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Status on the W monoblock type high heat flux target with graded interlayer for application to DEMO divertor

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HIGHLIGHTS

- Develop advanced actively cooled concept.
- Improve the quality of material joining for DEMO divertor to survive neutron irradiation and heat loading up to 20 MW/m^2 during transient.
- Use a W/Cu functionally graded material (FGM) interlayer instead of the copper interlayer which is used in the present ITER divertor design.
- Seven actively cooled mock-ups were manufactured. Each mock-up is equipped with 10 tungsten tiles.
- All the manufactured mock-ups were examined with infrared thermography (SATIR Facility) and US testing and reveal a good interface quality

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ABSTRACT

The divertor is the key in-vessel plasma-facing component being in charge of power exhaust and removal of impurity particles. In DEMO, divertor target must survive an environment of high heat fluxes (∼up to 20 MW/m^2 during transient) and neutron irradiation. This paper presents the first part of the development for the realization of an advanced actively cooled concept aiming at improving the quality of material joining. It is based on the use of a W/Cu functionally graded material (FGM) interlayer instead of the copper interlayer. For this preliminary development, the interlayer (∼25 μm) is made with PVD (Physical Vapor deposition) and composed of continuous gradient of W from 100% at the interior part of the tile to 0% at the external part while Cu varies from 0% to 100%. Hot isotactic pressing is realized to join the CuCrZr tube to W tile equipped with graded material. With infrared thermography (SATIR facility) and US non-destructive examinations, manufactured mock-ups show good interface quality.

1. Introduction

The European fusion Roadmap foresees a 'near-term' DEMO, a long-pulsed device with technology based on realistic extrapolation from ITER [1]. The baseline divertor plasma facing component is based on the ITER divertor design, and is consisting of tungsten monoblock as the plasma facing material and a CuCrZr structural pipe which are joined via a 'thick' (1 mm) copper interlayer [2]. Additionally, several other novel design concepts are being developed in parallel [1]. The operational reliability of the divertor target relies essentially on the structural integrity of the component, in particular, at material interfaces, where thermal stresses tend to be concentrated and thus cracks are most likely to initiate. In this context, the quality of material joining is of crucial importance and simultaneously a technological challenge. The use of a functionally graded material (FGM) as interlayer between W and CuCrZr is an option to improve bonding quality. As a first step to assess the applicability of FGM interlayer, we propose an approach based on the use of the tungsten monoblock type model with a similar geometry and materials combination for the armor and heat sink as in the ITER reference target design, but without any macroscopically identifiable soft copper interlayer. It is noted that a thin (< 100 μm) bond layer is still employed in the proposed design concept to attain a sufficiently robust bonding strength. With this technical choice the major benefits expected for this modified ITER-like design are as follows:

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1 The absence of the thick interlayer reduces the armor temperature as the heat conduction path to the heat sink is shortened. This effect is especially beneficial for the armor surface as it can mitigate fatigue cracking of the armor surface owing to lower temperature.
2 Under repeated high heat flux (HHF) loads, the soft Cu interlayer is likely to be subjected to plastic fatigue damage due to large plastic strain variations. The absence of a soft interlayer, being vulnerable to plastic fatigue, may enhance the structural integrity of a target component, in particular, under irradiation.

In this paper, an extensive engineering feasibility study is presented for the modified ITER-like divertor target design concept using a thin FGM interlayer. The results of dimensions definition based on finite element modeling (FEM), interface engineering, joining/fabrication of test mock-ups and non-destructive inspection test (NDT) are reported.

2. Requirements and assumptions

Main DEMO design parameters and requirements which impact the divertor design are listed in [3,4]. The peak incident heat flux is one of the "most significant" parameters. It will also prominently contribute to determine the wall heat flux and there-fore the margin to critical heat flux (CHF). At the strike point the maximum power density can reach about 20 MW/m^2 during slow transients. During a quasi-stationary operation the maximum power density is expected to reach 10–15 MW/m^2 [1]. Hydraulic parameters (pressure (p = 5MPA), inlet temperature (Tin = 150 °C) and water velocity (v = 16m/s)) were defined as input parameters for concepts developed within WP-DIV project [5]. The maximal wall heat flux (WHF) has to be lower than wall critical heat flux (WCHF) with a reasonable margin (i.e. ~1.4) [6]. For future development and in order to avoid possible CuCrZr tube erosion, the water velocity should be preferentially chosen lower than 16 m/s [7].

In this study, tungsten is considered as the armor material [8]. Although W armor does not constitute a structural part, it was decided that structural design rules (particularly fracture) should be applied for W, as armor failure may lead to a structural failure of tube. The selection of CuCrZr alloy (or Cu-base composites) as heat sink material of the PFC is owing to its thermal conductivity and mechanical properties required for a structural application such as strength and ductility at envisaged operation temperatures. The desired operation temperature range for the tube (150 °C and 350 °C) allows one to avoid irradiation embrittlement at lower temperatures and softening due to irradiation creep at higher temperatures [9].

In present ITER divertor concept, CuOFHC is used as a compliant layer between W and CuCrZr. However, in order to reduce the risk of debonding due to difference of thermal expansion between W and CuOFHC, we propose, instead of CuOFHC, a FGM between W and CuCrZr. In order to discriminate the separate functions of the interlayer (bonding and compliance between W and CuCrZr) on the bonding quality and on thermal heat exhaust capability, we introduce a thin FGM thickness (~25 μm) which does not constitute a compliant material. Considering the thickness layer to be coated and the process flexibility, physical vapor deposition (PVD) technique is chosen to manufacture FGM.

3. Finite element modeling (FEM)

3.1. Design optimization

Considering the thin FGM thickness, compared to the external monoblock dimensions (~28 mm * 28 mm* 4 mm), the effect of FGM on mock-up thermomechanical behavior may be neglected. Consequently, we made the choice not to integrate FGM in FEM model. The properties data for W and CuCrZr materials are taken from [10]. The CuCrZr pipe and the tungsten are modelled as elastic, and the CuCrZr is considered to be in its ideal "Solution Annealed and Aged Condition (Treatment B). A swirl with a twisted tape of 0.8 mm and a twist ratio of 2 is inserted into the cooling tube as in ITER divertor component [11].

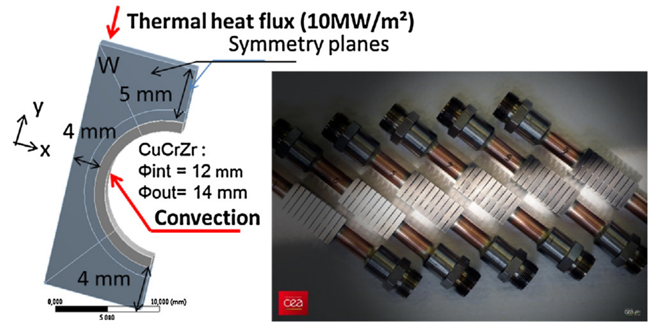

Fig. 1. Sketch representing half part of the Ad-IL-nI concept model, (left) and picture of manufactured FGM mock-ups (right).

Using monoblock elastic analysis procedure (MEAP) stresses [12] as mechanical criteria to be minimized, while taking into account manufacturing feasibility and requirements, optimum dimensions for W tile and CuCrZr tube are defined and presented in Fig. 1. These dimensions are representative of an advanced ITER-like concept integrating no interlayer (Ad-IL-nI). In the following, these dimensions were used for the manufacturing of the mock-ups equipped with thin FGM. Reserve factors for the Ad-IL-nI concept are reported for indication in Table 1 and compared with the ITER-like concept. It can be seen that stress intensity in CuCrZr for cyclic loads (Rule (1)) exceeds the allowable limit. It is noted that the elastic criterion is generally known to be conservative and that the implementation of a FGM as an interlayer would increase this reserve factor [13], just like more realistic kinematic boundary conditions [14].

3.2. Damage behavior

In the previous studies [15,16], critical issues (e.g. deep cracking in the W monoblock, plastic fatigue in Cu interlayer etc.) for the structure integrity of ITER-like divertor target component were identified. In this part, the risk of these potential failures has been evaluated by means of FEM simulation.

Commercial FEA code ABAQUS is employed. FEM model, materials [17]. The full thermal history of a typical target mock-up is considered for modeling which includes fabrication (cooled from stress-free temperature to room temperature), stand-by (preheated to coolant temperature uniformly) and HHF load cycles (cyclic heating and cooling) as illustrated in Fig. 2. The reference nodes selected to study low cycle fatigue (LCF) lifetime of W armor and CuCrZr tube are shown in Fig. 2.

The results are that at 10 MW/m^2 W behaves purely elastically. At 20 MW/m^2, the tensile residual stress is found in the upper part of the W monoblock as it is cooled down. The W monoblock is already elastic shakedown after the first cycle and thus undergoes no further plastic deformation during the cyclic HHF loading stage, indicating a low risk for crack initiation due to LCF failure. From the mechanical design point of view, this is considered to be a great advantage for the concept presented here, since a cyclic accumulation of plastic strain is expected in the divertor target at 20 MW/m^2 for ITER-like and many other divertor component designs. An elastic shakedown is observed after first cycle at the