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Fabrication of DEMO divertor target mock-up by HRP technology with tungsten fiber reinforced tungsten as armour material

Francesco Crea [a,*], Emanuele Cacciotti [a], Riccardo De Luca [a], Pierdomenico Lorusso [a], Selanna Roccella [a], Annunziata Satriano [a], Luigi Verdini [a], Jan Willem Coenen [b], Yiran Mao [b], Johann Riesch [c], Marius Wirtz [b]

[a] *ENEA, Nuclear Department, NUC-FUSEN-TES, 00044 Frascati, Rome, Italy*

[b] *Forschungszentrum Jülich GmbH, Institute of Fusion Energy and Nuclear Waste Management, Plasma Physics IFN-1, 52425 Jülich, Germany*

[c] *Max Planck Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching, Germany*

A R T I C L E I N F O

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A B S T R A C T

The current consolidated process for the fabrication of a target divertor for ITER foresees armour material monoblocks with Oxygen Free Electronic Grade copper (OFE-Cu, Cu) interlayer joined to CuCrZr ITER Grade (CuCrZr-IG) cooling pipes by diffusion bonding. ENEA's Special Technologies Laboratory (TES) developed the Hot Radial Pressing (HRP) technology which is the diffusion bonding technique eligible for the European DEMOnstration fusion power plant (EU-DEMO) divertor target.

Tungsten (W) is also the primary armour material candidate for the EU-DEMO divertor target. However, during operation at high temperature the intrinsic brittleness of W below the Ductile-to-Brittle-Transition-Temperature can generate fractures inside the plasma facing components. Alternative armour materials able to mitigate the intrinsic drawbacks of pure W are being investigated in the context of the EUROfusion work-package Materials (WPMAT). Among the many alternatives, tungsten fiber-reinforced tungsten (Wf/W) has showed an excellent improvement of the fracture toughness. In this work, a mock-up using Wf/W ITER-like monoblocks was fabricated. The Cu interlayer was made by casting. Once machined, the advanced Wf/W-Cu monoblocks were joined by HRP to the CuCrZr cooling tube. The fabrication of the mock-ups required an optimization of process parameters within the range in which the thermo-mechanical properties of the copper interlayer and the Wf/W-Cu armour blocks are not yet degraded.

Non-destructive examination (NDE) by ultrasonic inspection were performed on the advanced Wf/W monoblocks before mock-up fabrication, after OFE-Cu casting on the Wf/W-Cu blocks and after HRP joining of the blocks with the CuCrZr pipe.

1. Introduction

One of the missions of the European Roadmap is to develop new divertor materials and Plasma Facing Components able to withstand High Heat Fluxes (HHFs) and able to exhaust particles under plasmas conditions [1]. The current ITER-divertor design consists of Plasma Facing Units (PFUs) made of water-cooled CuCrZr ITER-grade (CuCrZr-IG) pipe and drilled W-monoblocks. The CuCrZr-IG pipe acts as heat sink material while the monoblocks act as armour material facing the plasma. Monoblocks are joined to the pipe by diffusion bonding [2]. The Hot Radial Pressing (HRP) technique developed by ENEA Special TEchnologies laboratory (TES) is the baseline bonding process to manufacture the PFUs of the future tokamaks [3,4].

Tungsten (W) is the most eligible Plasma Facing Material (PFM) for the ITER-like divertors due to its excellent properties such as low neutron activation, low tritium retention, high sputtering threshold, high melting point, adequate thermal conductivity and adequate thermal capacity [5]. One of the limitations of using W as PFM is related to its low fracture toughness and embrittlement under high temperature conditions, HHF cycles and neutron irradiation [6]. The cracks resistance of tungsten can be improved by using tungsten fiber-reinforced tungsten composite (Wf/W) materials made of W fibers and a W matrix manufactured by Field Assisted Sintering Technique (FAST), alternatively named Spark Plasma Sintering [7].

* Corresponding author.
E-mail address: francesco.crea@enea.it (F. Crea).

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This paper investigates the possibility of manufacturing ITER-like PFUs by using Wf/W monoblocks and joining them to the CuCrZr-IG pipe by HRP. A mock-up has been fabricated with the addition by casting of an Oxygen-Free High Conductivity copper (OFE-Cu, Cu) interlayer inside the monoblocks boreholes which acts as a coupling and stress mitigating layer between the armour material and the heat sink material. The casting process and the HRP joining technique were optimized according to the thermomechanical behavior of the Wf/W advanced material.

The integrity of the materials and the quality of the fabrication processes were investigated with Non-Destructive Examinations (NDEs) by Ultrasonic Testing (UT). Ultrasonic inspections were performed within the various fabrication steps: on the Wf/W monoblocks after fabrication, after OFE-Cu casting on borehole monoblocks and after the HRP process. The inspection by UT is based on a pulse-echo water gap technique in which the probe is positioned inside the part to be inspected, e.g. the pipe, the Wf/W monoblocks or the Wf/W-Cu blocks [8]. The UT scanning displacement is performed with a succession of a single angular movement and an axial translation along the borehole/pipe axis.

2. Wf/W monoblocks for divertor

Since decades of research activity within the EUROfusion program, W is the most promising PFM, and therefore it has become the material choice for ITER and EU-DEMO [9]. Within the EUROfusion Consortium, the Work Package Materials (WPMAT) is investigating in the development and characterization of advanced W composites and advanced W-alloys PFMs which can both overcome the performance limitations of EU-DEMO as well as to extend the operating domain towards conditions more relevant for future fusion power plants [10].

In order to improve toughness and to increase ductility, conspicuous research activity has focused on the study of Wf/W materials [11]. Most recently, the joined effort of Jülich Research Centre (FZJ) and Max Planck Institute for Plasma physics (IPP) research groups has led to the development of new Wf/W materials with a great improvement in fracture toughness and a consist limitation of crack propagation, exhibiting a pseudo-ductile behavior [12]. The “pseudo ductility” is generated by the interaction between the W fibers and the W matrix. The crack propagation inside the Wf/W is reduced by the energy-dissipation mechanisms such as fiber ductile deformation, fiber pull-out, crack deflection and interface de-bonding, when the crack encounters a fiber [13]. With a more simplified manufacturing process compared to conventional productions, such as production by chemical vapor deposition and other processes which require a fiber–matrix interface, short-fibers Wf/W has showed increased fracture toughness compared with pure W and pseudo-ductile behavior [14].

Wf/W can be manufactured by powder metallurgy i.e. FAST. There are various type of Wf/W developed, among which porous matrix Wf/W (PoMo-Wf/W) combine a very easy production process and advanced damage resilience [15]. The powders are made of pure W, the tungsten fibers are short and randomly distributed into the matrix. during the FAST consolidation, the sintering temperature was set to ~1450 °C, which is much lower than the normal sintering temperature of W. In this way, a porous matrix can be achieved, and a dedicated fiber/matrix interface can be saved to realize a weak bonding between fiber and matrix. It has been proven, PoMo-Wf/W show promising fracture toughness and fracture energy density without losing much of other fusion relevant properties, i.e. erosion resistance, fuel retention [16]. The monoblocks fabricated for this work are made of short-fibers Wf/W with porous matrix.

2.1. Wf/W monoblocks NDEs result

Four short-fibers Wf/W monoblocks have been fabricated by FAST (Fig. 1). The ITER-like divertor-target design is taken as a baseline for the nominal dimensions of the monoblocks, which are 28 × 23 × 12 mm in size, with internal hole diameter of 17 mm and armour thickness of 8 mm. The W matrix is porous. The fibers are randomly distributed on planes perpendicular to the HHF direction.

After fabrication, a preliminary NDE dimensional inspection for the qualification of the Wf/W monoblocks revealed that dimensions that involve the HHF side (named armour) are slightly lower than the ITER-like ones. In the specific, the armour size should be 8 mm while the values measured on the monoblocks range from 7.91 mm to 7.67 mm. Moreover, the surface roughness is high at the inner borehole surface, with the presence of cavities likely due to the porosity of the W matrix. These results have to be taken into account for the setting of the mock-up fabrication.

A second NDE via UT of the Wf/W monoblocks has been carried out. UT was performed by using a 15 MHz probe inside the borehole following a scanning grid resulting from the superposition of one axial translation along the borehole axis and one rotation. The back-wall echoes coming from the three lateral sides (Fig. 1a, b and e), which must correspond to a depth of 3 mm from the first interface, allowed a preliminary calibration of the sound speed in the short-fiber Wf/W material, estimated to be around 4000 m/s. On the other hand, the signal is affected by a noticeable attenuation caused by the porosity of the W matrix and by the fine and stochastic distribution of fibers in the W matrix. Such a fiber distribution into the porous W matrix causes signal scattering and attenuation, both increased when performing UT planar scanning, with the probe signal parallel to the borehole axis. It turned out that the back-wall echo is hard to distinguish from the intrinsic noise of the signal. Only by scanning from the inside of the borehole it was possible to detect the back-wall echo coming from the HHF side (Figs. 1f and Fig. 2), suggesting the absence of significant discontinuities in the Wf/W material monoblocks. UT signal is attenuated more and more as it penetrates deeper into the material. Therefore, only three discontinuities close to the borehole could be detected, one into monoblock #13 and two into monoblock #09 (Fig. 3), which are most likely larger pores within the matrix.

3. Fabrication of OFE-Cu interlayer inside the W/W monoblocks boreholes

OFE-Cu was cast into the borehole of the Wf/W monoblocks for the fabrication of the Cu interlayer. The process is a well-known and industrially available technique, already employed in the EUROfusion program. In fact, a number of companies have already supplied W-Cu blocks for divertor target development. In the case of Wf/W, the complication of the OFE-Cu casting process is related to the porosity of the matrix, the roughness of the surface and the inhomogeneity of the material to be wet. Prior to proceed with the Cu-interlayer fabrication, a wettability test campaign was required to define the set-up and the necessary preliminary steps of the casting process.

3.1. Wettability test campaign on short-fibers PoMo-Wf/W

The short-fibers PoMo-Wf/W material has a density of about 80 % and low impurity content [15,16]. The low density is due to the presence of microporosity in the W matrix. Fig. 4 highlights the intrinsic microporosity of the W-matrix and the presence of larger pores mainly at the boundaries between the fibers and the matrix.

Before the Cu interlayer fabrication, a Cu wettability test campaign was carried out. Four specimens were tested using a dedicated wettability test facility [17] (for specimens n°1, 2 and 4) and the vacuum furnace GALILEO (for specimen n°3). The test campaign suggested little to no wettability between copper and the Wf/W specimens (Figs. 5 and Fig. 6), which might be related to the microporosity of the matrix and the high roughness of the surface. Nickel was applied by electroplating on the surface as wetting agent. As a result, the specimen showed a good Cu wettability (Figs. 7 and Fig. 8).

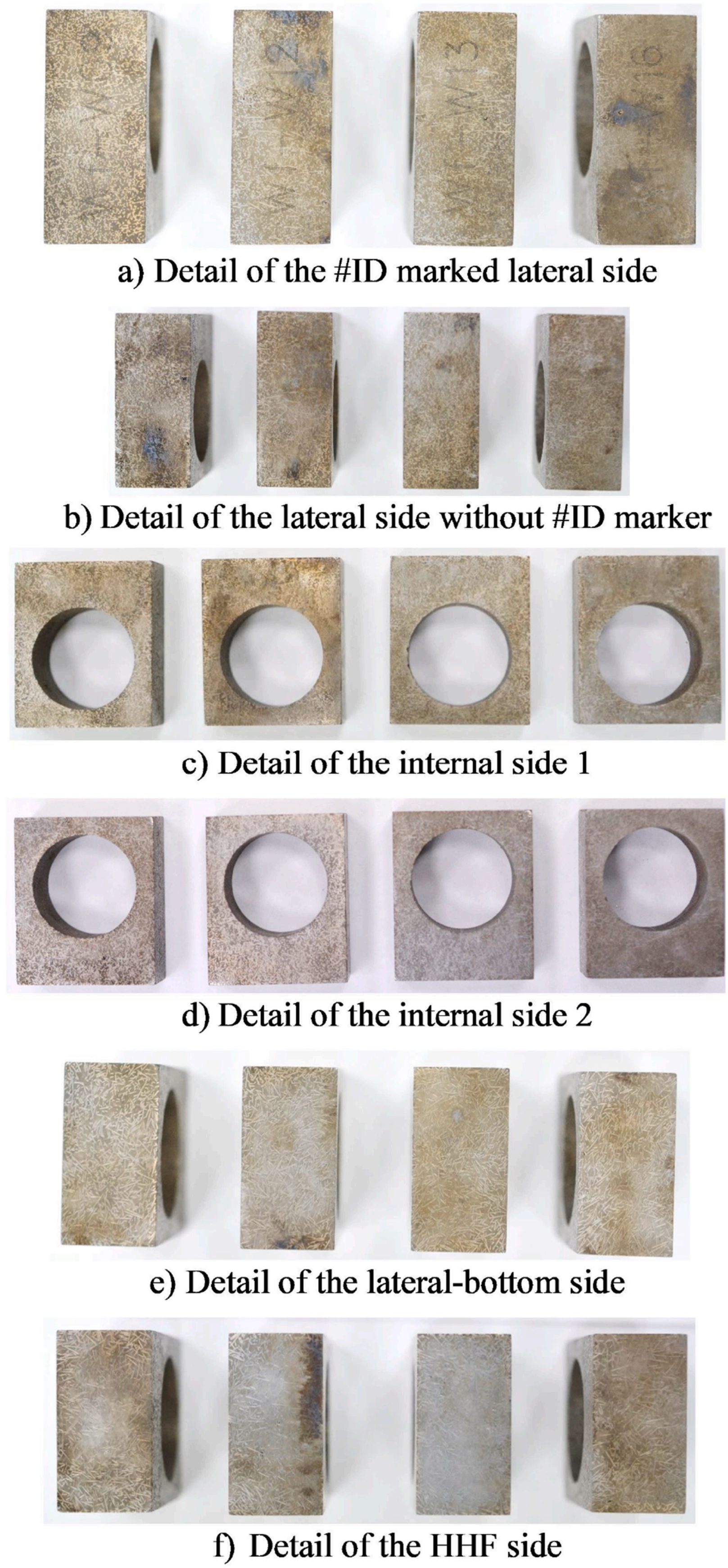


Fig. 1. Short-fibers Wf/W monoblocks after fabrication.

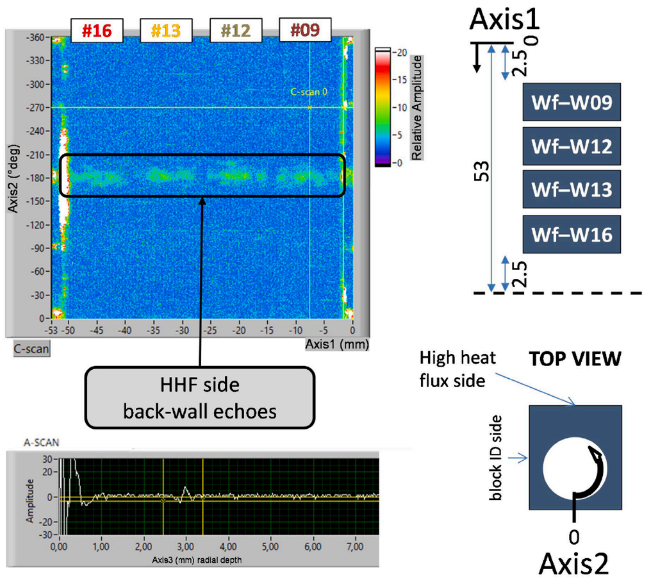


Fig. 2. UT C-scan and A-scan from inside the borehole Wf/W monoblocks which highlight the back wall echoes of the HHF side; radial depth calculated through the time-of-flight (TOF) and with a sound velocity (vs) of 4000 m/s.

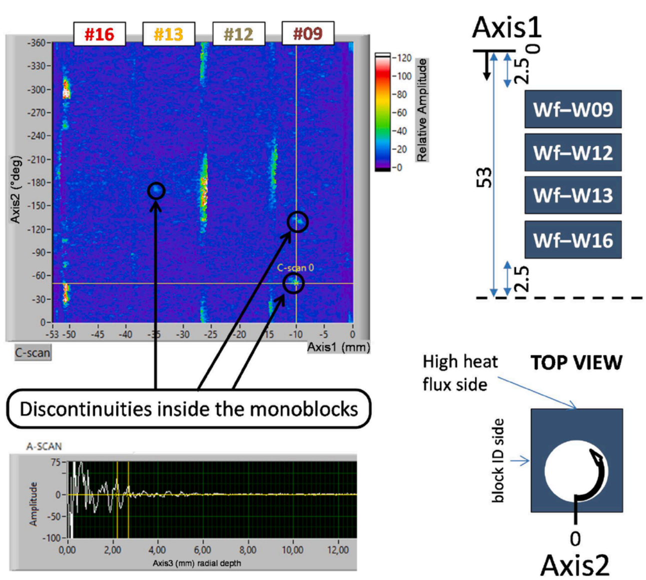
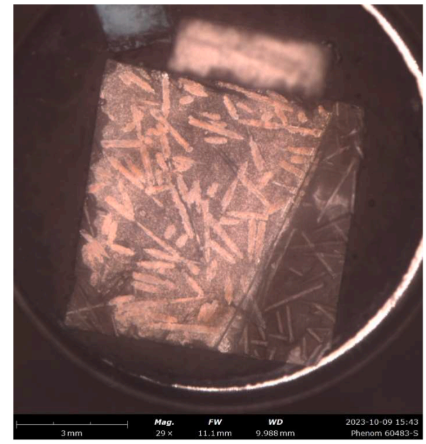


Fig. 3. UT C-scan and A-scan from inside the borehole Wf/W monoblocks which highlight three discontinuities inside the material; radial depth from TOF and v_s of 4000 m/s.

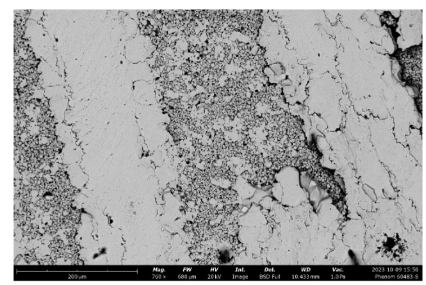
3.2. Casting for the fabrication of OFE-Cu interlayer

After the wettability test campaign on short-fibers PoMo-Wf/W, it was concluded that Cu interlayer fabrication by casting requires the application of nickel on the monoblocks boreholes. The utilization of high quantity of nickel into a fusion reactor is not possible because the element activates under neutron irradiation [18]. For this reason, nickel was applied by electroplating. This choice guaranteed low thickness of the coating, thus a very low nickel quantity. The OFE-Cu casting was realized in the GALILEO furnace, one monoblock per time. The steps followed for the fabrication of the Cu interlayer are described in [19]. Fig. 9 shows images of the Wf/W-Cu blocks after OFE-Cu casting.

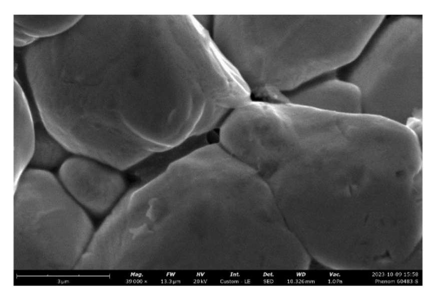
The quality of each Wf/W-Cu block interlayer produced in this context was checked by UTs, above all after OFE-Cu casting, after



a) Optical image of a Wf/W specimen with dimensions 7x7 mm.



b) SEM image which highlights W fibers and W porous matrix (Mag. 760x).



c) SEM image which highlights W particles and vacancies inside the matrix (Mag. 39000x).

Fig. 4. SEM images of a short-fiber PoMo-Wf/W specimen section.

a) Specimen n°1 b) Specimen n°2 c) Specimen n°3

Fig. 5. Short-fibers Wf/W specimens #1 #2 and #3 after Cu wettability tests.

borehole machining up to 12 mm internal diameter (13 mm for block #16) and after machining the interlayer to the final thickness of 1 mm. The UT inspections revealed the presence of several discontinuity indications, mainly at the bottom and upper edges of the borehole, (light green spots in Fig. 10) which are likely cavities or bubbles that contain outgassed material from the microporous of the Wf/W monoblocks.

Despite the presence of the Cu interlayer and the signal distortion within the Wf/W material, all the back-wall echoes were detected for each block. Fig. 11 shows the d-scan results for the Wf/W-Cu blocks with 1 mm interlayer, where the back-wall echoes from the lateral and

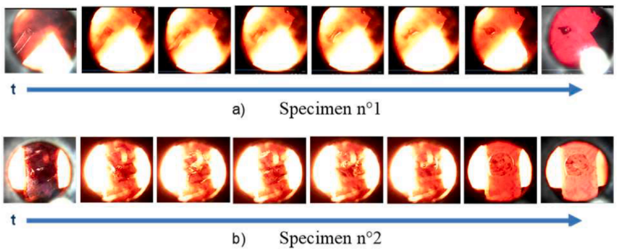


Fig. 6. Frames of the wettability test on short-fibers Wf/W specimens n°1 and n°2.

Fig. 7. Short-fibers Wf/W specimens #2 and #4 after Cu wettability test.

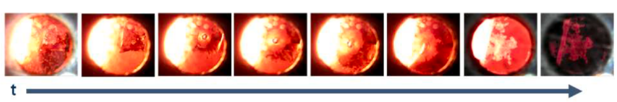


Fig. 8. Frames of the wettability test on short-fibers Wf/W specimen n°4.

Fig. 9. Wf/W-Cu blocks after OFE-Cu casting.

bottom sides (upper d-scan) and from the HHF sides (bottom d-scan) can be visually appreciated.

4. HRP for Wf/W mock-up fabrication

The qualified fabrication process of ITER vertical target divertor requires the joining of W-Cu blocks with a CuCrZr-IG pipe by HRP [20]. An ITER-like mock-up with four short-fibers Wf/W-Cu blocks was fabricated. The mock-up joining process was performed using the HRP-DEMO facility available at the ENEA-TES laboratory [21]. The fabrication was executed under the same process parameters used for the fabrication of the ITER divertor Inner Vertical Target [22] except for some tuning and optimization required by the thermo-mechanical characteristics of the Wf/W material. Fig. 12 reports the Wf/W final mock-up named ENEA 91.

Ultrasonic inspection was performed on ENEA 91. Fig. 12 shows the C-Scan and A-scan presentations at the CuCrZr/Cu interface. With the only exception of block #12, there are large detached areas at the blocks edges. Furthermore, the UT revealed also the presence of spot-sized detachments (from light green to red color). Visual inspection on ENEA 91 showed radial cracks on all the three lateral sides of each block. The damage is related to the presence of large voids inside the matrix. Three larger porous close to the borehole monoblocks were detected by UT (Fig. 13). Under pressure, the voids acted as crack initiation points, guiding the cracks propagation without involving the fibers [15]. Therefore, pseudo-ductile fracture behavior could not be achieved and the cracks critically extended up to the outside of the blocks. Since not all the material is compromised by the presence of voids, all four blocks present integer areas and do not show cracks at the HHF sides (Fig. 14). A Helium leak test was performed, with negative results, meaning that at least one crack goes from the inside of the pipe up to the outside of the blocks. Fig. 15 shows a thick crack in which the CuCrZr-IG pipe was free to deform to the point of creating a gap.

5. Conclusions

In the present work, an ITER-like mock-up, named ENEA 91, was fabricated using short-fibers Wf/W monoblocks, which were produced within the collaboration of FZJ and IPP, in the context of the EUROfusion WPMAT research activities. A Cu interlayer was fabricated by OFE-Cu casting while the Wf/W-Cu blocks were joined to a CuCrZr pipe by HRP. The Cu interlayer fabrication required a nickel pre-coating, deposited by means of electroplating deposition on the inner borehole surface, to improve the wettability of Cu on Wf/W. NDE of the mock-up fabrication process, both by visual inspection and UTs, revealed that the mock-up quality is affected by the microporosity of the matrix. ENEA 91

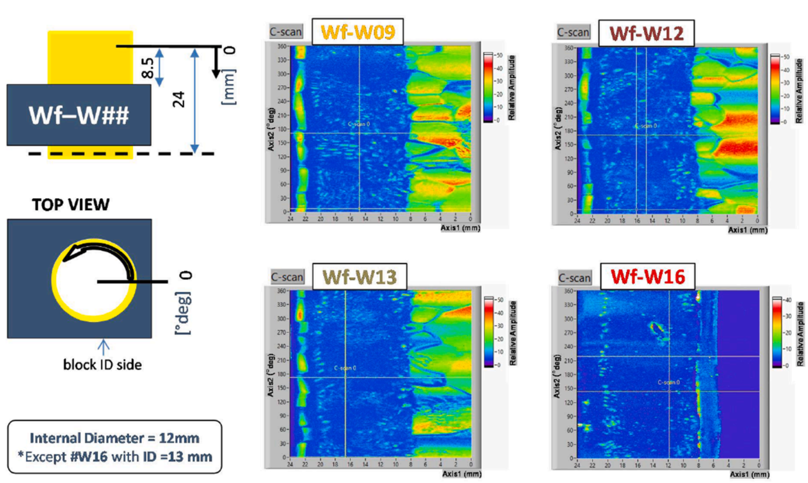


Fig. 10. UT C-scans at the Cu interlayer of the Wf/W-Cu blocks.

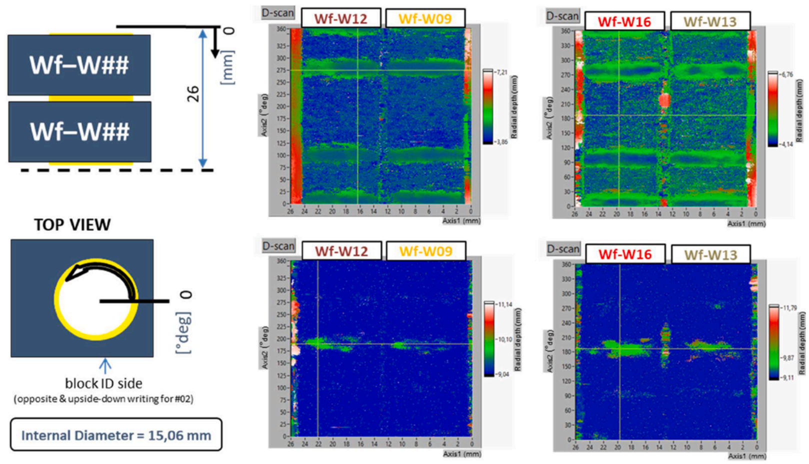


Fig. 11. UT d-scans of Wf/W-Cu blocks back-wall echoes.

Fig. 12. Mock-up ENEA 91 after fabrication.

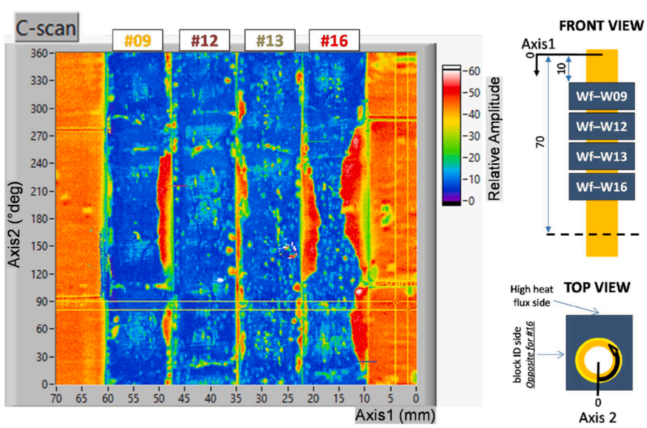


Fig. 13. UT C-scan at the CuCrZr/Cu interface of ENEA 91 after fabrication.

is affected by radial cracks starting from the lateral sides of the Wf/W monoblocks, which means that the porous matrix of the Wf/W is not able to withstand the pressure applied during the HRP process. Furthermore, the Helium leak test revealed that at least one crack goes from inside to outside the mock-up. Nevertheless, the visual inspection suggested that the integrity of the block at the HHF side and the UT revealed continuity among the HHF direction.

In conclusion, the fabrication of mock-up ENEA 91 demonstrated that PoMo-Wf/W monoblocks can be used to manufacture ITER-like PFUs by HRP only if the sintering of the Wf/W monoblocks do not leave voids between the fibers. Voids can act as pre-damages which lead under pressure to blocks cracking. Local inhomogeneous densification of W fibers and W matrix should be avoided during FAST process. The HRP process should be fine-tuned to maintain the Wf/W-Cu blocks in a compression state in radial direction. Nevertheless, this result is only based on one type of Wf/W with short fibers and porous matrix. The current design of Wf/W is more based on long fibers and dense matrix [12]. The future research efforts will concentrate on the fabrication of mock-ups with long-fibers dense-matrix Wf/W as armour material in which the joining behavior should be different than the effect in this

Fig. 14. HHF side of Wf/W blocks for mock-up ENEA 91.

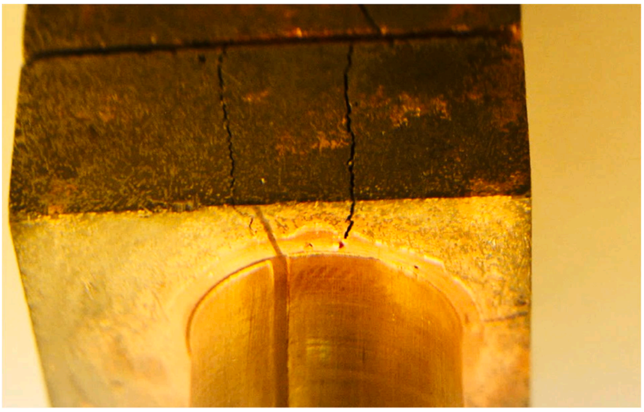


Fig. 15. Cracks on Wf/W block #16 visible from the external side to the Cu interlayer for mock-up ENEA 91.

study.

CRediT authorship contribution statement

Francesco Crea: Writing – review & editing, Writing – original draft, Validation, Supervision, Conceptualization, Investigation, Visualization. **Emanuele Cacciotti:** Investigation. **Riccardo De Luca:** Writing – review & editing, Investigation. **Pierdomenico Lorusso:** Investigation. **Selanna Roccella:** Supervision, Conceptualization. **Annunziata Satriano:** Visualization, Resources. **Luigi Verdini:** Supervision, Investigation. **Jan Willem Coenen:** Conceptualization, Resources, Writing – review & editing. **Yiran Mao:** Writing – review & editing, Conceptualization, Resources. **Johann Riesch:** Conceptualization, Resources. **Marius Wirtz:** Funding acquisition, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Data availability

Data will be made available on request.

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