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Diffusion bonding between tungsten base tiles and copper for fusion applications

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ABSTRACT

In the R&D of plasma facing components fabrication, it is required to develop joining technologies between dissimilar materials resistant to strong thermal gradients. When, as in the divertor or in a few positions of the First Wall, the thermal loads exceed 1 MW/m2, the choice of the heat sink material is almost mandatory: copper alloys such as CuCrZr ensure the necessary high thermal conductivity and yield strength.

The preferred plasma-facing material is currently Tungsten (W) (even in ITER, which in its previous design envisaged a Beryllium as plasma facing material for the First Wall, has been decided to replace with W to avoid the complications and additional costs related to the toxicity of Be).

The so-called ITER-like monoblock design is the reference design for the divertor targets of many fusion devices, already in operation, such as WEST or KSTAR, or in the design phase, such as DTT and the future W JT60-SA divertor . The monoblock design has demonstrated great reliability even with cyclic thermal loads up to 25 MW/m2. However, the monoblock is not always a viable solution, due to complex geometries as the W7X divertor, or necessary, when the expected loads do not exceed 5 MW/m2 as for some ITER FW modules or for the Dome. In these cases, the plasma-facing surface in W can be obtained with a flat geometry tile joined on CuCrZr heat sink by a more or less thick layer of pure Cu. The work presented in this paper focuses on qualifying the Diffusion Bonding (DB) process to join W tiles to a Cu substrate.

A number of samples were manufactured and the junction was verified by ultrasonic test non-destructive examination. Two samples were shear tested at room temperature up to the test system limit load without being detected by either visual or ultrasonic test (UT) inspection. Other samples were used to fabricate an actively cooled mock-up to be tested for thermal fatigue up to 5 MW/m2.

1. Introduction

The realization of Plasma Facing Components (PFCs) for nuclear fusion machines necessitates design solutions and material choices with the capability to withstand extreme heat fluxes, particle loads, huge electromagnetic forces and neutron irradiation while maintaining structural integrity over extended operational periods. In such challenging conditions the combined use of Copper Chromium Zirconium (CuCrZr) and tungsten (W) is of a particular relevance, since these materials serve complementary roles. Tungsten is highly valued for its very high melting point and resistance to sputtering, while CuCrZr excels in thermal conductivity and ensure the necessary structural strength. Concerning the design, at the present, the reference solution for PFCs of EU-DEMO, in the divertor target region where steady-state heat fluxes exceeding 10–20 MW/m^2 are envisaged in the so-called ITER-like monoblock design [1,2]. The targets, according to this design, consist of CuCrZr tubes (15 mm OD, 12 mm ID) clad with drilled W blocks and welded around the tube through a thin (1 mm) layer of pure Cu.

Among the operating facilities, the WEST tokamak is equipped with a lower divertor consisting of ITER-like actively cooled W-monoblocks. The experimental results showed that no failures were obtained even if localized melting and cracking have been observed only in the case of PFC misalignments [3]. As reported in [4] also in KSTAR a new lower tungsten actively cooled divertor was recently installed. The same

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ITER-like monoblock concept was also considered for the design of the DTT divertor [5], that of JT60-SA [6] and also for the DEMO inboard/outboard targets [7].

When the complexity of the divertor geometries cannot allows the use of monoblock solution (e.g., baffle unit with very small radii or elaborate shapes) alternative solutions such as flat tile geometry have to be considered for the W plasma facing surfaces. Generally, with the term flat tile is intend a geometry composed by Cu or Cu alloy heat sink and on which W flat tiles are joined as armour on the plasma facing surface.

A flat tile solution for the divertor is adopted for instance in the case of the stellarator Wendelstein 7-X. Due to the extremely complex shape of the first wall a flat-tile design was adopted [8]. Another example is provided by the DTT divertor where PFU have to turn 90-degrees between the central and inner targets. Additional complexity is created by the very limited allowable space and the necessity of shielding the bare cooling pipes from thermal load [9].

A flat joining between these dissimilar materials, namely W tile with pure Cu layer, can be performed by means of different technological solutions, as for instance vacuum Cu melting [9], vacuum brazing [10] and Diffusion Bonding (DB). As shown by the authors of [11], another possibility for the flat tile fabrication is represented by the adoption of Hot Isostatic Pressing (HIP) joining technique. This flat tile mock-up showed an early failure during high heat flux (HHF) testing campaign. To mitigate the failure risk due to cracking at Cu/W interface, an essential condition for DEMO reactor reliability, a novel composite tungsten particle-reinforced copper matrix composite is proposed. This solution shows a good HHF performances.

The work herein presented focuses on the fabrication of W and pure copper joining by diffusion bonding technique and describe the qualification activities carried out and the results obtained. Furthermore, in order to realize an actively cooled component with adequate mechanical resistance to be tested under cyclic heat flux, the W flat tile and copper samples were joined with CuCrZr heat sink. In this case, the welding of the Cu layer to CuCrZr heat sink could have been performed using brazing process or diffusion bonding as Hot Isostatic Pressing (HIP) [12, 13], or Hot Radial Pressing (HRP), a patented technology qualified by ENEA for the fabrication of the first full scale prototype of the ITER inner vertical target [14–16]. As shown in [17] the strength of CuCrZr drastically decreases as a function of the residence time at high temperatures when the temperature is greater than 500 °C. So, it was decided to use HRP to join the Cu with the CuCrZr because this process occurs at a sufficiently low temperature (600 °C) and for a sufficiently short time (2 h) to sufficiently preserve the mechanical characteristics of the copper alloy. Since diffusion between W and copper occurs at much higher temperatures than that between copper and copper, two successive steps are necessary in the manufacturing of a component; diffusion bonding of the W with the pure copper to have W flat tiles joined with the pure copper substrate and, subsequent, diffusion bonding of the pure copper with CuCrZr heat sink.

This manuscript deals with the explanation of steps needed to qualify the proposed technology. First of all, the feasibility study activity is reposted, whose aim is to demonstrate the repetitiveness and the robustness of the proposed manufacturing process. This task involves also the experimental setup, which comprises both the thermal cycle and the development of the tooling. Subsequently, the assessment of the diffusion bonding interface between W and Cu carried out by destructive and Non-Destructive Examinations (NDE) of the manufactured components will be deeply illustrated. Finally, a paragraph is dedicated to a W flat-tile mock-up manufacturing, to be tested at cyclic thermal flux. In this case, the welding of Cu layers and CuCrZr heat sink is performed through HRP process. The quality of the Cu/CuCrZr interface is analysed resorting to non-destructive Ultrasonic Test (UT).

2. Feasibility study

The feasibility study explained in this section is aimed at understanding both robustness and repeatability of the diffusion bonding process; the adopted sample parameters and dimensions are characteristic of this study.

The DB process was carried out inside a metallic vacuum furnace with diameter of 200 mm and height of ~350 mm. The furnace has the capability to reach a maximum temperature of 1150 °C and a high vacuum level up to ~$5 \bullet 10^{-6}$ mbar. If necessary, the furnace can operate in a controlled argon atmosphere. The process success is strictly related to the design of the equipment and to the tuning of thermal cycles to ensure optimal bonding conditions. Taking advantage from the work in [18], a similar thermal cycle was used for all the samples herein reported (see Fig. 1).

As represented by the piece-wise black line of Fig. 1, after a first ramp up of the temperature, there is an interval of time of 40minutes (instead of 10minutes of the reference cycle) with a stationary temperature of 250 °C. After that, another increase of the temperature leads to a flat top temperature at which the bonding process happens. After 2 h at 980 °C the furnace is inertially cooled until room temperature is reached. Unlike the theoretical cycle (black piece-wise lines) the actual cycle (red piece-wise lines) features an inertial cooling, that is strictly related to the vacuum furnace in which the process is accomplished. The equipment was instead tailored to accommodate the Cu blocks as well as the W tiles, whose dimensions are represented in Fig. 2a. The W tiles are identified with the nomenclature *FT01-###*, where *FT* stands for Flat-Tile and 01 indicates the size of the tiles as reported in Fig. 2a.

The Cu blocks were instead produced from an external mechanical workshop; the blocks were machined starting from a Cu OFE 30 mm round bar provided by ENEA. The surface roughness for W tiles is 1.6 μm and up to 3.2 μm for copper blocks. Before the diffusion process the surfaces are opportunely treated to remove possible traces of oils or oxides. As it is possible to observe from Fig. 2c, the Cu blocks foresee two slots aimed at tightly accommodating and maintaining the W tiles in their positions during the diffusion bonding process. Once the W tiles are positioned on the Cu block and this assembly is then coupled with the designed tooling, the whole assemblage is inserted inside the vacuum furnace for the diffusion bonding process. Being the contact pressure between Cu and W not directly measurable during the process, the tooling was designed to maximize the contact pressure. At the end of the process a permanent deformation of the copper block was observed. This indicates that the stress in the copper has reached the yield point at 980 °C and that the contact pressure has necessarily reached the maximum possible value.

For all the produced samples, collected in Fig. 3, the adopted nomenclature is ENEA-DB-###, where DB indicates the process,

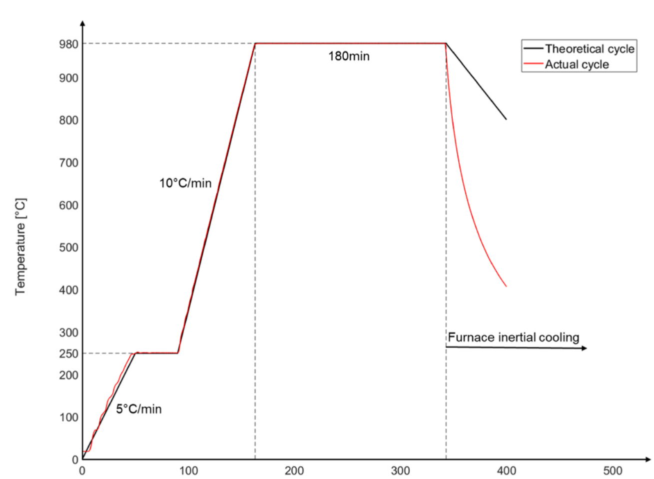

Fig. 1. Thermal cycle, theoretical vs actual, representative of the diffusion bonding processes presented in this work.

Fig. 2. Main dimensions of the W tiles and of the Cu block used for the diffusion bonding process (a); overview of some of the procured W tiles (b); Cu OFE block as manufactured from external mechanical workshop (c).

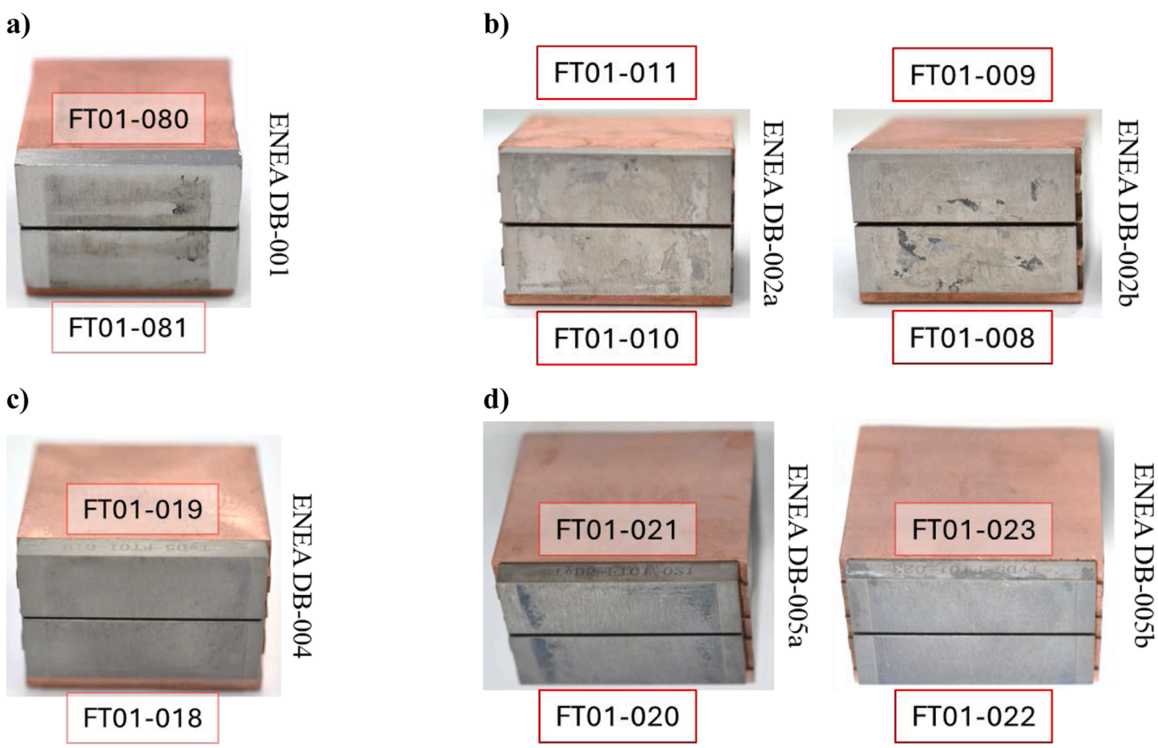

Fig. 3. Overview of the manufactured samples: ENEA DB-001 (a), ENEA DB-002 (b), ENEA DB-004 (c) and ENEA DB-005 (d).

namely the Diffusion Bonding, whilst ### a progressive number indicating the cycle in the oven.

The first-of-a-kind sample is ENEA DB-001 depicted in Fig. 3a. After the first experiment, the ENEA DB-002 samples were manufactured. As illustrated in Fig. 3b two blocks were realized within the same thermal cycle in the oven and named ENEA DB-002a, that is equipped with W tiles FT01–008 and FT01–009, and ENEA DB-002b with tiles FT01–010 and FT01–011. The third attempt, namely the ENEA DB-003 is not herein represented since an unexpected failure of the equipment was encountered during the cycle. This inconvenience led to the necessity of realizing again the equipment. The ENEA DB-004 was then the first sample realized with the new equipment depicted in Fig. 3c. In this case only one block was produced, because it was necessary to preliminary verify if the new equipment work properly during the cycle. The last samples, realized for the feasibility study, were the ENEA DB-005a, equipped with the W tiles FT01–020 and FT01–021, and ENEA DB-005b with tiles FT01–022 and FT01–023, both shown in Fig. 3d

3. Assessment of W/Cu junction

As a part of the qualification activity, this section is dedicated to the analysis of the W/Cu interface downstream of the diffusion process. The quality of the junction is evaluated adopting both non-destructive methods, specifically ultrasonic inspection, and destructive mechanical analyses, namely shear tests.

3.1. Non-destructive UT examinations

The UT system available at the ENEA laboratories employs the pulse-echo water gap technique and comprises an ultrasonic pulser/receiver unit. This equipment is integrated with a handling system featuring four degrees of freedom: three translation and one rotation, that are actuated by stepper motors and are controlled via a custom-developed LabVIEW-based software [19].

The piezoelectric crystal probe used is a focused probe of nominal frequency 20 MHz behaves as both a transmitter and receiver of ultrasonic signals. The presence of acoustic impedance discontinuities in the material, caused by either joining interfaces or defects, generates a reflected signal that is captured by the probe. By analysing the reflected signal, it is possible to distinguish defects from proper joining interfaces: the intensity of the reflected signal is proportional to the difference between the acoustic impedances before and after the discontinuity, so a signal reflected by a good W/Cu junction will have a lower intensity than that reflected by the defect. In the "C-Scan" representation, as those presented in Fig. 4, each pixel corresponds to a measurement point within the scanning grid which is 0.08 mm x 0.08 mm. The colour associated to each pixel is determined by the maximum amplitude in % Full Screen Height of the reflected signal within a user-defined time window. The C-scans at the interface between W and Cu of the samples realized are collected in Fig. 4. As explained above, even a defect-free junction determines a reflected signal. This signal appears in C-scans as a light blue corresponding to an intensity around 15–20 %FSH. In the ENEA DB-004 (Fig. 4c) and ENEA DB-005 (Fig. 4d) UT inspection a W tile not bonded to copper and simply stacked on the samples was included to be used as reference: the intensity of the signal reflected from the bottom of this reference tile is the same of signal that would be reflected from a defect at the same depth in a joined W/Cu samples. Looking at the C-scans in the Fig. 4c and one can conclude that, with the settings used for the scans, a defect at the interface should reflect with an intensity approximately of 40 %FSH and would appear green in the C-scan.

Therefore, observing the UT results of the produced samples, it can be concluded that in none of the produced samples were defects detected at the W/Cu interface, showing excellent reproducibility and reliability of the process.

3.2. Destructive shear tests

To evaluate the mechanical strength of the tungsten-copper joint obtained through diffusion bonding technique, shear tests on the sample ENEA DB-001 were conducted. For this purpose, a traction machine with a maximum applicable load of 100 kN was used. The tests were executed at room temperature controlling the displacement and registering the force. An ad hoc equipment, shown in Fig. 5a together with the traction machine, was developed to perform the shear tests on the manufactured sample. Despite the load capability of the traction machine, the applied load was limited to 10°kN in order to remain within the elastic limit of the punch used for the tests. With this limited load value and considering a junction area of ~190mm^2, a shear stress up to 52.7 MPa can be reached. Assuming a yielding strength of the copper in the range 56÷69 MPa at room temperature, as reported in [20], and assuming the distortion energy theory (i.e., $\tau_y = 0.577 \bullet \sigma_y$), the pure shear yield load is in the range 32.3÷39.8 MPa; these values are lower than the maximum applicable shear with an imposed load of 10 kN.

In Fig. 5b the results of the shear tests conducted on the tiles FT01–080 and FT01–081 of the sample

ENEA DB-001 are illustrated. As it can be observed, the reached shear stresses on the tile FT01–080 and FT01–081 are 44.80 MPa and 51.50 MPa respectively. These values are both over the range of τ_y for copper. Despite the shear stress limit according to the distortion energy theory was overcome, the junctions behave elastically, and similar slopes were obtained in both tests. The UT examination was performed also after the shear tests, to evaluate whether the performed tests caused the formation of any defects at the W/Cu interface. Observing the results reported in Fig. 5c, it is possible to assert that after the shear tests the joint is still flawless, thus confirming that the interface remained in the elastic regime. This is consistent with the behaviour observed during the shear tests, as shown in Fig. 5b

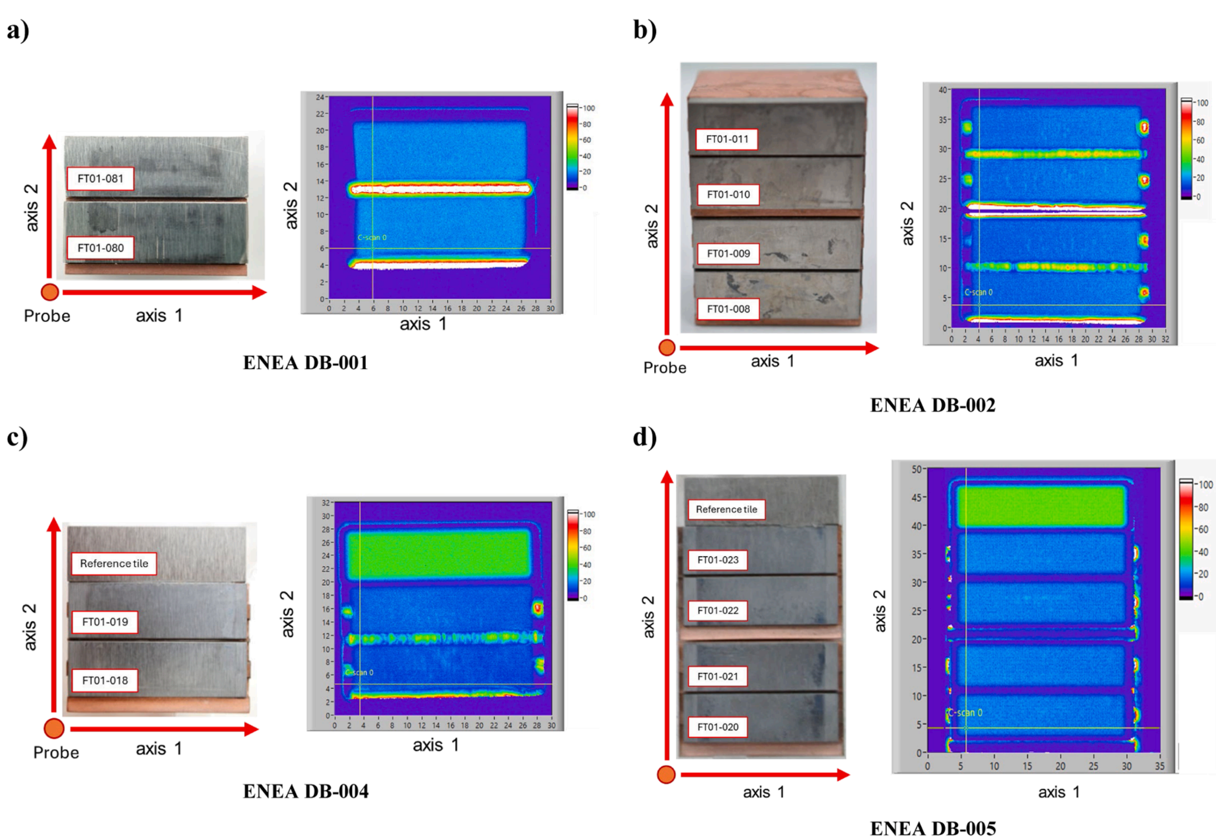

Fig. 4. Non-destructive UT inspection of the Cu/W joining interface after the diffusion bonding process of ENEA DB-001 (a), ENEA DB-002 (b), ENEA DB-004 (c) and ENEA DB-005 (d).

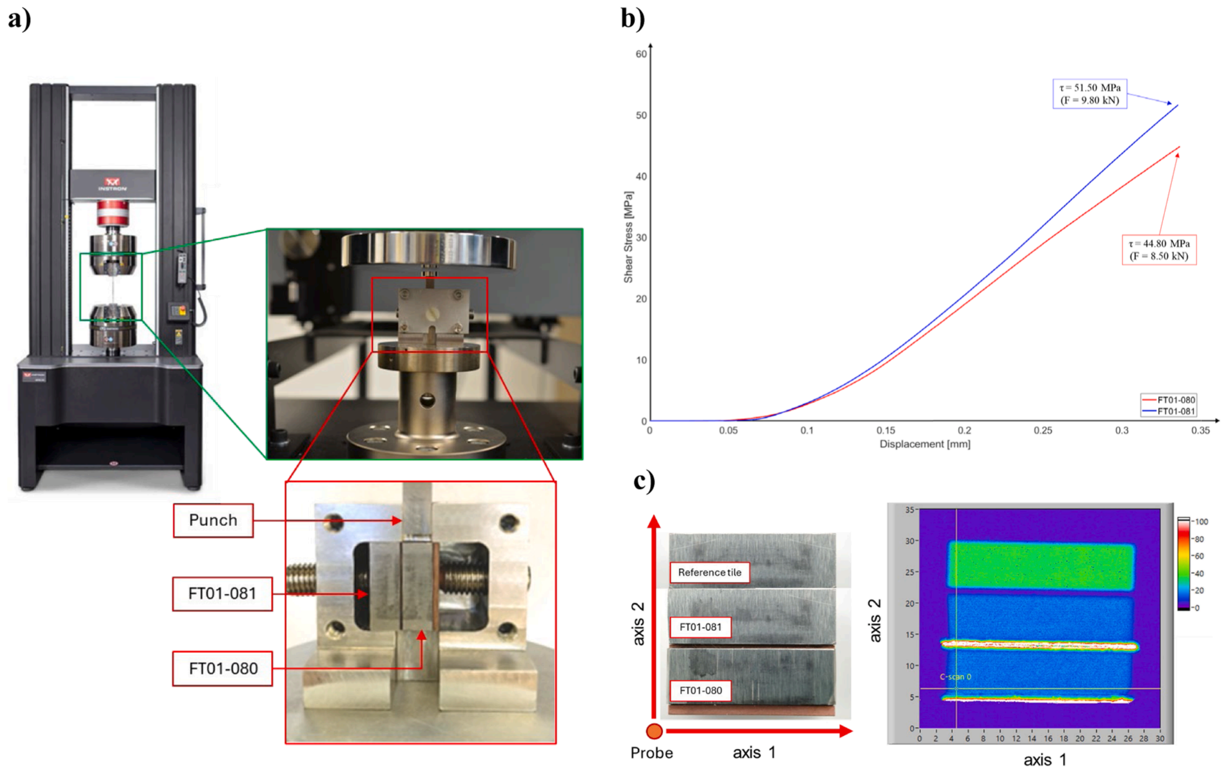

Fig. 5. Overview of the traction machine used for shear tests together with the experimental setup (a) and the shear test results, in terms of displacements vs shear stress, executed on the two W tiles of the sample ENEA DB-001 (b); UT test results performed after the tests (c).

4. Linear mock-up manufacturing

The last step for the qualification of the W-Cu joining is the HHF testing at the neutral hydrogen beam facility GLADIS [21] where an experimental campaign with 5000 cycles at 5 MW/m^2 and 300 cycles at 10 MW/m^2 is planned. For this purpose a linear mock-up was manufactured using the ENEA DB-005 samples

(see Fig. 6).

The ENEA DB-005 samples in Fig. 3d were slightly flattened on the copper sides and drilled (see Fig. 6a) to be assembled on a CuCrZr pipe with internal diameter of 12 mm and thickness of 1.5 mm. The joining between the Cu blocks and the CuCrZr pipe was performed by the HRP technique.

As described in [16], the HRP is a solid state diffusion bonding process that exploits the simultaneous application of temperature (up to 600 °C) and of pressure (up to 58 MPa), applied with an inertial gas from inside the CuCrZr pipe. The whole cycle process is performed inside a vacuum furnace. The non-destructive UT examinations were performed both after machining and after the HRP process. In the first case a scan of the Cu/W interface, performed from outside, was repeated in order to evaluate whether the machining process introduced any defects. The inspection of internal hole, performed from inside, was conducted both before and after the HRP process and a comparison of the results is useful to understand if the presence of a flaw, if any, is imputable to the machining or to the joining procedure.

The planar UT examinations from outside were carried out with the same in the same instrumentation and the same settings of the measurements conducted on the samples after the W/Cu junction. The results of the UT examination of the sample ENEA DB-005 after machining, are shown in Fig. 7a. Comparing the C-scan with the one in the Fig. 4d it is possible to state that the mechanical process had no effects on the Cu/W junctions.

Fig. 7b shows the results of the UT examination performed from inside. To respect the external scan, the degrees of freedom used are a translation (axis 1) with a measurement step of 0.08 mm and a rotation (axis 2) with a measurement step of 1° On the ENEA DB-005 samples holes internal surface it is possible to observe two scratches in correspondence of the tile FT01–022. It is possible also to notice circumferential lines which indicate a non-optimal surface finish. Based on the experience gained by the TES laboratory over the years, these types of

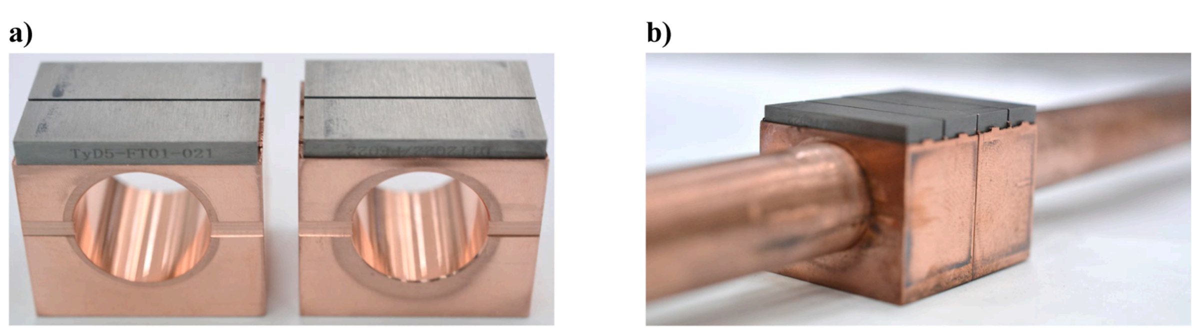

Fig. 6. Overview of ENEA DB-005 holed samples after machining (a) and linear mock-up after HRP process (b).

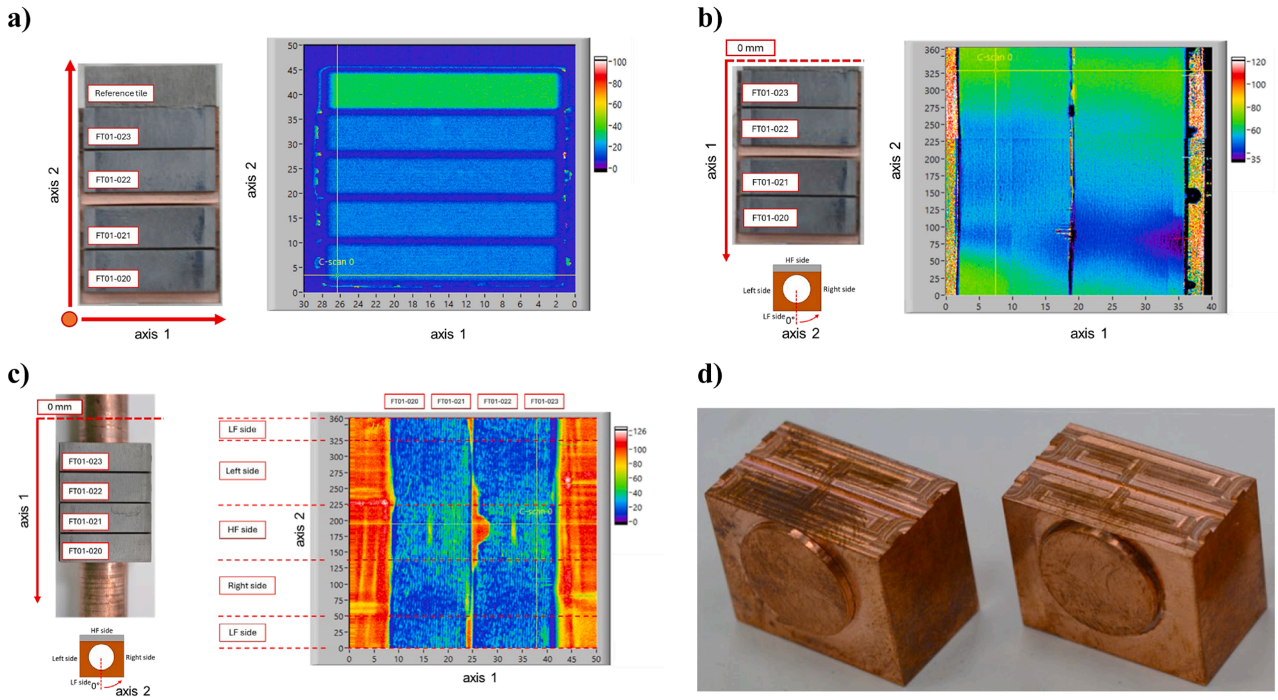

Fig. 7. Non-destructive UT inspection results of ENEA DB-005 samples after machining from outside at Cu/W interface (a) and from inside at hole internal surface (b); UT inspection results at Cu/CuCrZr interface after HRP process (c). Overview of the new Cu blocks shape (d).

defects can have a negative influence on the final result of the HRP joint.

In Fig. 7c is instead represented the UT examination results after HRP process, at the Cu/CuCrZr interface. The two vertical red bands on the right and left of the c-scan are portions of bare tube at the ends of the mock-up. Unlike the junction between dissimilar materials, where part of the signal is reflected even in the absence of defects, at the HRP junction between Cu and CuCrZr a defect-free junction does not reflect any signal since the two materials have the same acoustic impedance. The two vertical red bands on the right and left of the c-scan are portions of bare tube at the ends of the mock-up. From the C-scan in Fig. 7c, many defects can be observed.

First of all, you can notice a red spot positioned between 130° and 250°, that is the High Flux (HF) side, just below the FT01-022W tile. The position and the entity of this flaw could be attributable to both the tooling used in the process and the possible presence of trapped air in between the two Cu blocks.

This defect could be a matter of concern in view of the HHF tests, since HF side is the most stressed part from thermal point of view. The circumferential lines detected on the internal surface of the hole before the joining process (Fig. 7b), are clearly viewable also after the joining, highlighting how the surface finishing affects the joint quality between the CuCrZr pipe and the Cu blocks.

The extent of these defects could still allow this component to pass high thermal flux tests without failure. However, in the authors' opinion, these issues herein observed can be resolved by modifying the shape of the Cu blocks (as shown in Fig. 7d), as well as improving the surface finish of the holes.

5. Conclusions and future work

The use of flat-tile design offers a possible solution when the use of ITER-like monoblock is not a viable solution, e.g. at the extremity of a flat divertor target where the cooling pipes must turn by 90-degrees. A possible way for its realization is represented by the use of diffusion bonding technique to join W tiles to Cu blocks.

In this work the feasibility and robustness of diffusion bonding as a reliable joining technique between W and oxygen-free Electrolytic copper was demonstrated. The quality and strength of the W/Cu interfaces obtained through DB process was confirmed with both non-destructive UT and destructive shear tests validating the integrity and mechanical strength. UT analyses revealed defect-free joining interface in all samples, while shear tests exhibited stress values exceeding the theoretical yield strength of pure copper, further corroborating the robustness of the bonds. Moreover, the post-shear UT inspection showed the absence of flaws thus confirming that the junctions remained within the elastic regime.

The production of a linear mock-up, integrating DB-fabricated W/Cu samples with CuCrZr pipes through hot radial pressing, represents a critical step towards qualification under HHF testing. Initial UT evaluations identified minor surface defects attributed to the machining and tooling, which offers opportunities for further optimization.

Future work will focus on enhancing the quality and reliability of W/Cu and Cu/CuCrZr junctions. Key developments will include refining the tooling design, improving surface finishing. Additionally, the HHF testing of the linear mock-up at the GLADIS facility will provide critical insights into the performance of the bonded components under operational thermal loads. These findings will contribute to the optimization of joining technologies for next-generation fusion reactors, including DEMO, advancing the goal of sustainable nuclear fusion energy.

As a further future activity, the DB process will be used also to join W alloy (i.e., $W_{95}NiFe$) tiles to OFE-Cu in support of the technological R&D activities needed for the W transition of the W7X divertor.

CRediT authorship contribution statement

F. Giorgetti: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **P. Lorusso:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M. Cerocchi:** Writing – review & editing, Methodology, Investigation, Formal analysis. **F. Crea:** Writing – review & editing, Visualization, Conceptualization. **D. Caprini:** Writing – review & editing, Visualization, Data curation, Conceptualization. **R. De Luca:** Writing – review & editing, Visualization, Methodology, Formal analysis, Data curation. **L. Ferrante:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **A. Moriani:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **G. Mugnaini:** Writing – review & editing, Methodology, Investigation, Formal analysis. **S. Roccella:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Conceptualization. **L. Verdini:** Writing – review & editing, Visualization, Software, Methodology, Formal analysis. **J.H. You:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

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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