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Mock-ups fabrication by HRP technology with advanced W-alloy monoblocks for DEMO divertor target

Francesco Crea [a,*], Bernd Böswirth [b], Emanuele Cacciotti [a], Andrei Galatanu [c], Henri Greuner [b], Carmen García-Rosales [d,e], Pierdomenico Lorusso [a], Selanna Roccella [a], Elisa Sal [d,e], Luigi Verdini [a], Marius Wirtz [f]

[a] Department of Fusion and Nuclear Safety Technology, ENEA, FSN-FUSEN-TES, Frascati, Rome I-00044, Italy
[b] Max Planck Institute for Plasma Physics, Boltzmannstr. 2, Garching 85748, Germany
[c] National Institute of Materials Physics (NIMP), Magurele 077125, Romania
[d] CEIT-Basque Research and Technology Alliance (BRTA), Paseo de Manuel Lardizabal 15, San Sebastian 20018, Spain
[e] Universidad de Navarra, Tecnun, Paseo de Manuel Lardizabal 13, San Sebastian 20018, Spain
[f] Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung – Plasmaphysik, Jülich 52425, Germany

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ABSTRACT

Tungsten is the primary candidate armour material for the divertor target of the European demonstration fusion power plant. During operation at high temperature, pure tungsten is subject to fracture and recrystallization which results in a loss of strength and worsening of the thermal properties. Additionally, loss-of-coolant accidents with simultaneous air ingress can generate volatile and radioactive tungsten oxides. Advanced W-alloys were developed as alternative and upgrading armour materials of pure tungsten, such as potassium-doped tungsten laminates and self-passivating tungsten alloys. Three mock-ups were manufactured using potassium-doped tungsten laminates, W-10Cr-0.5Y and W-10Cr-0.5Y-0.5Zr as armour materials, each of them consisting of n°4 blocks. The fabrication required optimization and upscaling of the ITER-like process which foresees oxygen-free high conductivity copper as interlayer joined to W-alloy armour block and CuCrZr ITER grade pipe welded to the Cu/W-alloy blocks by hot radial pressing. For quality control of the fabrication steps, non-destructive examination by ultrasonic testing was done on the monoblocks as received, after casting, after hot radial pressing and after high heat flux testing. The results demonstrated that these W-alloys can be used as armour materials of the European demonstration fusion power plant divertor target.

1. Introduction

The current consolidated process for the fabrication of a target divertor for ITER foresees pure tungsten (W) monoblocks as armour material, Oxygen-Free High Conductivity copper (OFHC-Cu) as interlayer joined to the pure W monblocks, CuCrZr ITER Grade (CuCrZr-IG) alloy as heat sink material joined to the W-Cu blocks by Hot Radial Pressing (HRP) technology [1].

ENEA Special TEchnologies laboratory (TES) developed the HRP joining technique which is the baseline eligible for the conceptual design phase of the European demonstration fusion power plant (EU-DEMO) divertor target, as per the entire ITER-like target design [2,3]. W is currently the favourite candidate armour material of the EU-DEMO [4]. However, during operation at high temperature pure W is subject to recrystallization which results in a loss of strength and thermal properties, while loss-of-coolant accidents with simultaneous air ingress can generate volatile and radioactive W oxides.

Within the EUROfusion roadmap for the EU-DEMO reactor design, research activities have been promoted for the technological development of Plasma Facing Components (PFCs). One of the aims of the Work Package Materials (WP-MAT) is the development and fabrication upscaling of advanced W-based plasma facing materials (PFMs), willing to find the best advanced W-alloy candidate as armour material of the water-cooled EU-DEMO divertor target, improving risk mitigation and the operative thermo-mechanical properties of pure W [5].

In this paper, the fabrication of three mock-ups using advanced W-alloy monoblocks is reported. The Cu interlayer inside the monoblock hole acts as a coupling and stress mitigating layer and it was

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

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manufactured by OFHC-Cu casting method. For each mock-up, Cu/W-alloys blocks were joined to a CuCrZr-IG pipe through the HRP technique. The main issues in the mock-ups fabrication using advanced W monoblocks lies in the different chemical compositions and mechanical properties of the various armour material candidates. A good fabrication set-up for a W-alloy may not be good for another W-alloy and vice versa. Both the manufacturing processes (casting and HRP) required optimization of the fabrication parameters according to the different thermo-mechanical and chemical characteristics of each type of W-alloy monoblock. The mock-ups final geometry is the EU-DEMO-like divertor target one, which is compatible with High Heat Flux (HHF) facilities where the mock-ups were tested for performance comparison.

For quality control, Non-Destructive Examination (NDE) by Ultrasonic Testing (UT) was done on the monoblocks as received and after OFHC-Cu casting on hole monoblocks, in order to verify their integrity before the jointing process to the pipe. The UT non-destructive examination was performed also after the HRP process, for all the three mock-ups, and after HHF testing in the case of mock-up with W-10Cr-0.5Y monoblocks. The UT method used is based on a pulse-echo water gap technique [6]. The UTs were performed by polar scanning, meaning with the probe moving from the inside of the blocks holes or from the inside of the mock-ups pipes, making one angular movement and one axial translation.

2. Advanced W-alloy armour materials

Owing to its physical properties, W is still the most promising PFM for both ITER and EU-DEMO [7]. The WP-MAT research activities program has focused also on the development and qualification of advanced W-alloys for improving the less favorable properties of pure W [8].

Rolling is a process that can modify the microstructure of refractory metals. In particular, low-temperature rolling highly increase the ductility and strength of W [9]. Moreover, Reiser et al. has verified that cold-rolled W plates possess a lower brittle-to-ductile-transition temperature and a stable crack growth which is accompanied by crack bridging effects [10,11]. Laminated composites made of thin cold-rolled ultrafine-grained W can be used as PFM that can exploit the improved properties of cold-rolled W combined with the characteristic of other materials as interlayers between the W foils [12]. Different bonding technologies were investigated to manufacture laminated composite materials from thin single foils. One of these joining method is the Field Assisted Sintering Technique (FAST), alternatively named spark plasma sintering, which has the advantages of a short processing time, with subsequent lower recrystallization detrimental effect [13]. W is strongly sensitive to interstitial impurities, which may lead to inter-granular failure when the material is under a mechanical load. On the other hand, the beneficial effect of a proper doping of W with a low quantity of other elements is something heavily investigated and well-known in the lighting industry [14]. Potassium is a dopant used in W wires which creates nano K-bubbles dispersed at the grain boundaries. At high operation temperatures, typical for PFMs, K-bubbles can hinder the motion of grains, leading to the material strengthening and suppression of recrystallization [15–17]. K-doping is also effective in improving irradiation resistance of W [17]. NIMP has recently produced K-doped W Laminates (KdWL) samples by FAST which were tested under electron beam irradiation [18]. In this work, KdWL monoblocks were manufactured using foils with thickness of 0.1 mm (supplied by Plansee) joined together at NIMP by FAST. The KdWL monoblocks have been machined by EDM and polished in order that the foils that constitute each monoblock have parallel direction to the HHF at operating and testing conditions. The UT examination was performed by polar scanning. Some discontinuity indications have been detected on the first batch of monoblocks, thus another UT by planar scanning was performed for further investigation which revealed the presence of delaminations inside the monoblocks, including monoblock #62 with detected delamination (Fig. 1). The machining procedure was improved in the second batch of monoblocks and no discontinuitiy indications have been detected for these monoblocks. The final mock-up was made with two monoblocks of the first batch and two monoblocks of the second batch.

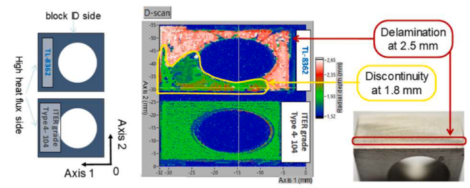

Fig. 1. Monoblock #62 and UT D-scan by planar scanning on #62 and a type-4 pure W monoblock which revealed the presence of two discontinuity indication with total area of a full section of the monoblock; radial depth calculated through the time-of-flight (TOF) and with a sound velocity (v_s) of 5200 m/s.

Under operating conditions, the armour materials of the blanket first wall may reach temperatures up to about 650 °C. Besides, in case of a loss-of-coolant accident, the in-vessel components may reach temperatures above 1000 °C due to the decay heat; if simultaneous air ingress takes place, volatile and radioactive species of WO_3 will be formed [19]. Self-passivating W alloys provide a safety advantage in comparison to pure W mainly by the addition of chromium, which reduces oxidation by the formation a Cr_2O_3 layer protecting the underlying W material [20]. The addition of a small amount of yttrium strongly contributes to self-passivation [21]. W-Cr-Y alloys were successfully produced at lab-scale via mechanical alloying (MA) followed by either hot isostatic pressing (HIP) or FAST [22,23]. The two self-passivating W alloys manufactured for this work by CEIT are ternary W-Cr-Y and quaternary W-Cr-Y-Zr PFMs [24,25]. The fabrication required MA, HIP and a heat treatment (HT) to finally get W-10Cr-0.5Y and W-10Cr-0.5Y-0.5Zr bulk alloys with low impurity content and density above 98 %. The machining from bulk material to monoblock shape was critical due to the hardness and brittleness of these alloys, which led to stress concentrations and relaxation cracking at the sharp edges. The UT revealed the presence of discontinuity indications inside the monoblocks, but the quality was improved in the later W-10Cr-0.5Y-0.5Zr batch (Figs. 2 and 3).

All monoblocks (either KdWL and self-passivating) had dimensions 28 × 23 × 12 mm with internal hole of 17 mm and armour thickness of 8 mm.

3. Casting for the fabrication of OFHC-Cu interlayer

The OFHC-Cu interlayer of the blocks was obtained by casting of the OFHC-Cu into the W-alloys monoblocks bore hole using the vacuum furnace GALILEO of ENEA TES and an ad-hoc apparatus developed for the process. The monoblocks were processed with outgassing threatment, they were cleaned by solvent to remove organic contaminations and by acid to remove external oxides. The pre-casting steps and the

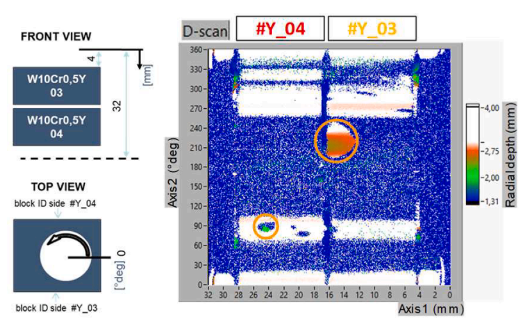

Fig. 2. UT D-scans of monoblocks #Y_03 and #Y_04 with highlighted in orange the main discontinuity indications detected; radial depth from TOF and v_s of 5200 m/s.

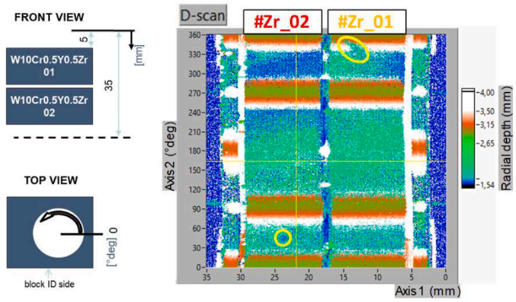

Fig. 3. UT D-scans of monoblocks #Zr_01 and #Zr_02 with highlighted in yellow the main discontinuity indications detected; radial depth from TOF and v_s of 5200 m/s.

casting set-up were defined accordingly to the chemical and mechanical properties of each type of W-alloys. The Cu/W-alloy blocks were later processed to remove the surplus OFHC-Cu and get the Cu interlayer according to the technical specifications of the EU-DEMO monoblocks.

3.1. OFHC casting for KdWL monoblocks

The OFHC-Cu casting was performed on the KdWL monoblocks without any specific treatment of the bore hole surface. The monoblocks were processed one by one to get the higher quality Cu interlayer. After the casting step and before performing the UT, the blocks were machined to get an internal diameter of 12mm (Fig. 5). The UT C-scans of Fig. 4 showed few discontinuity indications in the copper close to the Cu/W-alloy interface, mostly for the monoblocks #62 and #52. #62 had discontinuities in correspondence, and close to, the pre-existing delaminations observed with the UT on the monoblocks as received (Fig. 1).

Further small discontinuity indications (one for #58 and two for #62) have been detected by UT in the region of the Cu interlayer close to the internal hole. Nevertheless, all the small discontinuity indications are not relevant for affecting the heat removal capability of the mock-up.

3.2. OFHC-Cu casting for W-10Cr-0.5Y and W-10Cr-0.5Y-0.5Zr monoblocks

The W-10Cr-0.5Y monoblocks inner holes were previously treated to improve the wetting of the copper on the W-alloy. The hole of monoblock #Y_01 was treated by etching and nickel electroplating. The etching was performed to erase any trace of oxide layer which might be generated during the cutting of the hole. Nickel was used as wetting agent to improve the wettability of copper on W. After nickel electroplating, OFHC-Cu was cast on the hole of monoblock #Y_01. The UT C-scans showed three discontinuity indications in the copper interlayer (Fig. 8) but they were not relevant to affect the heat removal capability of the mock-up. The monoblocks #Y_02, #Y_03 and #Y_04 were treated

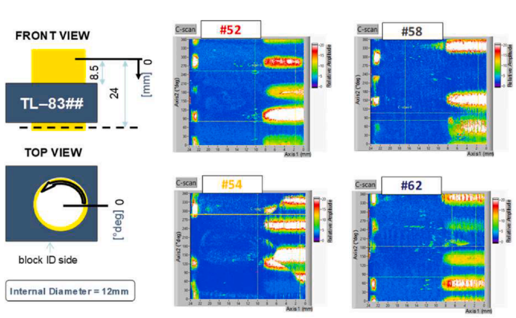

Fig. 4. UT C-scans at the Cu interlayer and close to the Cu/W-alloy interface of KdWL blocks after OFHC-Cu casting.

Fig. 5. KdWL blocks after OFHC-Cu casting and bore hole machined to 12 mm.

by etching and later all together by a deposition of a commercial brazing alloy (Ticuni® by Morgan Advanced Materials plc) on the bore hole by means an HT in the GALILEO furnace. This activation method has been used and patented for carbon/carbon fibre composite (CFC) monoblocks [26–28]. The issue of this treatment is that Ticuni® alloy bonds to both the hole but also to neighboring surfaces. Downstream Ticuni® activation, OFHC-Cu was cast on the holes of blocks #Y_02, #Y_03 and #Y_04 together (Fig. 6). The UT C-scans showed groups of discontinuity indications in the copper interlayer (Figs. 9 and 10). Therefore, in the case of W-10Cr-0.5Y alloy, activation by nickel electroplating should be preferred. However, nickel activates under neutron irradiation [29]. The deposition of nickel by electroplating guaranteed the low thickness of the coating, thus the nickel quantity was very low in comparison of the activation method by Ticuni®.

The OFHC-Cu casting was performed on the W-10Cr-0.5Y-0.5Zr monoblocks without any specific treatment of the bore hole surface. The apparatus and parameters of the GALILEO furnace were optimized from previous trials with W-10Cr-0.5Y alloy, thus the activation surface treatment was not necessary for the W-10Cr-0.5Y-0.5Zr monoblocks and nickel was avoided. The monoblocks were processed one by one to get the higher quality Cu interlayer (Fig. 7). After OFHC-Cu casting, before to perform the UT, the blocks were machined to get an internal diameter of 12 mm. The UT C-scans of Fig. 11 shows low porosity and no discontinuity indications in the Cu interlayer.

4. HRP joining for mock-ups fabrication

The advanced Cu/W-alloys blocks were joined to a CuCrZr-IG pipe by HRP. Three final mock-ups were manufactured, one per each type of advanced Cu/W-alloys blocks, and respectively named ENEA 80 for Cu/KdWL blocks, ENEA 63 for Cu/W-10Cr-0.5Y and ENEA 86 for Cu/W-10Cr-0.5Y-0.5Zr blocks. All the three mock-ups have four blocks each one (drawing in Fig. 12). The HRP parameters were the ITER-like ones [30] except for tuning and optimization required by the thermo-mechanical characteristics of each specific advanced W-alloy. The joining was performed with the HRP-DEMO facility in ENEA-TES [31].

4.1. HRP joining for Cu/KdWL blocks

Final mock-up ENEA 80 was fabricated with the four Cu/KdWL blocks joined to a CuCrZr-IG pipe by HRP with ITER-like parameters (Fig. 13). The UT in Fig. 14 shows the good quality of the joining and the absence of significant defects. The HRP did not damaged the Cu/KdWL blocks and only the previous delamination on block #62 was detected by UT. ENEA 80 was later tested at HHF cyclic thermal fatigue in GLADIS facility with excellent results.

Fig. 6. Blocks #Y_02, #Y_03 and #Y_04 after OFHC-Cu casting and bore hole machined to 15.06 mm.

Fig. 7. W-10Cr-0.5-Y-0.5Zr blocks after OFHC-Cu casting.

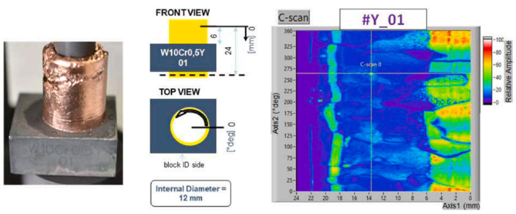

Fig. 8. Block #Y_01 after OFHC-Cu casting and UT C-scan in the Cu interlayer with bore hole machined to 12 mm.

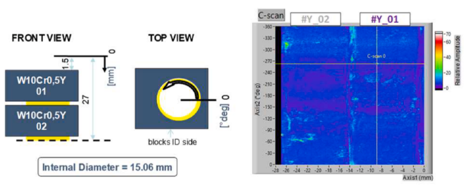

Fig. 9. Blocks #Y_01 and #Y_02 after OFHC-Cu casting and UT C-scan in the Cu interlayer with bore hole machined to 15.06 mm.

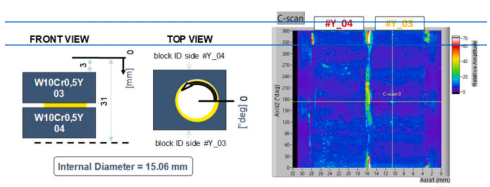

Fig. 10. Blocks #Y_03 and #Y_04 after OFHC-Cu casting and UT C-scan in the Cu interlayer with bore hole machined to 15.06 mm.

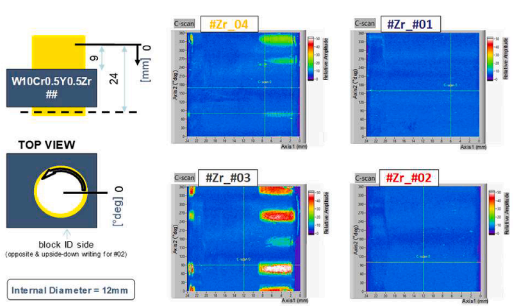

Fig. 11. UT C-scans at the Cu interlayer of W-10Cr-0.5-Y-0.5Zr blocks after OFHC-Cu casting.

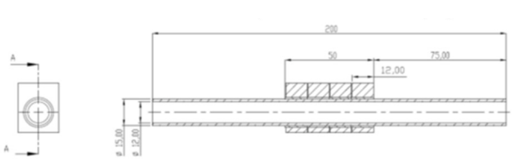

Fig. 12. Drawing of the final mock-ups.

Fig. 13. Mock-up ENEA 80 after fabrication.

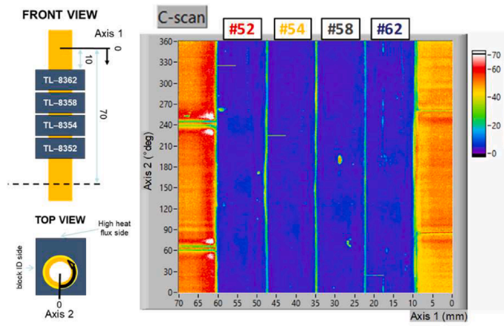

Fig. 14. UT C-scan at the CuCrZr/Cu interface of ENEA 80 after fabrication; radial depth from TOF and $v_s = 5000$ m/s.

4.2. HRP joining for Cu/W-10Cr-0.5Y blocks and Cu/W-10Cr-0.5Y-0.5Zr blocks

HRP was performed also to fabricate two final mock-ups with Cu/W-Cr self-passivating blocks and CuCrZr-IG pipes, respectively ENEA 63 with four Cu/W-10Cr-0.5Y blocks (Fig. 15) and ENEA 86 with four Cu/W-10Cr-0.5Y-0.5Zr blocks (Fig. 16). For both these mock-ups the HRP parameters were modified from the ITER-like ones to reduce the stress inside the monoblocks and the consequent risk of stress relaxation cracking due to the intrinsic brittleness of this type of advanced W-alloys. Nevertheless, the later UT scanning revealed cracks inside the blocks (Fig. 17). The cracks originated and propagated from previous discontinuities in the bulk W-Cr alloys after HIP or after machining. Although ENEA 86 was too damaged to be HHF tested, ENEA 63 was in good sufficient conditions, particularly in correspondence of block #Y_01, so that the mock-up was tested at HHF in JUDITH-2 facility with good results.

5. Conclusions

In the present work, three mock-ups of the EU-DEMO divertor target were fabricated with advanced W-alloys, Cu interlayer made by OFHC-Cu casting, a CuCrZr-IG pipe joined by HRP. A mock-up named ENEA 80 was fabricated with KdWL monoblocks manufactured by NIMP using cold-rolled K-doped W foils joined by FAST. Two mock-ups named ENEA 63 and ENEA 86 were fabricated respectively with W-10Cr-0.5Y and W-10Cr-0.5Y-0.5Zr manufactured by CEIT using MA, HIP and a HT. For ENEA 80, the Cu interlayer of the blocks was fabricated by OFHC-Cu casting without activators and good quality HRP joining was achieved without damaging the mock-up at the materials interface and inside the W-alloy either. The delaminations of one of the blocks did not affect the final quality of the mock-up. ENEA 80 showed excellent performance during the later HHF test in GLADIS facility, in which the mock-up was tested up to 1500 pulses, 10 s each one, at 20 MW/m^2 (cooling water T_{in} = 130 °C, flow rate 1.6 l/s) without compromising the efficiency. New delaminations appeared after HHF test on all the blocks, and they were detected both by UT and by visual inspection (Fig. 18). Fig. 19 shows UT

Fig. 15. Mock-up ENEA 63 after fabrication.

Fig. 16. Mock-up ENEA 86 after fabrication.

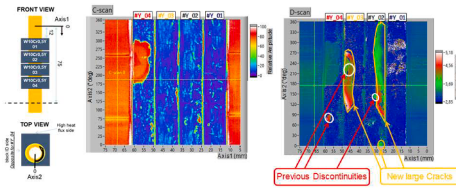

Fig. 17. UT C-scan at the CuCrZr/Cu interface and D-scan back wall echoes of the HHF side of ENEA 63 after fabrication; radial depth from TOF and a v_s = 5000 m/s.

Fig. 18. Mock-up ENEA 80 after HHF test in GLADIS facility (20 MW/m^2, 1500 pulses, 10 s pulse, cooling water T_{in} = 130 °C, flow rate 1.6 l/s).

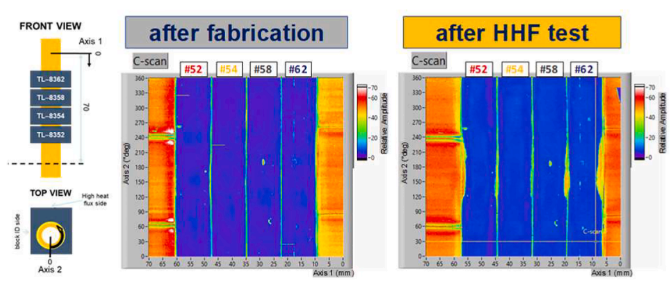

Fig. 19. UT C-scans at the CuCrZr/Cu interface of ENEA 80 before and after HHF test in GLADIS.

C-scans at the CuCrZr/Cu interface of ENEA 80 before and after HHF test in GLADIS.

The Cu interlayers of the Cu/W-10Cr-0.5Y and Cu/W-10Cr-0.5Y-0.5Zr self-passivating blocks were fabricated by different types of OFHC-Cu casting. The good quality of the Cu interlayer for block #Y_01 was achieved by activating the interface with a nickel electroplating layer. The OFHC-Cu casting process was optimized for W-10Cr-0.5Y-0.5Zr monoblocks and good quality of the Cu interlayer was achieved without using nickel. Both ENEA 63 and ENEA 86 were fabricated with the same custom HRP process to preserve the brittle self-passivating blocks. During HRP, the previous defects generated by the machining of the W alloy expanded up to become relevant cracks, thus ENEA 86 was not selected for HHF testing. Some cracks were detected in ENEA 63 after HRP, but the main parts were integer, thus ENEA 63 was tested at cyclic thermal fatigue in JUDITH-2 in correspondence of block #Y_01. This block resisted at 200 cycles of 2 MW/m^2 and 100 cycles per each additional MW/m^2, up to 100 cycles at 6 MW/m^2, during which the surface temperature reached 1000–1200 °C (Figs. 20 and 21). Instead, the previous cracks inside blocks #Y_02 and #Y_03 expanded to the entire block thickness (Fig. 21).

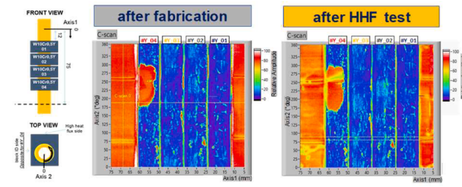

Fig. 20. UT C-scans at the CuCrZr/Cu interface of ENEA 63 before and after HHF test in JUDITH-2.

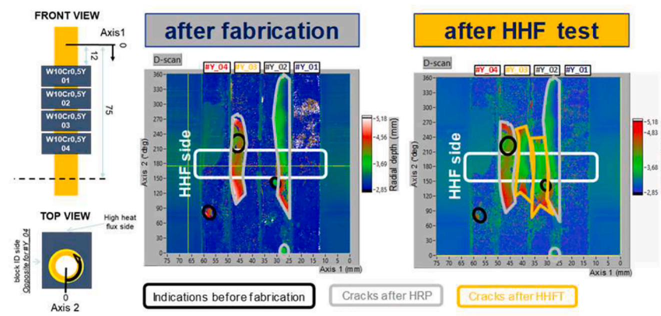

Fig. 21. UT D-scans of ENEA 63 highlighting cracks into the self-passivating alloy before and after HHF test in JUDITH-2 radial depth from TOF and a v_s = 5000 m/s.

In conclusion, the final HHF test on the new ENEA 80 demonstrated that KdWL is an excellent candidate as armour material of the future DEMO divertor target. The brittleness of the ternary W-Cr-Y and quaternary W-Cr-Y-Zr self-passivating alloys can generate cracks, even smalls, that expand during HRP or under operation at HHF, thus the fabrication should require improvements on the manufacturing of the bulk W-alloy and mainly on the machining of the blocks. The HHF on ENEA 63 demonstrated that W-Cr self-passivating alloys can be used as armour material in some parts of the divertor target.

CRediT authorship contribution statement

Francesco Crea: Data curation, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. **Bernd Böswirth:** . **Emanuele Cacciotti:** Data curation, Investigation, Supervision. **Andrei Galatanu:** Investigation. **Henri Greuner:** . **Carmen García-Rosales:** Investigation. **Pierdomenico Lorusso:** Data curation, Investigation. **Selanna Roccella:** Formal analysis, Methodology, Supervision. **Elisa Sal:** Investigation. **Luigi Verdini:** Supervision. **Marius Wirtz:** Investigation.

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.

Data availability

Data will be made available on request.

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