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Technological review of the HRP manufacturing process R&D activity

Eliseo Visca[a,*], A. Pizzuto[a], P. Gavila[b], B. Riccardi[b], S. Roccella[a], D. Candura[c], G.P. Sanguinetti[c]

[a] Associazione EURATOM-ENEA sulla Fusione, C.R. Frascati, Via E. Fermi 45, IT-00044 Frascati, Italy
[b] Fusion For Energy, C. Josep Pla 2, ES-08019 Barcelona, Spain
[c] Ansaldo Nucleare S.p.A., Corso Perrone 25, IT-16121 Genova, Italy

HIGHLIGHTS

- R&D activities for the manufacturing of ITER divertor high heat flux plasma-facing components (HHFC).
- ENEA and Ansaldo have jointly manufactured several actively cooled monoblock mock-ups and prototypical components.
- Successful manufacturing by HRP (hot radial pressing) and PBC (pre-brazed casting) of both W and CFC armoured small and medium scale mockups.
- ENEA-ANSALDO participate to the European programme for the qualification of the manufacturing technology for the ITER divertor IVT.
- A qualification divertor inner vertical target prototype successfully tested at ITER relevant thermal heat fluxes.

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ABSTRACT

ENEA and Ansaldo Nucleare S.p.A. have been deeply involved in the European International Thermonuclear Experimental Reactor (ITER) R&D activities for the manufacturing of high heat flux plasma-facing components (HHFC), and in particular for the inner vertical target (IVT) of the ITER divertor.

This component has to be manufactured by using both armour and structural materials whose properties are defined by ITER. Their physical properties prevent the use of standard joining techniques. The reference armour materials are tungsten and carbon/carbon fibre composite (CFC). The cooling pipe is made of copper alloy (CuCrZr-IG).

During the last years ENEA and Ansaldo have jointly manufactured several actively cooled monoblock mock-ups and prototypical components of different length, geometry and materials, by using innovative processes: HRP (hot radial pressing) and PBC (pre-brazed casting).

The history of the technical issues solved during the R&D phase and the improvements implemented to the assembling tools and equipments are reviewed in the paper together with the testing results.

The optimization of the processes started from the successful manufacturing of both W and CFC armoured small scale mockups thermal fatigue tested in the worst ITER operating condition (20 MW/m^2) through the achievement of record performances obtained from a monoblock medium scale mockup.

On the base of these results ENEA-ANSALDO participated to the European programme for the qualification of the manufacturing technology to be used for the procurement of the ITER divertor IVT, according to the F4E specifications. A divertor inner vertical target prototype (400 mm total length) with three plasma facing component units, was successfully tested at ITER relevant thermal heat fluxes.

Now, ANSALDO and ENEA are ready to face the challenge of the ITER inner vertical target production, transferring to an industrial production line the experience gained in the development, optimization and qualification of the PBC and HRP processes.

1. Introduction

The ITER operation programme foresees for the IVT strike point region, a steady state thermal flux of 10 MW m^{-2} and shorter transients during which the heat flux can reach up to of 20 MW m^{-2}. The plasma facing units are identified as the plasma facing components that have to deal with these high thermal and particles loads. Such high heat fluxes can be sustained only by components designed and manufactured accordingly. The technical design solutions have to guarantee a reasonable lifetime and to be affordable. The lifetime is limited mainly by thermal fatigue caused by cyclic thermal loads that induce high mechanical stresses to these components.

* Corresponding author. Tel.: +39 0694005581.
E-mail address: eliseo.visca@enea.it (E. Visca).

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The technical solutions considered today for the PFU of the ITER divertor IVT are mainly based on carbon or tungsten as plasma facing materials and copper alloys for the heat sink [1].

The selection of these materials is based on ITER physical and thermo-mechanical requirements [1]. Tungsten is a refractory metal with an extremely high melting point (3410 °C) and a RT thermal conductivity of approx. 140 $Wm^{-1} K^{-1}$. Its brittle behaviour will not impact its fatigue performances because it is used as functional armour material. Similar considerations can be applied to carbon materials, like carbon-fibre reinforced carbon matrix composite (CFC), when used in IVT because it can withstand very high-heat loads without the risk of melting. However, sublimation of carbon at elevated temperatures ($T > 2200$ °C) and tritium retention has to be considered as important issues.

Different requirements are foreseen for the heat sink. It has been identified in general terms as a precipitation hardened copper alloy structure that, by means of pressurized water coolant, is able to remove the incoming thermal load. To reduce stresses thermally induced by the thermal gradient during plasma exposure and enhanced by the mismatch of the CTE of the plasma facing (armour) and the heat sink materials, a pure copper compliant layer is used between them two.

2. R&D activities for the ITER divertor high heat flux components

The ENEA R&D activity on these subjects started at the beginning of the 2000 [2] and was focused to develop suitable technologies that were able to solve in a reliable way some technological issues:

- Capability of the component to withstand to high thermal loads at ITER relevant hydraulic conditions.
- Reliability of the joining technologies for copper to CFC and W bondings.
- Definition of the acceptance criteria for the components and in particular the lowest admissible defect size at the different joint interfaces.
- Development of non-destructive testing technique and procedure suitable for the ITER acceptance criteria.
- Performance degradation of the component under thermal fatigue cycling.

The ITER technical specification as well as the materials taken into account have followed the evolution of the ITER design and requirements.

In fact, the materials choice has been oriented towards industrially available materials and proven manufacturing technologies. Physical and mechanical properties, maintainability, reliability and safety requirements remain however the main aspects to be granted. The required good basic material properties have to be maintained through the manufacture process.

For the heat sink the investigated materials have been essentially copper alloys. Finally only two materials have been considered as candidates for ITER: CuCrZr and GlidCop®Al25. For CuCrZr the IG (ITER grade) has been identified and it differs from the standard one, mainly by its narrower range of Cr (0.6–0.9%) and Zr (0.07–0.15%) content. Also for GlidCop®Al25 the fabrication process was optimized, obtaining an improvement of ductility and reduction of anisotropy. The CuAl25-IG material is provided by the manufacturer under the trademark Glidcop®Al25-LOX-CR (low oxygen, cross-rolled).

The choice of plasma-facing materials for the high heat flux components is determined mainly by plasma compatibility, erosion lifetime and safety. The main material candidate is W, especially for the baffle zone, because of its resistance to erosion, low sputtering yield and its higher sputtering threshold energy. Several W grades from different suppliers (pure sintered W, cast W alloys, W–1%La_2O_3) were selected for investigation.

It has to be noted that both GlidCop®Al25 and W–1%La_2O_3 are not any more among the reference materials of ITER.

Since the beginning of ITER project, CFC has been the reference design solution for the lower part of the inner vertical targets (IVTs) due to its absence of melting, high thermal shock and thermal fatigue resistance (low crack propagation) and high thermal conductivity.

In view of the ITER procurement, in order to establish a competitive scenario among the EU industries, not only for the manufacturing technologies, but also for the suppliers of the various materials, several CFC grades have been identified and investigated. The 3D CFC Sepcarb®NB 41 produced by Herakles (former Snecma Propulsion Solide)–France is now the reference material. Meggitt MEGGAGARD 3D CFC (produced by Meggitt – UK) and Toyo Tanso CFC CX 2002U (2D felt-type material) – Japan are valuable alternatives which are being assessed.

Recently, IO has decided to assess the possibility to use a full W divertor from the start of ITER operation. This is on line with the F4E initiative to develop a full W divertor which was undertaken in 2010.

3. Design evolution: issues and technical solutions

The main achievement is that the manufacturing technology for the ITER divertor IVT has been prequalified.

The PBC/HRP (pre-brazed casting, hot radial pressing), developed by ENEA-ANSALDO has confirmed that the maximum target heat flux of 20 $MW\,m^{-2}$ for the straight part where CFC is foreseen can be sustained with good reliability [2–5].

The curved part where W is foreseen reaches in ITER a maximum heat flux of 15 $MW\,m^{-2}$. Also in this case the qualified technologies (casting and HIPing or HRP) have demonstrated that they can guarantee the required reliability in term of heat flux and operational life.

Even if the ITER requirements for divertor HHF components have not changed during years, the technological solutions that have been investigated and tested for the design and manufacturing have been modified and improved.

However, the objective to arrive to a reliable manufacturing technology foreseen a qualification path (Fig. 1) that passes through the quality acceptance that consists in suitable non destructive controls and final high heat flux cycling testing reproducing the operational requirements.

Three main geometries (Fig. 2) have been considered suitable for the design and each one presents advantages and disadvantages in terms of performance and robustness [6]. A copper interlayer, that acts as a compliant layer to reduce the residual stresses after the joining and during operation, is still foreseen between armour and heat sink.

All these three options have been developed following the requirements of the ITER design.

The ‘flat tile’ design where the armour is used as a tile to protect the massive heat-sink was widely investigated. The advantages of this solution are that the armour material (CFC, W) is the expensive part of the component that in this case its amount is as much as it needs to protect the heat sink and its easier manufacturing and repairing process. The disadvantage is the high residual stresses that are concentrate in the edges that and which constitute initiators for the joint failure. The cooling channel is obtained by machining the bulk heat-sink.

The ‘brush’ design can be considered as an evolution of the ‘flat tile’ where the armour surface is deeply machined in the