observation of surface temperatures using infrared endoscopes and fibres which were developed within the CIEL project [16]. The diagnostics have been partly installed. However, this monitoring is influenced by many parameters like additional thermal resistance in the structure or surface dust and layers. Their evolution in time complicates the thermal analysis and notably the transposition of surface temperatures to heat fluxes, which is the required information for the safety monitoring of actively cooled components.

Two experimental campaigns (2002 and 2003) have been carried out in Tore Supra since the complete upgrade of all plasma facing components. The toroidal pump limiter (TPL) allows reliable steady state operation at significant injected power (up to 8.5 MW peak, 4.3 min at 3 MW). One of the primary results is related to the abundance and diversity of carbonaceous deposits on plasma facing surfaces. These deposits and layers distort the infrared measures and the deduction of the incident heat flux from the temperature is difficult. However on highly loaded zones, this effect is minimised by erosion and it appears that such components operate with a constant surface temperature, regardless of the discharge duration. The delay until thermal steady state is characterised by the thermal time constant, which thus allows assessing the thermal status of the component. A simple 1D thermal calculation tool linked to the database has been developed and is used to allow flexible analysis of the ageing of the bond between the tile and the metallic cooling structure from the surface temperature measurement [17]. So far, no evidence of ageing has been observed after the two first years of operation.

It gives confidence in the bonding technology used to manufacture the high heat flux components of Tore Supra.

5. Conclusions

A pioneering activity has been developed by CEA and the European industry in the field of actively cooled high heat flux plasma facing components from the very beginning of Tore Supra operation. This work is today culminating with the routine operation of an actively cooled toroidal pumped limiter (TPL) capable of sustaining up to 10 MW/m^2 of nominal convected heat flux. This success is the result of a long lead development and industrialization program (about 10 years) marked out with a number of technical and managerial challenges that were taken up and has allowed us to build up a unique experience feedback database. This is illustrated in this paper with the specific example of the development of a high heat flux CFC-on-CuCrZr component from the design phase to tokamak operation.

Although ITER and Tore Supra HHF components designs are different, we believe that some general lessons learned from this experience do apply to ITER construction, in particular as far as the divertor plasma facing components are concerned. This, in particular, applies to the extreme importance of developing the characterization and qualification of the whole element, including R&D but also prototype and preseries qualification, preparing in detail acceptability procedures (criteria, test facilities) and fallback issues (repair processes), so that the margins remain under control up to delivery.

Finally, it is worth mentioning that recent R&D results [18] on the enhanced configuration of the technical solution adopted for Tore Supra (flat tiles AMC© bonded on hypervapotron concept) have reached the ITER divertor HHF requirements for the CFC components. As explained in this paper, the bonding techniques used has already proven to be mastered at the industrial level, which makes this enhanced concept an attractive candidate as a fallback solution to the reference design of the ITER divertor HHF components.

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