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Performance of high heat flux W monoblock type target using thin graded and copper interlayers for application to DEMO divertor

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In the frame of the development of a divertor for DEMO, the European WPDIV project is underway since 2014. The first phase of the project (2014-2016) aims to provide mock-ups adapted to DEMO operation requirements and the second phase aiming to furnish mock-ups with standardized geometry. Within the WPDIV project, several concepts are developed. One of this concept aims to replace the thick copper interlayer, used for ITER divertor components, with a very thin bond coat (functional gradient material or pure copper) for armor-to-pipe joining. One of the benefits is related to armor temperature which is decreased as the distance of heat conduction path is shortened. Some blocks equipped with thin functional gradient material as interlayer proved, in 2016, to handle high cycling performances without any degradation (no surface change aspect and no decrease of thermal heat exhaust capability) up to 1000 cycles at 20 MW/m². In this paper we show the last results obtained under high heat flux tests from the first phase mock-ups. The recrystallized tungsten layer is also characterized. In the recent achievements, presented in this paper, the second phase mock-ups were manufactured, examined, tested under high heat flux and finally cut for metallographic examinations.

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

1 Introduction

Due to extreme and complex loadings on DEMO divertor target components, the design of such component is a key issue [CITATION You16 \l 1036]. While tungsten (W) is considered as the best candidate as armour plasma facing material, CuCrZr is presently selected as a structural material for components subjected to the highest heat flux (up to 20 MW/m²). The baseline DEMO divertor concept is the ITER divertor one [CITATION Mer10 \l 1036]. It is based on the use of array of rectangular monoblocks of tungsten with a CuCrZr cooling pipe as heat sink at the middle. This concept uses CuOFHC (~1 mm) as interlayer between tungsten and CuCrZr. Additionally to this reference concept, several other novel design concepts are being developed in parallel within Eurofusion WPDIV project [CITATION You16 \l 1036]. Among these concepts, it is proposed to use functionally graded material (FGM) as interlayer between W and CuCrZr [CITATION Ric171 \l 1036][CITATION Ric172 \l 1036]. The primary motivation of this concept was to replace the thick copper interlayer with a very thin bond coat for armor-to-pipe joining in order to avoid the potential risk of fast fracture of the copper interlayer to be embrittled under irradiation. Another benefit of this concept is related to armor temperature which is decreased as the distance of heat conduction path is shortened. Some experimental results proved that such mock-ups have high cycling performance since blocks handled, without any degradation (no surface change aspect and no decrease of thermal heat exhaust capability), 1000 cycles at 20 MW/m² [CITATION Ric171 \l 1036]. This article presents a brief overview on the recent achievements of the development of thin interlayer concept focusing on the design, mock-up production, inspection, high heat flux (HHF) qualification test campaign and post-examinations.

2 Requirements and scope

Within WPDIV project, the baseline divertor to be developed is constituted of tungsten as armor material and CuCrZr as structural material[CITATION Ric171 \l 1036] [CITATION Ric172 \l 1036].Water cooling is the baseline option for the PFCs and cassette body. The temperature and pressure of the coolant is 130 °C and 5 MPa, respectively [CITATION You18 \l 1036]. Inner wall heat flux has to be lower than the critical heat flux with a 1.4 margin. In normal operation phase it is assumed that surface heat flux reaches 15 MW/m² [CITATION You18 \l 1036]. Considering the geometry requirements of developed WPDIV concepts, the initial thickness of the armor (distance from the interlayer to the plasma-facing surface) was set at 5 mm [CITATION You15 \l 1036], in the 1st phase of the project (2014–16), while in the 2nd phase (2017–18) it was set at 8 mm[CITATION You18 \l 1036]. Considering the ITER-like concept as reference [CITATION FCr15 \m Bar16 \l 1036], it was decided to use, for the 2nd phase, as much as possible the same geometries as the ITER-like concept ones. Consequently for the 2nd phase, the inner diameter of the cooling pipe is set at 12 mm and the thickness at 1.5 mm. The block thickness is also set at 12 mm. Thin FGM interlayer (~25 µm) mock-ups, from the 1st phase of WPDIV project, handled without any degradation 1000 cycles at 20 MW/m², meaning that no surface change aspect and no decrease of thermal heat exhaust capability are noticed. In order to check the performance of mock-ups equipped with FGM interlayer and respecting the geometry requirements

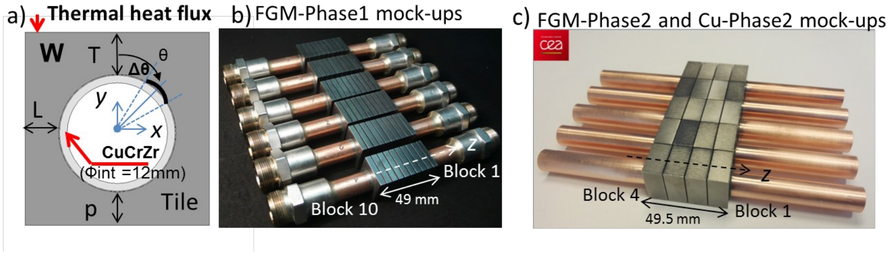

Fig. 1: Tile dimensions (a); pictures and dimensions of: FGM-Phase1 -b) FGM-Phase2 and Cu-Phase2 (c) mock-ups

Table 1. Geometries, material grade and MEAP results for manufactured mock-ups

Mock-up type- (Mock-up name)	W batch	W thickness / mm			Interlayer		CuCrZr Φout / mm	Pipe ratchetting (451MPa)	Pipe fatigue (6000 cycles)	Pipe max. temp. (350°C)	Wall peak heat flux (44.4MW/m²)	Armor Max. Temp. (1800°C)
		T	p	L	Composition	Thickness / µm						
FGM-Phase1 [CITATION Ric171 \l 1036][CITATION Ric172 \l 1036] Mock-ups 2 and 4	1	5	4	4	FGM	25	14	0.68	2.04	1.35	3.1	2.2
FGM-Phase2 Mock-ups 9 and 10	2	8	3	4	FGM	25	15	0.61	1.18	1.12	2.11	1.36
Cu-Phase2 Mock-ups 7 and 8	2	8	3	4	Cu	25	15					

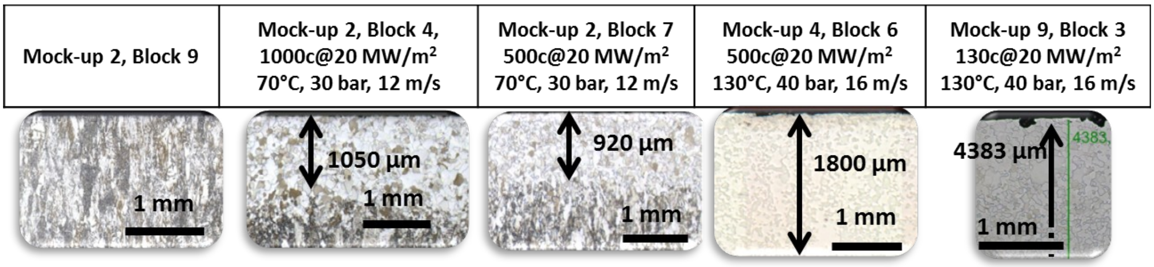

Fig. 2. SEM images of tungsten, for FGM-phase1 mock-up after the complete manufacturing process (Mock-up 2 block n°9), after 1000c@20 MW/m², (70°C, 30 bar, 12 m/s) (mock-up 2 block n°4), after 500c@20 MW/ m², (70°C, 30 bar, 12 m/s) (mock-up 2 block n°7), after 500c@20 MW/ m², (130°C, 40 bar, 16 m/s) (mock-up 4 block n°6) and for FGM-phase2 mock-up after 130c@20 MW/ m², (130°C, 40 bar, 16 m/s) (mock-up 9 block n°3)

related to the 2nd phase, mock-ups equipped with thin FGM interlayer were manufactured for the 2nd phase. Moreover, in order to check if graded layer is the key responsible for the good thermo-mechanical performance obtained for mock-ups from the 1st phase, mock-ups equipped with thin Cu interlayer (~25 µm) were manufactured for the 2nd phase. In this regard, 3 types of mock-ups are studied in this paper: mock-ups with thin FGM interlayer developed during the 1st phase (called here later FGM-Phase1), mock-ups with thin FGM interlayer developed during the 2nd phase (called here later FGM-Phase2) and mock-ups with thin Cu interlayer developed during the 2nd phase (called here later Cu-Phase2).

3 Mock-up geometry and performance simulations

Geometries and main characteristics of manufactured mock-ups are included in Table 1. Phase1 and phase2 mock-ups are composed of 10 blocks and 4 blocks, respectively. Block dimensions are 22 mm (width) * 23 mm (height) * 4 mm (depth), for FGM-Phase1 mock-ups. Block dimensions are 23 mm (width) * 26 mm (height) * 12 mm (depth), for FGM-Phase2 and Cu-Phase2 mock-ups. As presented previously, armor thickness is 5 mm and 8 mm for Phase1 and Phase2 mock-ups, respectively. Tube inner diameter is always 12 mm and tube outer diameter is 14 mm and 15 mm for Phase1 and Phase2 mock-ups, respectively. As shown in Fig. 1, in total 11 mock-ups were manufactured: 6 for FGM-Phase 1, 2 for FGM-Phase2 (namely 9 and 10) and 2 for Cu-Phase2 (namely 7 and 8).

Considering these geometries, some performance simulations are performed. Detailed inputs for finite element modeling (FEM) are presented in [CITATION Ric172 \l 1036]. Monoblock elastic analysis procedure (MEAP) stresses[CITATION Bar16 \l 1036] is used to define reserve factor with regard to mechanical behavior. Reserve factors are reported in Table 1. Geometries and performance results for FGM-Phase1 mock-ups, were described in detail in [CITATION Ric172 \l 1036]. One can note that FGM-Phase1 mock-ups have higher reserve factors compared to the FGM-Phase2 and Cu-Phase2 mock-ups. This is mainly due to the block thickness, armor thickness and to the tube outer diameter, being higher for FGM-Phase2 and Cu-Phase2 mock-ups compared to FGM-Phase1 mock-ups. Moreover, with a higher armor thickness, a higher maximum temperature on tungsten is reached. FGM-Phase2 and Cu-Phase2 mock-ups will consequently be more prone to recrystallization compared to FGM-Phase1 mock-ups. As a general conclusion, as reserve factors are lower for phase 2 mock-ups compared to phase 1 mock-ups, FEM analysis shows that geometry requirements set for the 2^{nd} phase may lead theoretically to a detrimental impact on the performance of mock-ups equipped with thin interlayer.

4 Fabrication and examinations

4.1 Mock-up fabrication

W and CuCrZr properties should comply with the ITER requirements. W blocks are machined from W plate which is supplied in stress relieved condition. For each phase of the project, a dedicated batch was delivered. CuCrZr raw material is a bar with an outer diameter of 42 mm (Le Bronze Industriel, CRM16 TER grade) which is machined to fit to final desired CuCrZr tube dimension.

FGM interlayer fabrication is realized with physical vapor deposition (PVD) in order to obtain a deposit at the inner surface of the bore hole inserted in the tungsten blocks, while mastering the progressive deposit of Cu and W [CITATION Ric171 \l 1036]. At the W interface the coating consists of 100 at% of W from where the W concentration is decreased continuously up to the interface with the CuCrZr tube. At this position, the deposit is composed of 100 at% of Cu. Cu interlayer fabrication for Cu-Phase2 mock-ups is also realized with PVD. Methods to characterize the deposits are presented in [CITATION Ric172 \l 1036]. The mean thickness (21.5 µm) and the standard deviation (4.6 µm) obtained for FGM-Phase1 mock-ups are presented in [CITATION Ric171 \l 1036]. For FGM-Phase2 mock-ups, mean thickness is 23.1 µm and standard deviation is 3.5 µm. For Cu-Phase2 mock-ups, they are estimated to be 25 µm and 7.6 µm, respectively.

W blocks equipped with thin interlayer are bonded to CuCrZr tube via hot isostatic pressing (HIPping; 950 °C, 120 MPa, 2 h) [CITATION Ric171 \l 1036]. A thermal ageing has been applied on the component at 475 °C during 3 h in order to partially recover thermal-mechanical properties of CuCrZr.

Table 2. Thermal imperfection position and size (θ, Δθ) after manufacturing measured with infrared thermography (IR) and ultrasonic testing (UT)

Mock-up		8	10			
Block		4	1	2	3	4
IR	θ	24°,	-5°,	-27°,	0°,	-20°,
	Δθ	288°	195°	215°	170°	245°
US	θ	8°,	-39°,	1°,	5°,	-11°,
in W	Δθ	288°	274°	169°	152°	198°

4.2 Non-destructive examination after manufacturing

A global thermal assessment test with SATIR/STING facility, a test bed using infrared thermography [CITATION RIC18 \l 1036] was performed. With this test-bed, thermal imperfection is reported in terms of probable EQuivalent thermal Imperfection at the external surface of the CuCrZr tube (EQI), being quantified by its extension (Δθ) and its position (θ)[CITATION Gal17 \l 1036] (Fig. 1). Ultrasonic tests (UT) in ENEA were also performed. Defects of FGM-Phase1 mock-ups are presented in [4]. Defects detected with non-destructive examinations (NDEs) for FGM-Phase2 and Cu-Phase2 mock-ups are presented in Table 2. No defect was observed after fabrication with SATIR/STING in mock-ups 7 and 9. With UT, only small detachments are detected at the free end of blocks 1 and 4 for mock-up 7. For mock-ups 8 and 10, defects were detected both by SATIR/STING and UT. UT testing reveals that these defects are wide and always located inside tungsten. When comparing results obtained from UT and IR, one can note that defect detection are similar for two defects (block 4 on mock-up 10 and block 3 on mock-up 10). For other blocks, some differences are noticed which may be due to the defect detection methods which are different for these two NDEs.

Table 3. Main results for tested mock-ups in GLADIS high heat flux test facility

Mock-up	HHF results
2 FGM-Phase1	No damage for cold water tests in JUDITH-2 (Up to 500 cycles @ 20 MW/m²) (blocks 3 to 8) + No damage for cold water tests in JUDITH-2 (Up to 500 cycles @ 20 MW/m²) (blocks 3 to 5) [CITATION Ric171 \l 1036]
4 FGM-Phase1	No damage for cold water tests in GLADIS [CITATION Ric171 \l 1036] No damage for hot water tests but continuous increase of surface temperature (500 cycles at 20 MW/m²)
7 Cu-Phase2	No damage for cold water tests in GLADIS Damage at 132^{th} cycle at 20 MW/m² for block 1 and at 153^{th} cycle for block 4 for hot water test
8 Cu-Phase2	Damage for cold water tests (10 MW/m²) in GLADIS (Block 4) No hot water test
9 FGM-Phase2	No damage for cold water tests Damage at 130^{th} cycle at 20 MW/m² for hot water test (blocks 1 and 4)
10 FGM-Phase2	Damage for cold water tests (6 MW/m²) in GLADIS (Blocks 1 to 4) No hot water test

4.3 HHF tests

In order to assess the thermal heat exhaust capability under relevant heat flux, an high heat flux testing campaign was performed. Mock-up 2 (FGM-Phase1) handled up to 1000 cycles at 20 MW/m² with cold water cooling (70°C, 30 bar, 12 m/s) in JUDITH-2 facility [CITATION Ric171 \l 1036]. 3 blocks were tested up 1000 cycles while 3 blocks, on the same mock-up, were tested up to 500 cycles. The other mock-ups were HHF tested in GLADIS facility [CITATION Gre07 \l 1036]. Two ranges of HHF tests are performed: under cold (20 °C, 10 bar, 12 m/s) and hot (130°C, 40 bar, 16 m/s) water cooling conditions.

For FGM-Phase1, the details of the begining of the HHF tests are are presented in [CITATION Ric171 \l 1036]. For FGM-Phase1 mock-ups, the HHF test campaign was mainly devoted to blocks and related mock-ups for which no defect was detected. For related tested mock-ups, no damage is noticed except for a block for which a defect was detected before HHF tests [CITATION Ric171 \l 1036]. Some additional tests were performed since [CITATION Ric171 \l 1036] on mock-up 4, consisting in testing this mock-up in GLADIS with hot water condition up to 500 cycles at 20 MW/m². For FGM-Phase2 and Cu-Phase2 mock-ups, cold water tests in GLADIS consisted in: screening tests up to 25 MW/m² followed by 100 cycles at 10 MW/m². Hot water condition tests consist in performing 300 cycles at 20 MW/m².

For all mock-ups, the results in terms of presence of damage, emphasised with surface temperature evolution during HHF testing, are presented in Error: Reference source not found. After the testing campaign of mock-ups 2 and 4 (FGM-Phase1) no damage was observed. For FGM-Phase2 and Cu-Phase2 mock-ups, the blocks with the manufacturing defects did not succeed, as expected, the HHF tests under cold water condition. Consequently HHF test with hot water cooling condition were not possible to be performed for these mock-ups, even if well-fabricated blocks did not show degradation after initial HHF assessment. Mock-ups, which presented no defect during cold water cooling conditions were tested with hot water cooling. With this conditions, damages were observed on blocks 1 and 4 of mock-ups 7 and 9. These results may be linked to the small detachments observed by UT at the free end of blocks 1 and 4 on mock-up 7. One can also note that the same range of number of cycles at 20 MW/m² are reached for FGM-Phase2 and Cu-Phase2 mock-ups. Some further investigation are needed to understand the reason of damage propagation and a special care to define if FGM-Phase2 and Cu-Phase2 mock-ups have the same performance under HHF tests will be performed in the future

4.4 Metallographic examinations

Metallographic examinations are performed, on some blocks presenting no damage during HHF tests. The recrystallized thickness at the upper part of the cooling tube (Fig. 2.) and FGM interfaces integrity (FGM to W and FGM to CuCrZr) are checked. For comparison, the microstructure of raw material is also presented. For mock-up 2, one can note a tungsten recrystallized layer of 1050 µm on block 4 (920 µm on block 7). The difference between blocks 4 and 7 is due to a higher loaded time at a temperature above recrystallization temperature, for block 4 compared to block 7 (1000 and 500 cycles, respectively). For mock-up 4 block n°6, recrystallized layer is ~1800 µm. The difference between mock-ups 4 block n°6 and mock-up 2 block n°7 may be due to the difference of cooling conditions during HHF testing. As comparison, recrystallized tungsten layer of ITER-like mock-up after 1000 cycles@20 MW/m² is 2000-4000 µm [CITATION GPi13 \l 1036]. Recrystallized layer in mock-up 9 is ~4380 µm. The difference between mock-ups 2 and 4 may be due to the armor thickness which is higher for mock-up 9 (8 mm) compared to mock-ups 2 and 4 (5 mm). For all studied blocks, the FGM interfaces remained intact.

5 Conclusions

DEMO divertor target is solicited with extreme and complex loadings. The design of such component is a key issue. To develop adapted components, R&D efforts within two phases have been achieved in the WPDIV project since 2014. One concept developed within this program uses thin interlayer (functional gradient material or copper) between tungsten armor material and CuCrZr tube. The first phase of the project (2014-2016) led to the production of successful mock-ups with functional gradient material as interlayer, for which no degradation at the interface is noticed after 1000 cycles at 20 MW/m² with cold cooling condition and after 500 cycles at 20 MW/² with DEMO relevant cooling condition (130°C,40 bar, 16 m/s). As expected, a low recrystallized tungsten layer is noticed (~1050 µm). For the 2nd phase of the WPDIV project, mock-up geometries were standardized. Mock-ups equipped with thin interlayer were manufactured. As for mock-ups from first phase, some defects were detected after manufacturing. All mock-ups were high heat flux (HHF) tested and half of them passed successfully, with cold cooling conditions, screening test up to 25 MW/m² followed by 100 cycles at 10 MW/m². Damaged blocks observed during HHF tests are consistent with the ones emphasized with non-destructive examinations after their manufacturing. After this successfully HHF test step, mock-ups were HHF tested with hot water cooling conditions. No damage was observed up to ~130 cycles at 20 MW/m². HHF tests were not possible to be followed, even if well-fabricated blocks did not show dramatic degradation under HHF tests (50% of the tested blocks). The complete characterization of these damages will be performed in the future realising metallographic examinations.

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