Performance assessment of thick W/Cu graded interlayer for DEMO divertor target

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The development of a divertor target for DEMO is of great importance, being able to sustain the harsh environment that is imposed on this component. To fulfill the loading requirements, different concepts were developed within the EUROfusion WPDIV project. The baseline concept is based on the ITER divertor target W-monoblock design. It is made of tungsten as armour material, CuCrZr as structural material and Cu-OFHC as compliant layer. One of the proposed alternative concepts aims to minimize the stress at interfaces by replacing the thick copper interlayer by W/Cu functionally graded material (FGM). In this study, the FGM interlayer, with a thickness of 500 µm, is composed of stacked elementary layers with the following three compositions: 25 vol.%W+75 vol.%Cu, 50 vol.%W+50 vol.%Cu, 75 vol.%W+25 vol.%Cu. Several FGM interlayers were studied. In total three monoblock type mock-ups were manufactured. This paper describes the steps needed to manufacture mock-ups and characterization of elementary layers (composition, porosity, Young's modulus). HHF tests applying up to 1000 cycles at 20 MW/m² and sub-sequent post-mortem examinations were performed to qualify the concept performance.

Keywords: DEMO, Divertor, Plasma-facing component, functional graded material, Non-destructive examinations

1 Introduction

For DEMO, the design of the divertor target components is of great importance [1]. The ITER divertor target concept has been determined to be the reference option for DEMO [2]. Accordingly, the component is actively cooled and consists of tungsten (W) as plasma facing material, CuCrZr as heat sink material and soft Cu-OFHC (1 mm), which is used as interlayer between W and CuCrZr [3]. Requirements for ITER and DEMO divertor target are not fully equivalent since the amount, and therefore the importance, of neutron irradiation significantly increases for DEMO. This is the reason why, within the EUROfusion WPDIV project [1], several divertor target concepts were developed in parallel. One of the concepts proposes to use a functionally graded material (FGM) composed of W and copper (W/Cu) as interlayer. Compared to the reference concept, the motivations are to avoid the potential fast fracture of copper under neutron irradiation and to reduce thermal stresses at interfaces [4].

Two possibilities of FGM interlayer thickness were considered during the development: 25 µm and 500 µm. In the case of mock-ups equipped with thin interlayer, PVD (Physical Vapor Deposition) was used to manufacture the continuously graded layer (from W to Cu) of 25 µm using tungsten as the base armour material. The joining between the CuCrZr tube and the W blocks equipped with the thin graded layer was performed using hot isostatic pressing (HIP) [5] [6]. Mock-ups equipped with thin FGM interlayer showed good performances; however it proved that, for WPDIV project reference geometry, the performance was limited to 130 cycles at 20 MW/m² [7]. In order to improve the performance of mock-ups with reference geometry by reducing stresses at interfaces, insertion of thick FGM interlayer was proposed. This article describes, from design to high heat flux test qualification, all the results obtained for providing high performance divertor mock-ups equipped with thick FGM interlayer.

2 Mock-up description

Each mock-up is constituted of four W blocks as armour material and a CuCrZr tube as heat sink material. W and CuCrZr material properties fulfill the ITER material requirements [5]. They are water-cooled components. The DEMO specifications for the coolant temperature and pressure are 130 °C and 5 MPa, respectively [8]. For the comparison of the concepts developed within WPDIV project, main block dimensions are identical to the ones of other concepts [9]. Consequently, the minimum distance from the interlayer to the plasma-facing surface is 8 mm [9], block dimensions are 23 mm (width) × 27 mm (height) × 12 mm (depth) (Figure 1). The tube inner and outer diameters are 12 and 15 mm, respectively.

FGM interlayer (500 µm) and stacked elementary layer thicknesses were chosen in order to minimize the stresses at interfaces.

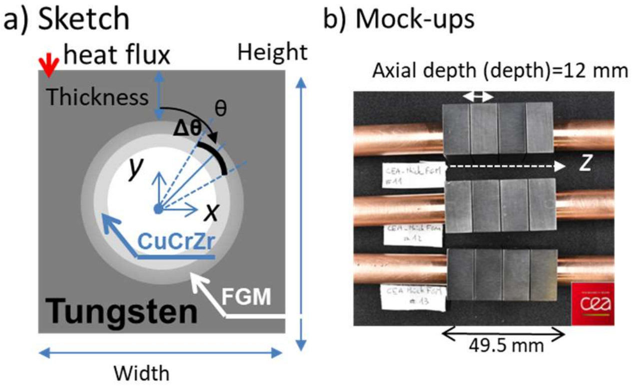

Figure 1: Thick FGM mock-ups: (a) sketch and (b) picture of the three manufactured mock-ups (#11, #12 and #13) with thick FGM

3 Design and reserve factors

Monoblock elastic analysis procedure (MEAP) is used to define reserve factors [10]. The obtained results for the studied mock-ups are presented in Table 3. For comparison, results of mock-ups equipped with thin FGM interlayer are recalled [7] in Table 3. For mock-ups with WPDIV project reference geometry (depth of 12 mm, thickness of 8 mm, width of 23 mm), reserve factors are higher for mock-ups equipped with thick FGM interlayer and consequently were expected to provide a better performance than those equipped with thin FGM interlayer.

4 Fabrication and examinations

4.1 W/Cu elementary layer fabrication and characterization

Elementary layers, composed of W and Cu, were manufactured with thermal spray technique (Gas dynamic cold spray) [5]. This industrial coating technique is based on the acceleration of particles within a gas stream and presents the advantage to provide high density materials (>95%) and no metal oxidation during the process [11] [12]. During impact with the substrate, particles undergo plastic deformation and adhere to the surface. Process parameters [5] were defined in order to obtain controlled chemical composition and thickness (500 µm). Coating chemical compositions were set arbitrarily for this study: W content of 75 vol. % + Cu content of 25 vol. %; W content of 50 vol. % + Cu content of 50 vol. %, W content of 25 vol. % + Cu content of 75 vol.%. Porosity and Young's modulus [14] were measured for individually W/Cu deposited layers. The obtained values (Table 1) are higher than those obtained by other manufacturing processes [4]. This difference may be due to the porosity which was 5 % in [4] and 3.1 % in the current study (Table 1).

Table 1: Porosity (%) and Young's modulus (E in GPa) measured at 20°C of elementary layer composed of W and Cu

	25 vol.%W +75 vol.%Cu (25 vol.%W)	50 vol.%W +50 vol.%Cu (50 vol.%W)	75 vol.%W +25 vol.%Cu (75 vol.%W)
Porosity	1.2	2.8	3.1
E	130	150	160

Table 2: Thicknesses of FGMs (variation of ±15 µm)

FGM	100 vol.%Cu (µm)	25 vol.%W (µm)	50 vol.%W (µm)	75 vol.%W (µm)
25_1	25	445	-	-
25_2	65	405	-	-
50_1	25	220	225	-
50_2	65	200	205	-
75_1	65	135	135	135

4.2 FGM interlayer

The thick FGM tube was chosen to be constituted of stacked elementary layers. Each of them was manufactured as described in 4.1. In the following, the nomenclature for each of the W/Cu layer will be reduced to their W-content, e.g. 25 vol.%W for a layer composed of 25 vol.%W + 75 vol.%Cu. The first layer of the coating (25 vol.%W) was applied on a cylindrical Cu substrate. Each subsequent layer was coated onto the previous layer. The product was then machined and the cylindrical Cu substrate almost fully removed in order to form a free standing layer in tube shape.

Considering the W particle size (D90 = 16 µm) and the number of layers to achieve the FGM, a reasonable minimum elementary layer thickness was set at 130 µm. To produce a total FGM interlayer thickness of 500 µm, a maximum of three elementary stacked layers was consequently set. For mock-up performance assessment, influence of the number of stacked layers constituting the FGM interlayer was studied. The related thicknesses and chemical composition are presented in Table 2. For example, the FGM interlayer referenced as 50_2, is composed of a 50 vol.%W layer (205 µm) coated on a 25 vol.%W layer (200 µm). An optical micrograph of this FGM interlayer is presented in Figure 2. After FGM manufacturing, the maximum difference between required and measured composition and thickness for all elementary layers is 7 vol.% and 15 µm respectively.

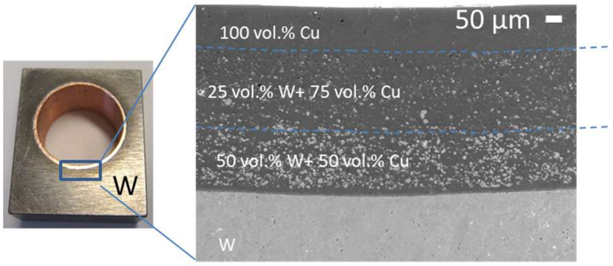

Figure 2: W block with FGM at its internal part and corresponding FGM 50_2 configuration observed with scanning electron microscope

Table 3. Geometries, material grade and MEAP results for manufactured mock-ups

Mock-up type	W dimensions/ mm				Interlayer thickness / µm	CuCrZr external diameter / mm	Pipe ratchetting	Pipe fatigue (6000 cycles)	Pipe max. temp. (350°C)	Wall peak heat flux (44.4 MW/m²)	Armor Max. Temp. (1800°C)
	Thickness	Width	Height	Depth							
Thin FGM [7]	5	22	23	4	25	14	0.68	2.04	1.3	3.1	2.2
	8	23	26	12	25	15	0.61	1.18	1.1	2.1	1.4
Thick FGM	8	23	27	12	500	15	0.87	1.68	1.1	2.8	1.6

4.3 Mock-up manufacturing

After the realization of the FGM tube, a first HIP cycle was applied (1000°C, 1400 bars during 2h) to join FGM tube to W blocks. After machining, individual W blocks with FGM at the internal part were obtained (Figure 2). Then the second HIP cycle (1000°C, 1400 bars during 2h) was realized to join the CuCrZr tube. In total, 3 mock-ups (namely #11, #12 and #13) were manufactured (Figure 1). The FGM interlayer types for the different mock-ups and blocks are presented in Table 4.

Table 4: FGM interlayer types for the different mock-ups

Mock-up \ Block	1	2	3	4
#11	25_1	50_1	50_1	25_1
#12	25_2	50_2	50_2	25_2
#13	25_2	75_1	75_1	25_2

4.4 Non-destructive tests after manufacturing

Non-destructive examinations (NDE) (Ultrasonic tests (UT) and global thermal assessment test with SATIR facility [16]) are performed to detect possible thermal imperfection at the different interfaces (quantified by the extension ($\Delta\theta$) and the position (θ)) [17] (Figure 1).

Detected defects are presented in Table 5. No defect was observed after fabrication for 100 % of blocks constituted with 25_1, 25_2, 50_2 interlayers. While 50% of the blocks constituted with 50_1 interlayer had no defect and 100% of the blocks constituted with 75_1 interlayer had defect. Defects were detected with both techniques. They are 360° extension and located at FGM interlayer to W interface. To confirm these NDE results, mock-up#13 was cut and block #2 was observed with Scanning Electron Microscope (Figure 3). A 360° crack localized at W to FGM interlayer interface, which propagates within 75 vol.%W layer, is observable. For this reason, for future mock-ups manufactured with the current manufacturing process, the integration of 75_1 FGM interlayer will be avoided.

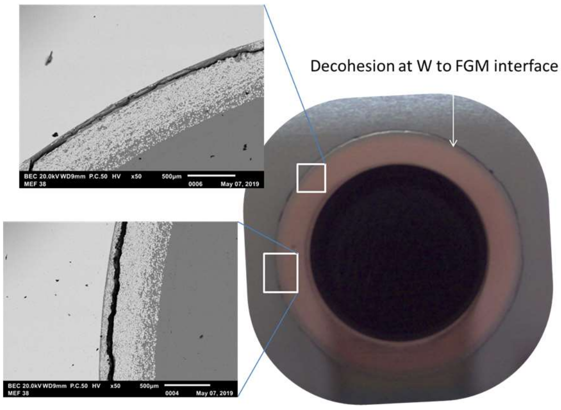

Figure 3: Decohesion of W block to FGM after fabrication (Mock-up #13 block #2)

Table 5: Defects (marked with a cross) detected before and/or after high heat flux tests

Mock-up		Blocks			
		1	2	3	4
#11	Before		x		
	After	No HHF		x	
#12	Before				
	After				
#13	Before		x	x	
	After	No HHF			

4.5 High heat flux tests

Thermal heat exhaust capability is checked with cyclic high heat flux (HHF) testing. Thereby, one cycle consists of 10 s of heat loading to obtain steady state conditions in the mock-up followed by 10 s dwell time. Due to the position of the defect within mock-up #13, this block was not part of the HHF test campaign. From mock-up #11, blocks #3 and #4 were tested with cold water cooling (70°C, 30 bar, 12 m/s) in the JUDITH-2 facility [18]. Block #3 was tested up 972 cycles at 20 MW/m² and block #4 up to 1000 cycles at 20 MW/m² followed by 10 cycles at 23.5 MW/m². During loading at 20 MW/m² a surface temperature of 2500°C, measured with two-color pyrometer [5], was reached. For Block #3, after the 972nd cycle an overheating was noticed (2700°C measured by Infrared camera) so that the cycling was stopped. During cooling down of this block, the characteristic cool-down time was measured. An effect of HHF tests was noticed (806 ms before the cycling and 1825 ms after the occurrence of overheating), meaning that power handling was reduced due to HHF tests. No overheating was noticed during the heat loading of block #4. The limit in terms of imposed heat load (23.5 MW/m²) was due to the significant surface temperature measured by the two-color pyrometer (3200°C). No modification of the power handling performance was noticed for this block, since the characteristic cool-down time was the same before and after the completion of the cycling (i.e 699 ms before and 710 ms after).

The remaining mock-up #12 was HHF tested in the GLADIS facility [19]. HHF test condition consisted, as for the other concepts tested in the frame of the WPDIV project, in performing 500 cycles at 20 MW/m² under hot water cooling conditions (130 °C, 40 bar, 16 m/s) [5]. During the HHF testing campaign, no damage was observed since no overheating was noticed. The infrared picture of the last cycle performed at 20 MW/m² is presented in Figure 4. The surface temperature (2400°C) was in the same range as the one obtained during the HHF testing performed in the JUDITH-2 facility. The behaviour observed during HHF tests is in total agreement with the results from the NDE.

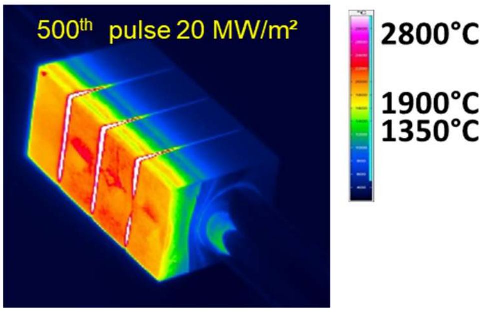

Figure 4 : Infrared picture from high heat flux tests (latest cycle at 20 MW/m²) of mock-up#12

4.6 The integrity of mock-ups after HHF tests

NDEs (SATIR and UT) were performed after HHF tests. Detected defects are presented in Table 5. Only one measurable defect, located on block #3 on mock-up #11, was generated during HHF test (θ=5° and Δθ=170° measured by SATIR and θ=5° and Δθ=150° measured by UT). Metallographic examination revealed decohesion between W to FGM interface (θ=5° and Δθ=150°) (Figure 5). Defect size is consistent with NDE results. Propagation of the crack within 50 vol%.W layer is observed. Two cracks (800 µm) are located at W/FGM interface and propagate within W block. Decohesion between 25 vol%.W to 100 vol%.Cu layers is observed.

It was detected at the W to FGM interlayer interface. This block should be analyzed with metallographic examination in the future to understand the failure reason.

Global picture of the mock-up #12 block #1 is presented in Figure 6. This HHF loaded block (500 cycles at 20 MW/m²) was classified as non-damaged with regard to results obtained during HHF tests and with NDE. For this block, 25_2 FGM interlayer is implemented. This block does not show any W surface modification nor crack formation at interfaces or in CuCrZr (Figure 6). HHF test conditions were the same for the block #2 of the same mock-up. For this block, 50_2 FGM interlayer is implemented. The interface integrity was also emphasized after HHF tests (Figure 6). Considering FGM interlayer thickness after mock-up manufacturing and HHF tests, one can note a maximum difference of 24 % with regard to the ones measured after the coating process. This difference may be due to HIP process, which decreases material thickness by diffusion process occurring during pressure loading.

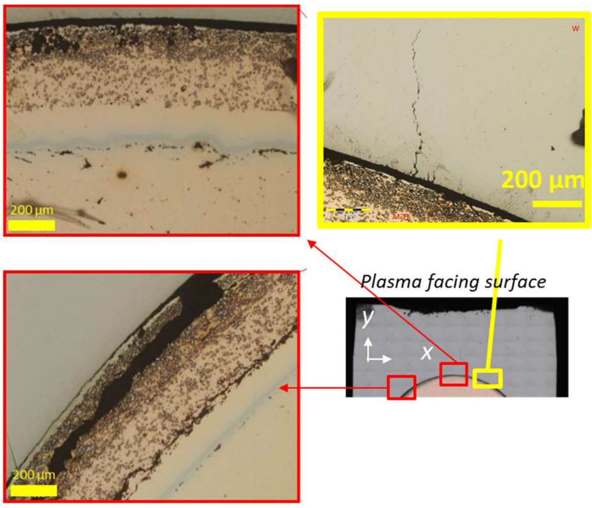

Figure 5: Mock-up #11 block #3 equipped with thick FGM interlayer (50_1) after 972 cycles at 20 MW/m² and cutting preparation: Decohesion at W to FGM interface (upper left) crack from W/FGM interface to W block (upper right) Decohesion between 25 vol%.W to 100 vol%.Cu layer and propagation of crack within 50 vol%.W layer (lower left)

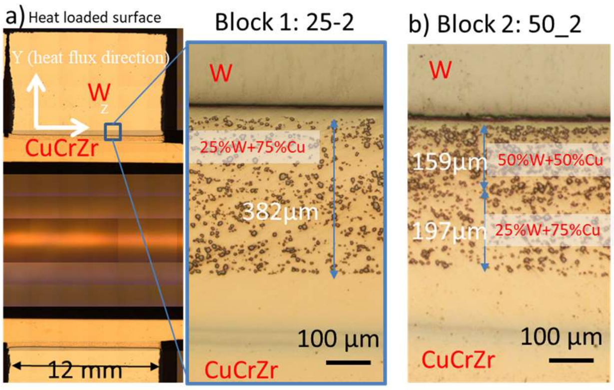

Figure 6: Images of mock-up #12 equipped with thick FGM interlayer after 500 cycles at 20 MW/m² and cutting preparation: block #1 (a) block #2 (b)

5 Summary and conclusions

For DEMO divertor target, one concept uses W/Cu graded material (FGM) as interlayer between W armor material and CuCrZr tube. FGM interlayer, with a total nominal thickness of 500 µm and constituted of a maximum of three elementary stacked layers composed of W and Cu, were successfully manufactured. Indeed, after FGM manufacturing, the required FGM thicknesses and compositions (25 vol.%W + 75 vol.%Cu, 50 vol.%W + 50 vol.%Cu, 75 vol.%W + 25 vol.%Cu) were achieved within variations of 7% and ± 15 µm respectively. To manufacture mock-ups, two HIP cycles were applied: the first one to join W block to FGM tube interlayer, the second one to join CuCrZr tube. No defect was observed after fabrication for ~75% of the blocks. Defects detected by NDE were located at W to FGM interlayer interface in particular for FGMs comprising all three elementary compositions. Accordingly, it was decided to focus the HHF testing on mock-ups equipped with FGM interlayer constituted of only one layer (composed of 25 vol.% W + 75 vol.% Cu) or two layers (composed of 25 vol.% W + 75 vol.% Cu and 50 vol.% W+50 vol.% Cu). Mock-ups showed good high heat flux performances by providing identical results for all the investigated compositions and thicknesses sustaining up to 500 cycles at 20 MW/m². Selected blocks were tested up to a maximum of 1000 cycles at 20 MW/m² followed by 10 cycles at 23.5MW/m². The integrity of W, FGM interlayer, CuCrZr and material interfaces after 500 cycles at 20 MW/m² lead to conclude that thick FGM interlayer, composed of W and Cu, have positive potential for DEMO divertor application since that these mock-ups showed no damage and that the graded interlayer could exhibit benign irradiation behavior without drastic embrittlement as pure copper shows.

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