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Realization of graded W/CuCrZr mock-ups
for DEMO reactor divertor

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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/m² during transient) and neutron irradiation. This paper presents an advanced actively cooled concept aiming to reduce the thermal stress at the bond interface due to distinct difference in thermal expansion between tungsten and CuCrZr which may cause a mismatch during thermal cycling. This concept is based on the use of a W/Cu functionally graded material (FGM) interlayer instead of the copper interlayer. Mock-up geometrical definition was performed based on available technology to manufacture FGM in a monoblock configuration, with regard to Eurofusion divertor DEMO project specifications and minimizing as much as possible thermomechanical stresses during operation. The interlayer (~25 µm) is made with PVD (Plasma 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 pressure is realized to assemble the CuCrZr tube to W tile equipped with graded material. With Infrared (SATIR) and US nondestructive examinations, mock-ups show good interface quality. Relevancy of low thickness FGM as a bonding solution between armour and structural materials for divertor application will be checked in a near term future with high heat flux tests.

Keywords: DEMO, Divertor, Plasma-facing component, Functional graded material

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 constituted of a tungsten monoblock as the plasma facing material and a CuCrZr structural pipe [2]. 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. This paper presents the status of the development of such components performed within the Eurofusion DEMO Divertor project (WP-DIV).

2. Requirements and assumptions

The irradiation damage has an impact on the materials physical properties and therefore on their suitability to be used especially for structural materials. Actually this parameter seems to constitute one of the main differences between nowadays ITER divertor, and DEMO divertor requirements [5].

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, because it will determine the thermal gradient (and relevant thermal stresses) in the plasma facing wall. 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/m² during slow transients. During a quasi-stationary operation the maximum power density is expected to reach 10-15 MW/m² [1]. In this study, we therefore define a water cooled monoblock concept in order to sustain expected heat loads. For thermo-mechanical analyses, we will use design rules [1].

Hydraulic parameters were defined as an input parameter for concepts developed within WP-DIV project: p= 5MPA, Tin=150°C and V= 16m/s [6]. With regard to the CHF, the maximal wall heat flux (WHF) has to be lower than wall critical heat flux (WCHF) with a reasonable margin (i.e. ~1.4) [7]. Taking into account recent information [8], for future development and in order to avoid possible CuCrZr tube erosion, the water velocity has to be preferentially chosen lower than 16m/s.

In this study, tungsten is considered as the armor material. It is currently considered as the most favored armor material for Plasma Facing Component (PFC) of fusion reactors [9]. This is due to the unique characteristics of tungsten, particularly such as refractory nature, low sputtering erosion, high strength, reasonable thermal conductivity and acceptable n-activation. 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 heat sink material has a structural function as well as functions to

redistribute the heat flux towards the coolant channels and to provide hermetic coolant confinement. The selection of CuCrZr alloy (or Cu-base composites) as heatsink 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 [5].
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 decided to propose a FGM between W and CuCrZr. As a consequence the compliant CuOFHC interlayer has been removed. In order to analyse the effect of FGM on the bonding quality and thermal heat exhaust capability, we decided to use a process which generates low FGM thickness (~25 µm). As a consequence, with this configuration, the FGM does not constitute a compliant material so that effect of separated functions of the interlayer (Bonding and compliance between W and CuCrZr) may be analyzed. Due to its flexibility, the chosen technic to manufacture FGM is PVD (Plasma Vapor Deposition).

3. FEM

3.1 Design optimization

We present the calculations performed in order to make an assessment of the definition of the « monoblock geometry » integrating a FGM as an interlayer. The properties data for W and CuCrZr materials are taken from [9]. 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). The monoblock is constructed from tungsten armour block and CuCrZr pipe. Considering the low interlayer thickness (~ 25 µm), the FGM is not modeled. With this condition, thermo mechanical stresses at the interface between W and CuCrZr will be higher than expected with FGM. Applied hydraulic conditions are: 5MPa, T=150°C, v= 16 m/s and a twisted tape of 0.8 mm TR=2 as in ITER divertor component [10]. Monoblock Elastic Analysis Procedure (MEAP) is used [11] to provide reserve factors with regard to specified rules.
Using MEAP stresses as mechanical criterions to be minimized, the optimum geometry was obtained and is presented in Figure 1. Reserve factor are presented and compared with the ITER-like design in Table 1. It can be seen that stress intensity in CuCrZr for cyclic loads (progressive deformation or ratcheting) exceeds the allowable limit. FEM were indeed performed in the most conservative case for which no compliant layer is used. 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 [12]. Moreover more realistic kinematic boundary conditions affect this result [13]. For other rules, reserve factors are higher than 1. Reserve factor concerning the maximum temperature in W, is higher for FGM concept than for ITER-like concept being due to the lower thickness from heat loaded surface up to the external diameter of the tube. In a future study, we will compare the FEM and experimental results in order to take into account FGM material in a more realistic way in modeling.

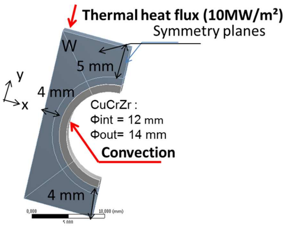

Figure 1: Tile geometry and condition for thermal FEM

MEAP rules and minimum reserve factors [11]	Design limit for reserve factor calculation :	Reserve factor for ITER-like concept [11]	Reserve factor for FGM concept
(1) Ratchetting (3Sm)	451MPa	0.95	0.68
(2) fatigue	6000 cycles	2.27	2.04
(3) Pipe max temp	350°C	1.04	1.35
(4) Wall peak heat flux	44.4MW.m^{-2}	2.88	3.1
(5) Armor max temp	1800°C	2.07	2.2

Table 1: ITER-like and FGM PFCs MEAP results.

3.2 Damage behavior

Based on previous studies [14, 15], plastic deformation accumulation and tensile stress concentration may cause failure in divertor. The aim of this work is to simulate these major failure features of the mock-up for FGM concept during fabrication process and under HHF loading by means of FEM simulation. In particular, prominent failure types such as brittle fracture and plastic fatigue (low cycle fatigue) shall be modelled. In the calculation of this work, the FGM interlayer is not modelled due to the small thickness (~ 25 µm) yielding a conservative estimation.
For the definition of possible brittle fracture of W armor, we identify the most critical site for cracking and estimate J-integral for an assumed initial crack size (e.g. 0.5 mm) at the critical site. In the case of possible plastic fatigue failure, we assess the maximum amplitude of equivalent plastic strain over a HHF load cycle and estimate the low cycle fatigue (LCF) lifetime.
Commercial FEA code ABAQUS was employed. FEM model, materials & boundary conditions are presented in [16]. The full thermal history of a typical target mock-up was considered for modelling which includes fabrication

(cooled from stress-free temperature to room temperature), stand-by (pre-heated to coolant temperature uniformly) and HHF load cycles (cyclic heating and cooling) as illustrated in Figure 2. The reference nodes selected to study LCF of W armor and CuCrZr tube are shown in Figure 2. The results are that at 10 MW/m² W behaves purely elastically. At 20 MW/m² the constant value of accumulated equivalent plastic strain (0.2 %) with respect to the number of cycles indicates that the W block is already elastic shakedown after the first cycle. The most critical site for brittle fracture of W is the middle line along the axial direction at the top surface, and the brittle propagation for the assumed initial crack will stop at a crack length of 1.5 mm based on the J-integral calculation. An elastic shakedown is observed after first cycle at the reference node of CuCrZr tube at 10 and 20 MW/m². As the LCF behavior is considered to be dominant by the plastic strain accumulation, no LCF failure in W armor nor in CuCrZr tube is expected during the HHF loadings at 10 or 20 MW/m².

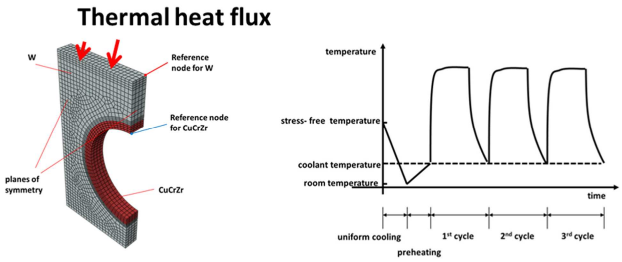

Figure 2 : Conditions for FEM calculations: (Left) Quarter model (mesh, materials, reference node) and (Right) Schematic illustration of the thermal history considered for modelling.

4. Fabrication and non-destructive techniques

4.1 Raw materials

Mock-up is composed of 10 tungsten tiles with FGM as interlayer assembled onto CuCrZr tube. Taking into account margin with regard to the possible non-acceptable tiles during the manufacturing process 150 W tiles were asked to be delivered. Tungsten tile dimensions were checked by the manufacturer and none of the tile was out of specification. Tungsten material characteristic is typical of the ITER tungsten grade [17]. As specified, W tiles are machined from W plate which is supplied in stress relieved condition. Visual, microstructural and ultrasonic examinations were performed. Chemical analysis, density, grain size and hardness were also measured. Results of these examinations and measurements meet the requirements with regard to the specification. Tungsten tiles were considered as accepted.

CuCrZr tube characteristics are typical of an ITER CuCrZR grade [18]. The raw material is a CuCrZr bar with an outer diameter of 42 mm. The CuCrZr was a Le Bronze Industriel in the CRM16 TER grade. The raw material is then machined in order to be assembled to the coated W tile.

4.2 FGM materials

The FGM fabrication in DEPHIS company was realized in order to obtain an adhesive deposit at internal part of a tungsten tile in the range of 10 to 40 µm, while mastering the variation of Cu and W concentration in the deposit. At the internal side of the coating 100 at% of W is deposited then W concentration is decreased continuously. From the side where the tile will be assembled to CuCrZr, the deposit is composed of 100 at% of Cu.

Within a same batch up to 9 tiles may be installed. One tile is dedicated to the destructive examination. In total 117 tungsten tiles were coated within 13 batches. Results of characterization (chemical composition, thickness and mechanical adherence) were analyzed in terms of homogeneity and reproducibility. Characterizations were performed within a same tile at two different positions (position 1 and 2 as presented in Figure 3), from tile to tile within a same batch and also from batch to batch.

For each batch, the chemical composition was measured using EDX and SDL technics. EDX measurements were performed on tiles and SDL measurements were performed on a witness sample with a flat substrate placed in the chamber during the realization of the batch. The chemical composition varies continuously in two linear steps from 100 % W to 0 % W, while the Cu concentration increases in the same way (Figure 3). Within a same tile, from Figure 3, one can note a maximum thickness variation of 4% between Position 1 and Position 2. On average, thickness and standard deviation is higher for position 2 than for position 1 (Table 2). This result may be attributed to orientations, with regard to W and Cu targets, of substrate at positions 1 and 2 which are different in the PVD chamber. The thickness uniformity from tile to tile within a same batch is ±5%. Taking into account all batches and the two positions the mean thickness is 21.5 µm and the standard deviation is 4.6 µm.

Using SDL, a maximum percentage of ~9.5at% of Oxygen is measured in the coated interlayer. Atomic percentages of other species are also measured: C is lower than 0.15% and H is lower than 0.7%. No nitrogen is detected in deposit.

The mechanical coating adherence on the substrate was checked with scratch test. This test is performed by applying a progressive loading almost linearly increasing (100 N/min and 10 mm/min). This test was performed for the W coating on the W substrate and also for FGM coating onto W substrate. After these tests, no delamination of the coatings is obtained showing that W and FGM deposits are adherent on the W substrate.

As a global conclusion about the FGM manufacturing, the fitness of the chemical composition variations from batch to batch and the oxygen content in the coating will be analyzed with regard to the thermomechanical behavior of the component under HHF tests and correlated to the information obtained after metallographic examination which will be performed after HHF tests.

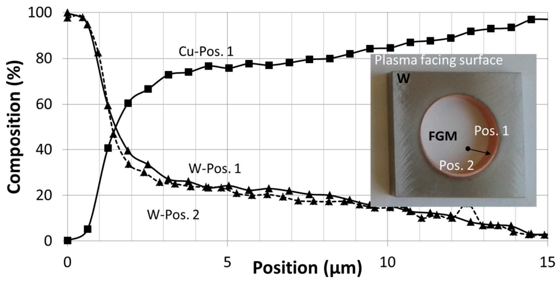

Figure 3: W and Cu Variation in FGM interlayer for position 1 and position 2

	Mean	Standard deviation
Position 1	20.8 µm	3.3 µm
Position 2	22.2 µm	5.6 µm

Table 2: FGM thickness (mean and standard deviation)

4.3 Assembly of FGM coated tiles onto CuCrZr tube

After the realization of the FGM in the interior part of tile, mock-ups were assembled. Each mock-up is constituted with 10 tiles which are assembled with Hot Isostatic Pressure (HIP) onto the CuCrZr tube.

A first mock-up was assembled at 550°C at 1200 bars during 2h. Using these conditions, the FGM material was assembled to the CuCrZr tube, but W part of the FGM material was not attached onto the tile. As a consequence, it was decided to increase the temperature during HIP process to 950°C. Moreover, to test the necessity of the FGM interlayer for the HIP assembly of W to CuCrZr, a dedicated mock-up was manufactured (Mock-up #00): half of the tile constituting this mock-up was equipped with FGM material and the other half was not equipped with FGM material. With this configuration, tiles with FGM are bonded to the tube whereas tiles without FGM are not bonded (Figure 4). We conclude that 950°C is a sufficient temperature to assemble mock-up and that FGM interlayer is necessary to assemble tile and CuCrZr. In total 7 mock-ups (#0 to #6) using W tiles including FGM were assembled (950°C, 1200 bars during 2h) with FGM as interlayer. A picture of mock-ups (#1 to #6) is presented in Figure 5. As CuCrZr is heated up to 950°C, a thermal ageing has been applied on the component. In order to estimate CuCrZr mechanical strength after the complete manufacturing process, mechanical characterization will have to be performed.

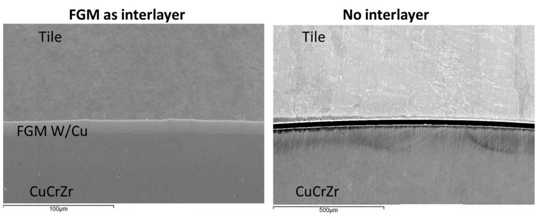

Figure 4: Interfaces for tiles (Left) with FGM as interlayer and (Right) no interlayer

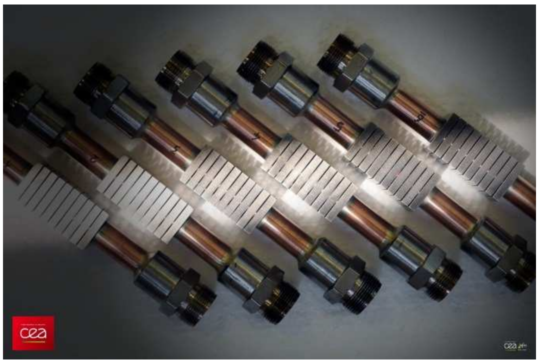

Figure 5: Mock-ups #1 to #6

4.4 Non-destructive examination

A global thermal assessment test with SATIR [19] was performed. DTref maps are obtained on the external measured and visible tungsten surfaces. When DTref are higher than 8°C, a thermal imperfection could probably be present. This thermal imperfection may be attributed to a degraded thermal characteristic which may impact the thermal exhaust capability (heat exchange coefficient [20], tungsten or/and CuCrZr thermal conductivities or/and thermal resistance into the monoblock [21]). Thermal imperfection are statistically more likely linked to debonding at interfaces [19]. For this reason, thermal imperfection are reported in terms of probable equivalent thermal imperfection at the external surface of CuCrZr tube (EQI), being quantified with an extension (Δθ) and position (θ). Localisations of Δθ and θ are presented in Figure 6.These dimensions are given using the geometric projection of DTref map onto the surface of the external CuCrZr tube [22] and a treshold value of 8°C. Estimation of the EQI are presented Table 3. When Δθ is 360°, EQI is only presented with Δθ. To correlate these results, some ultrasonic tests (UT) were also performed (Table 3).

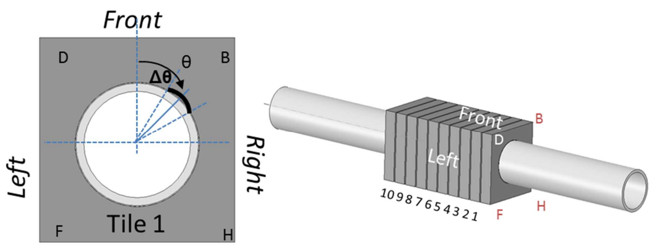

Figure 6: Nomenclature of thermal imperfection (extension (Δθ) and position (θ))

For mock-up #00, EQI is 360° and UT revealed also a total debonding. These results are consistent with the debonding observed on macrographs (Figure 4). With SATIR tests, 94 % of monoblocks (for mockup #0 to #6) revealed no thermal imperfection. 1 monoblock reavealed a small thermal imperfection (Δθ =10°, θ=35°). This imperfection needs to be further investigated to analyse the impact of such imperfection on the thermomechnical behavior under hight heat flux sollicitation. Furthemore, 3 monoblocks revealed an EQI extension higher than 135°. One can also note a good corelation and some complementarities between SATIR and UT non-destructive examination methods. Indeed, with UT 2 monoblocks were not possible to be examined due to scratches into the CuCrZr, contrary to SATIR which is abble to examine all monoblocks. With UT, 1 monoblock was detected with an important defect ($\Delta\theta$ =80°, θ =90°), which is not detected with SATIR. Finally one thermal imperfection revealed with SATIR was not detected at the interface with UT. Further diagnostic of the tile was performed with UT and revealed a defect ($\Delta\theta$ =173°, θ =65°) into the W itself at a distance of 0.3 mm after CuCrZr external diameter. An advanced investigation of this tile will be performed in order to attibute the reason of this thermal imperfection. To define the absolute impact of defects on the thermal exhaust capability, HHF tests will be performed and results will be correlated to these non destructive examinations.

# Mock-up		#Monoblock →	10	9	8	7	6	5	4	3	2	1
	00	EQI					Ref.	360°	360°	360°	360°	360°
		UT						360°	360°	360°	360°	360°
	0	EQI								Ref		(10°,35°)
		UT		(80°, -107°)								
	1	EQI			Ref.							
		UT										
	2	EQI	(300°,140°)							Ref		360°
		UT	(270°,145°)									360°
	3	EQI								Ref.		
		UT	Not possible									
	4	EQI								Ref.		
		UT										
	5	EQI								Ref.		
		UT										
	6	EQI	(135°,70°)							Ref.		
		UT										

Table 3: Results of SATIR tests (EQI) and UT in terms of extension and position

5. Conclusions

To improve bonding quality, a concept using functionally graded material as interlayer between W armour tile and CuCrZr structural pipe was developed within Eurofusion divertor DEMO project since 2014. Geometry of the mock-ups was optimized with regard to thermomechanical stresses. As a common procedure within this project, modelisation using elastic analysis procedure (MEAP) was used.

An adhesive graded material into the tungsten tile was successfully obtained by PVD (~25 µm).

In order to obtain a diffusive bonding between CuCrZr and FGM, a temperature of 950°C during HIP has been used. Seven mock-ups of about 10 monoblocks each were manufactured. Infrared (SATIR) and US nondestructive examinations have shown that 94% of monoblocks present no thermal imperfection. Relevancy of FGM as an interlayer to improve bonding quality will be validated with the results obtained with high heat flux tests.

Acknowledgments

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