Fusion Engineering and Design 205 (2024) 114514

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Brazing alloys characterization for EU-DEMO Divertor Target

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ARTICLE INFO

Keywords:
DEMO plasma facing components
Divertor target mock-ups
Divertor materials
Brazing alloys characterization
Nondestructive analysis

ABSTRACT

In the framework of the roadmap of the DEMO reactor design pursued by the EUROfusion Programme, R&D activities have been promoted for the technological development of Plasma Facing Components (PFCs). Dedicated research activity has been undertaken at ENEA to support the development of technological solutions for the monoblock-pipe joining in order to reduce the use of materials having high activation and/or a degradation under neutron irradiation. For this purpose, a preliminary brazing alloy screening was carried out: a total of seven brazing alloys were identified and tested (i.e. Gemco, Nicuman23, TiCuNi, CuTiZrNi and three alloys with different percentages of Cu and Ge). For each brazing alloy, a wettability test on joint base materials (i.e., W and Cu) was performed. Then, three samples were fabricated joining tungsten monoblocks, without Cu interlayer, on a W fiber-reinforced Cu composite cooling pipe; other three samples were realized joining W monoblocks, with and without Cu interlayer on standard ITER-grade CuCrZr pipes. Non-destructive Ultrasonic Testing (UT) examinations were performed on each sample and showed that the monoblocks surface was not fully attached to Wf-Cu pipes; as regard the samples with CuCrZr pipes, excellent results have been achieved both in the case with and without Cu interlayer. From the results, Gemco seems to be the most promising commercial alloy among the tested ones, thanks to its low amount of Nickel and the good joining capabilities.

1. Introduction

Within the roadmap of the DEMO reactor design [1] pursued by the EUROfusion Programme [2], R&D activities have been promoted for the technological development of the Divertor [3]. The divertor is the in-vessel Plasm Facing Component (PFC), having in charge of exhaust the thermal power and remove impurity particles, withstanding to extreme thermal loads on the, so called, targets [4]. In the frame of the WorkPackage Divertor (WPDIV), a dedicated research activity deals with the consolidation and verification of the current target concepts envisioned for DEMO Divertor [5]. The current reference design of DEMO divertor targets is the ITER-like concept consisting in CuCrZr cooling pipes joined to tungsten monoblocks to be shielded from the plasma erosion. The monoblocks, holed Tungsten (W) blocks with a 1 mm Oxygen free copper (OF-Cu) interlayer in the hole, can be joined to the CuCrZr pipe with different technologies (diffusion bonding or brazing). However, copper is a highly activated material and its use in a reactor should be limited [6]. Furthermore the degradation of the mechanical characteristics of the CuCrZr tube under neutron irradiation requires using this material in a very narrow temperature window [6] often in contrast with those of the other materials present in the divertor, such as Eurofer, making the overall design of the divertor cooling circuit very challenging.

Aiming at enhancing the strength of the cooling tube, a back-up solution is under study that foresees the adoption of W fiber-reinforced Cu composite cooling pipe (Wf-Cu pipe) [7] instead of CuCrZr pipes. This pipe can be joined with the monoblocks by brazing because; contrary to the CuCrZr, it does not suffer from the high temperatures of brazing process and does not require subsequent tempering treatments. Conversely, diffusion bonding processes, which require intimate contact of the surfaces to be joined, are difficult or perhaps impossible to apply since, to recover the assembly gap, it is not possible to rely on the thermal expansion of the tube which, having a very high W density, is much lower than that of copper, nor of mechanical deformations through pressurization, as occurs in the Hot Radial Pressing diffusion bonding process, due to the extremely high circumferential

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https://doi.org/10.1016/j.fusengdes.2024.114514
Received 13 October 2023; Received in revised form 6 May 2024; Accepted 14 May 2024
Available online 5 June 2024

stiffness coming from the weaving of the fibers.

In this framework, research activities were carried out at the ENEA Special Technologies Laboratory (FSN-FUSEN-TES) in Frascati, with the main objectives of finding alternative design solutions and materials for target armour [8] and cooling tubes, leading to a full-scale target manufacturing. In particular, a dedicated task aims at finding alternative technological solutions for joining the pipe with the tungsten monoblocks in order to reduce the use of high activation materials, such as Ni, as well as materials whose properties degrade under neutron irradiation. In the past, good results were obtained using Au80Cu brazing alloy for the manufacturing of target mock-up (see [5]) which, however, was abandoned due to the gold transmutation under neutron irradiation.

This paper presents the preliminary screening of the brazing alloys, carried out to identify the most suitable ones for joining the monoblocks with the Wf-Cu pipes. The use of brazing alloys with a reduced content of Ni is preferred, due to its high activation under neutronic irradiation. Seven brazing alloys were identified and tested: Gemco, Nicuman23, TiCuNi, CuTiZrNi and three alloys with different percentages of Cu and Ge. Gemco, Nicuman23 and TiCuNi are commercial brazing alloys, while CuTiZrNi and the Ge-based alloys are made at Universidad Rey Juan Carlos (URJC) within the activities carried out in WorkPackage Materials (WPMAT). For each brazing alloy, a preliminary wettability test on W and Cu specimens was performed.

On the basis of the results of the wettability tests, Gemco, Nicuman23 and TiCuNi brazing alloys were selected to realize small samples, joining W-monoblocks on Wf-Cu composite pipes and on CuCrZr pipe for comparison. Furthermore, the experimental analysis also aims at assessing the influence of the adoption of the Cu interlayer, usually applied inside the W monoblocks hole to reduce the stresses at the interface between W and CuCrZr pipes due to the difference in thermal expansion coefficient of the two materials and which may not be necessary in the case of the Wf-Cu pipe. For this purpose, three samples were fabricated joining W-monoblocks without Cu interlayer on Wf-Cu pipes with each one of the selected alloys. A second set of three sample was fabricated joining W monoblocks with and without Cu interlayer on CuCrZr pipes using Gemco and Nicuman23 alloys.

2. Identification of the brazing alloys

A proper selection of the brazing alloy is fundamental to limit the use of high activation materials. The brazing alloys identified and tested are the following:

- Gemco [9]: a high-purity Cu, Ge and Ni alloy, provided in foil shape of 0.1 mm thickness;
- Nicuman23 [10]: a high-purity Cu, Mn and Ni alloy, provided in foil shape of 0.1 mm thickness;
- TiCuNi [11]: a high-purity active brazing filler in composite form containing Ti, Cu and Ni, developed for direct application to ceramic surfaces. The alloy was provided in foil shape of 0.1 mm thickness;
- Cu-Ge: with three percentage of Cu and Ge. The different quantity of Ge in the alloy affects its melting temperature, which decreases with the increase of the Ge percentage. The samples of the brazing alloys along with their characteristics have been provided by URJC;
- CuTiZrNi: brazing with Cu, Ti, Ze and Ni. The alloy was provided by URJC in strips shape.

The data sheets of the brazing alloys are reported in [6-8] and the main characteristics are listed in Table 1.

3. Wettability test

W and Cu are the base materials of the monoblocks and the cooling pipes which are the elements to be joined for the fabrication of targets. This means that the key point to achieve a high-strength joint by brazing is to adopt a brazing alloy having a high wettability with these two materials. For this reason, W and Cu have been selected as supporting materials to test the suitability of the brazing alloys listed in Table 1. In particular, for each brazing alloy, preliminary wettability tests were performed by melting them on W and Cu specimens. Moreover, the CuTiZrNi alloy was also tested on Boron Nitride (BN) and graphite (C) specimens. These tests were performed to verify that the tools in the vacuum furnace during the joining process made in these materials are not damaged by spills of molten alloy. A dedicated device (Fig. 1) was used to perform the wettability tests. The specimen and the brazing alloy are placed on a support made of Tantalum inside a small vacuum chamber. The support is crossed by electric current and heats up due to the Joule effect, heating in turn, by thermal conduction, the specimen and the brazing alloy. Once that the chamber has been closed, the vacuum has been achieved and the elements have been heated up.

Once that the brazing alloy melting temperature is reached, the fragment starts to melt. By keeping high the temperature, the melted alloy starts to wet the surface of the specimen. Once that the specimen is wetted, the system is cooled down and the resulting sample is extracted from the vacuum chamber. The test was repeated for W and Cu specimens and for each brazing alloy.

The results of the wettability tests performed with Gemco, Nicuman23 and TiCuNi on W and Cu samples, reported in Figs. 2 and 3, showed a good wettability of the alloys on both the specimens, suggesting their suitability for the application in the target mock-up joints.

The results of the tests performed on W and Cu specimens with Cu-Ge alloys are shown in Figs. 4 and 5 and demonstrated that the two brazing alloys with lower percentage of Ge (i.e., Cu-13.5Ge and Cu-19.5Ge) provide the highest wetting capability, since they covered uniformly the entire surface of the W specimens, as demonstrated by Fig. 4a) and b). On the opposite, the brazing alloy with the highest percentage of Ge

Table 1
Summary of samples main features.

Brazing alloy	Composition (%wt)	Melting temperature
Gemco	Cu 87.75 % Ge 12 % Ni 0.25 %	975 °C
Nicuman23	Cu 67.5 % Mn 23.5 % Ni 9%	955 °C
TiCuNi	Ti 70 % Ni 15 % Cu 15 %	960 °C
Cu-13.5Ge	Cu 86.5 % Ge 13.5 %	955 °C
Cu-19.5Ge	Cu 80.5 % Ge 19.5	824 °C
Cu-33.2Ge	Cu 66.8 % Ge 33.2 %	696 °C
CuTiZrNi	Restricted WPMAT (URJC)	Restricted WPMAT (URJC)

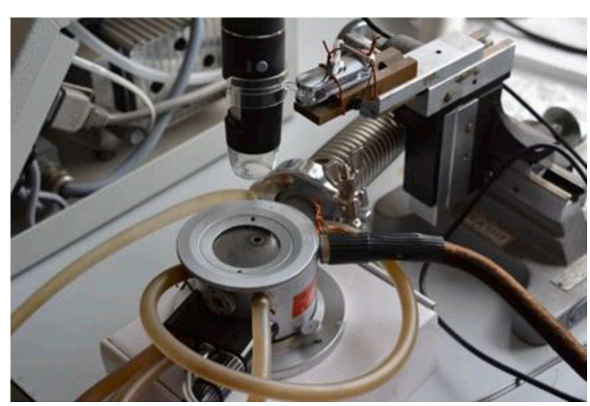


Fig. 1. Experimental device for wettability tests.

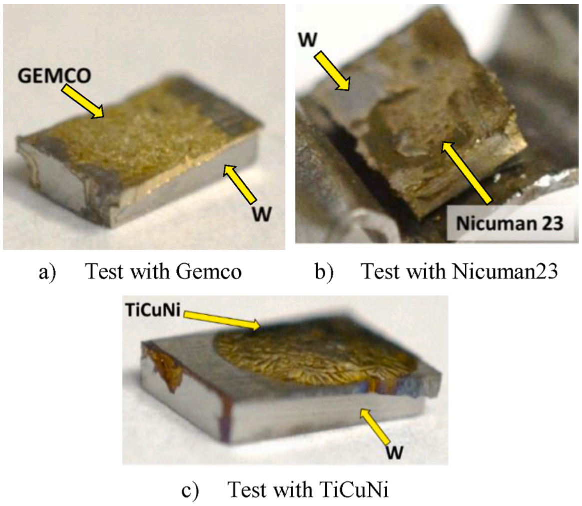


Fig. 2. Wettability tests on W specimens with brazing alloy a) Gemco, b) Nicuman23, c) TiCuNi.

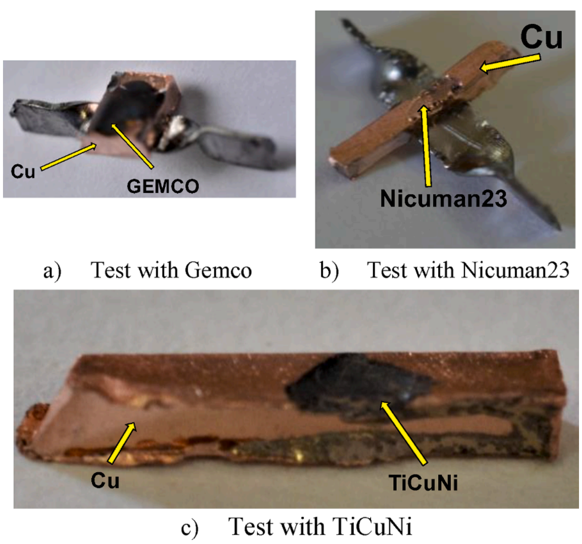


Fig. 3. Wettability tests on Cu specimens with brazing alloy a) Gemco, b) Nicuman23, c) TiCuNi.

(i.e., Cu-33.2Ge) has a not adequate wetting capability, proved by the surface of the W specimen remained not-wetted after the test (see Fig. 4c)). This means that, despite the advantage of the low melting temperature, this last brazing alloy is not suitable for monoblock-pipe joining with the direct Cu-W joint, but it can be used for Cu-Cu joint only (i.e., using monoblocks with Cu interlayer).

Concerning the CuTiZrNi brazing alloy, good wetting capability on W and Cu can be observed (Fig. 6). On the opposite, the alloy showed little to no wettability on BN and C, which makes such materials suitable for the tools to be used in furnace during the brazing process.

4. Sample fabrication and characterization

4.1. Fabrication

In order to test the brazing alloys, six samples have been realized, each one composed by a cooling pipe and tungsten monoblocks. Their joining is realized through brazing alloy foils with a thickness of 0.1 mm, inserted in the gap existing between the pipe and the monoblock bore. The selected brazing alloys are Gemco, Nicuman23 and TiCuNi. A first

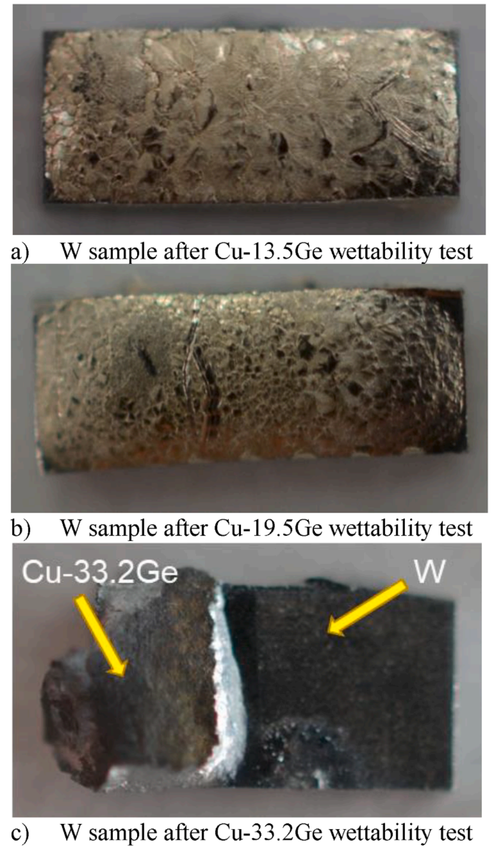


Fig. 4. Wettability tests on W specimens with brazing alloy a) Cu-13.5Ge, b) Cu-19.5Ge, c) Cu-33.2Ge.

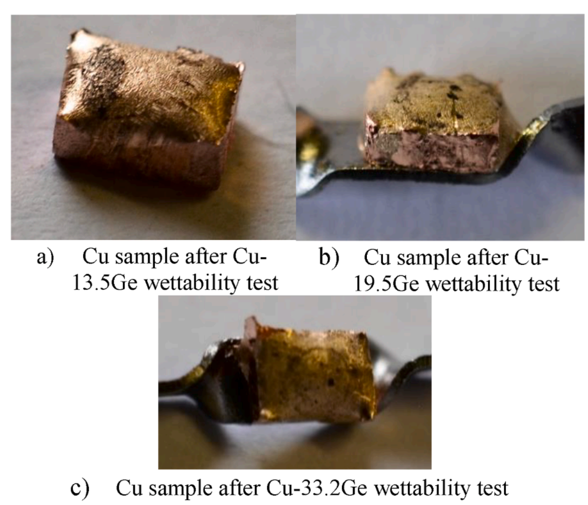
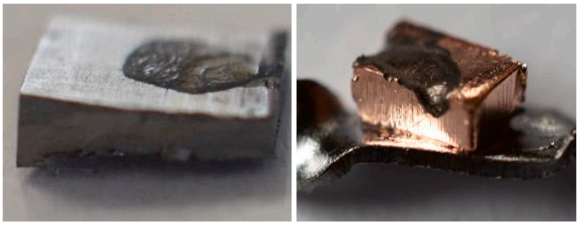


Fig. 5. Wettability tests on Cu specimens for a) Cu-13.5Ge, b) Cu-19.5Ge, c) Cu-33.2Ge.

set of three samples was realized to test the three alloys on Wf-Cu pipe. On each sample have been brazed two W-monoblocks without Cu interlayer (Type-1). The Wf-Cu pipes used for the joining tests have been provided to ENEA by Max Planck Institute for Plasma Physics (IPP). The aim of such composite tubes is to be suitable for the operating temperature range of high heat flux components, avoiding the strength degradation suffered by CuCrZr tubes above 300 °C [12]. Furthermore, the use of Wf-Cu pipes could also help to reduce the amount of high activation materials (such as Cu). In fact, they contain a much lower



a) W sample after CuTiZrNi wettability test b) Cu sample after CuTiZrNi wettability test

Fig. 6. Wettability tests for CuTiZrNi on specimens a) W, b) Cu.

amount of Cu than CuCrZr tubes, since it is partially replaced by W fibers (about 50 % of volume), having low activation.

Before the execution of the brazing tests, the visual inspection of the available Wf-Cu tubes highlighted the presence of few surface porosities of the Cu matrix and defects deriving from the machining of the pipes needed to accommodate the brazing foil.

A second set of samples was realized using Nicuman23 and Gemco alloys, joining two W-monoblocks on standard CuCrZr pipes. These samples were made to verify not only the possibility of joining Cu and W, of which the wettability tests on both had already given an indication of feasibility, but also that the cleaning and assembly methodology, the thermal cycle and the tools used were suitable for the manufacturing of these specific components, being able to attribute any differences in the results only to specific characteristics of the Wf-Cu tube.

The tests were performed using one W monoblock with Cu interlayer (Type-4) and a second one without Cu Interlayer (Type-1) to assess the compatibility of the alloys both with Cu and W. Furthermore, an additional sample has been fabricated using Gemco and Type-4 monoblock, in order to demonstrate the repeatability of the junction test. A summary of the main characteristics of the fabricated samples is reported in Table 2.

4.2. Non-destructive examination

Non-destructive examinations by Ultrasonic Testing (UT) [13,14] were carried out on each target sample. The scanning is performed from inside the pipe. The results obtained are shown in the followed figures through the so-called C-scan representation. In the C-scan representation the horizontal axis reports the axial displacement of the probe inside the pipe (z [mm]), while the vertical axis gives the rotation angle ([°]). The pixel color gives the maximum amplitude of the signal which is reflected back to the probe at a chosen depth in% of the full screen (fs) of the echograph.

Table 2
Summary of samples main features.

Sample id	Cooling pipe	Brazing alloy	Monoblock
Braz01	Wf-Cu composite pipe	Gemco	Type1–16 (w/o Cu interlayer) Type1–17 (w/o Cu interlayer)
Braz02	Wf-Cu composite pipe	Nicuman23	Type1–18 (w/o Cu interlayer) Type1–21 (w/o Cu interlayer)
Braz03	Wf-Cu composite pipe	TiCuNi	Type1–23 (w/o Cu interlayer) Type1–24 (w/o Cu interlayer)
Braz04	CuCrZr pipe	Nicuman23	Type4–092 (with Cu interlayer) Type1–102 (w/o Cu interlayer)
Braz05	CuCrZr pipe	Gemco	Type1–103 (w/o Cu interlayer) Type4–103 (with Cu interlayer)
Braz10	CuCrZr pipe	Gemco	Type4–098 (with Cu interlayer)

The UT examinations carried out on the first set of samples show that W monoblocks joined with Gemco brazing alloy is attached only for the half of the surface (attached areas are in blue and azure in Fig. 7(b)), while the remaining surface is not attached (red, yellow and light green areas in Fig. 7(b)). A such clear separation between the attached and detached parts suggested that the reason could be the non-uniform surface obtained following the machining of the Wf-Cu tube. This machining, necessary to adequately accommodate the brazing foil between the monoblock and the cooling tube, is made difficult by the co-presence of two materials, W and Cu, which require completely different machining parameters. The surface irregularities may have caused a not uniform distribution of the alloys, affecting the brazing process result.

For one of the two monoblocks brazed with Nicuman23, Ty-21, the result is very similar to the previous one, while the second presents defects distributed over the entire welded area (see Fig. 8(b)) which are difficult to attribute to the mechanical processing of the surface. In this case the defects would seem more linked to surface interferences and porosity due to voids and bubbles in the copper matrix of the tube which emerged on the surface especially following machining and which were not visible in the tube sample used for the sample made with the Gemco.

As regard the third sample, composed by two W monoblocks without Cu interlayer joined on Wf-Cu pipe with TiCuNi, the UT examinations highlight, also in this case, large defective areas. In particular, the attached area (blue and azure areas in C-scan of Fig. 9(b)) is very small, even lower than the case with Nicuman23, indicating that most of the monoblock surface is not attached.

Even if the number of samples produced was limited, due to the extremely limited availability of Wf-Cu tubes, based on the few obtained results it was decided to exclude TiCuNi from further testing and to fabricate two additional samples with Nicuman23 and Gemco, Braz04 and Braz05, respectively, consisting of two W monoblocks and CuCrZr pipes. Moreover, in order to assess whether a soft coupling material between the tube and the monoblock could improve the result, two types of monoblocks, with and without Cu interlayer, were joined to the pipes.

Non-destructive UT examinations have been carried out and the results are reported in Figs. 10(b) and 11(b). Concerning the monoblocks with Cu interlayer (Type4-092 and Type4-103), the surface is almost completely attached to the CuCrZr pipe, as showed by the blue areas reported in the C-scan of Figs. 10(b) and 11(b) of both the BRAZ04 and in the BRAZ05 samples. The C-scan of the UT examination on sample BRAZ04 reveals two red lines which run the entire length of the monoblock inner surface with a consequent lack of the brazing alloy, which is caused by two circumferential grooves on the outer surface of the tube due to the machining process.

Regarding the monoblocks without Cu interlayer (Type1-102 and Type1-103), Fig. 10(b) and Fig. 11(b) demonstrates that the surface is completely attached to the CuCrZr pipe, using both Nicuman23 and Gemco alloys. The different colors (green and blue) of the attached areas of Type4-092/103 and Type1-102/103 are due to the different amplitude of the reflected signal in case of monoblock with and without interlayer. In fact: (i) in the case without interlayer, the CuCrZr-W joint has two materials with different acoustic impedances which cause a reflected signal (green areas) even in the case of a perfect joint; (ii) in the case with interlayer, the CuCrZr-Cu joint has two materials with same acoustic impedances which cause no reflected signal (blue areas).

The results show that Nicuma23 perfectly joined both the monoblock with interlayer and the one without, while the Gemco seems to work better when directly joined to the W. However, to evaluate this aspect, further samples were made with monoblocks with interlayer, Gemco and CuCrZr tube like the one reported in Fig. 12 which have refuted this preliminary result.

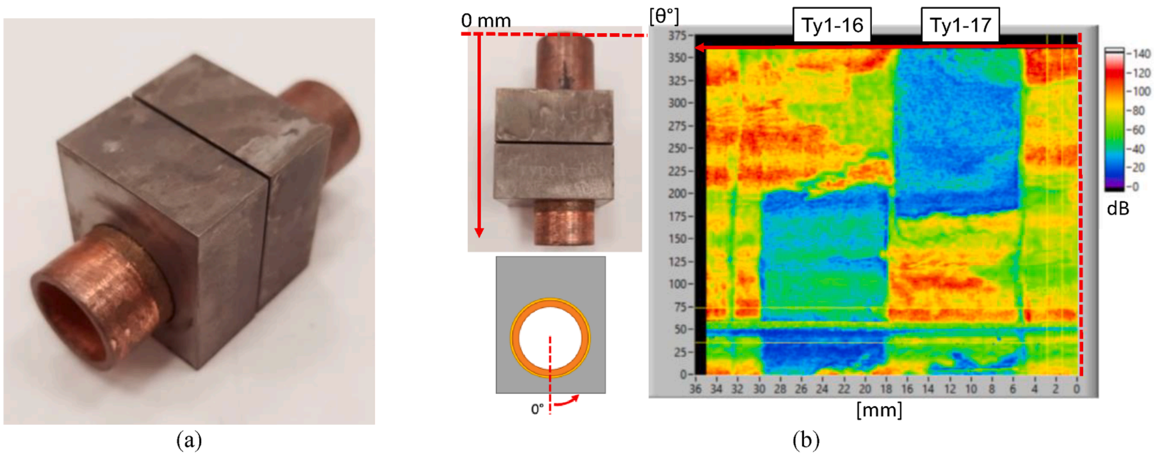


Fig. 7. View of the sample Braz01 (a) joined with Gemco alloy and C-scan of the UT on sample Braz01 (b).

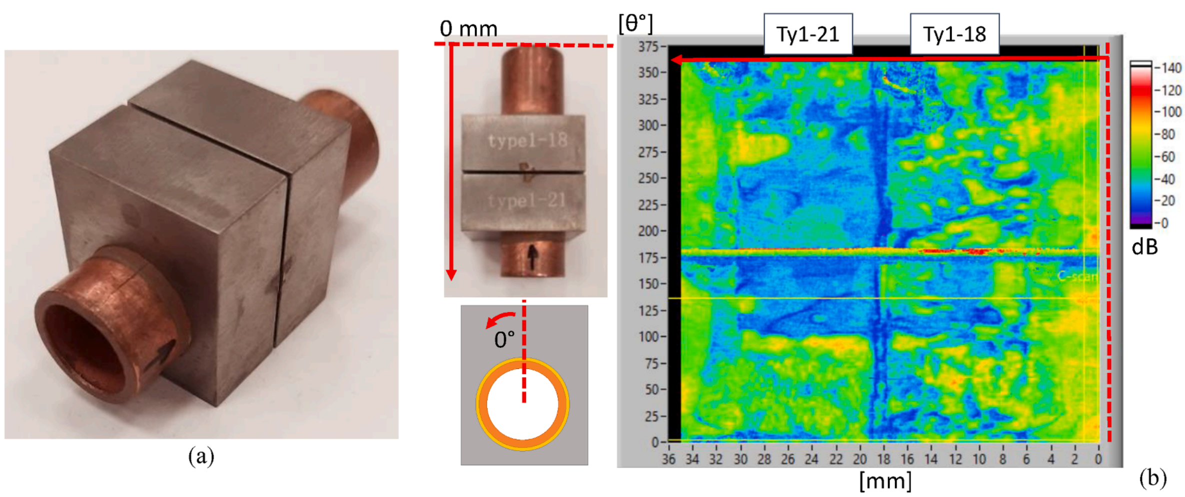


Fig. 8. View of the sample Braz02 (a) joined with Nicuman23 alloy and C-scan of the UT on sample Braz02 (b).

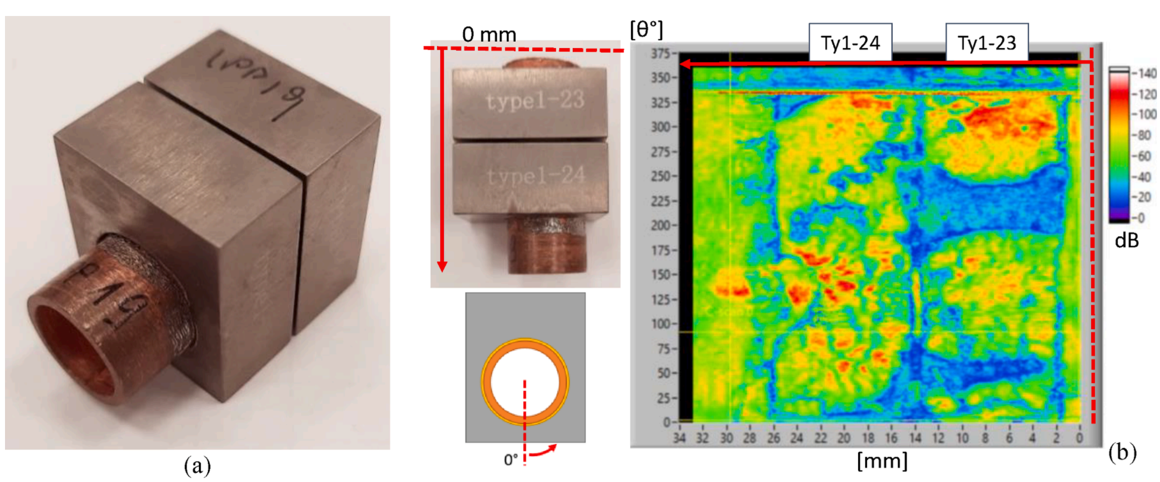


Fig. 9. View of the sample Braz03 (a) joined with TiCuNi alloy and C-scan of the UT on sample Braz03 (b).

The UT examination of the sample reported in Fig. 12 shows a full attachment of the monoblock to the CuCrZr pipe (blue color corresponds to attached area).

Despite the small number of samples it seems possible to conclude that with a proper quality of the surfaces to be joined, Nicuman23 and Gemco brazing alloys are suitable for joining both monoblocks with interlayer and without. Furthermore, considering the lower percentage of Ni and thus the lower neutronic activation, Gemco brazing alloy can be considered a candidate for PFCs technology as a replacement for the gold-based alloy previously used.

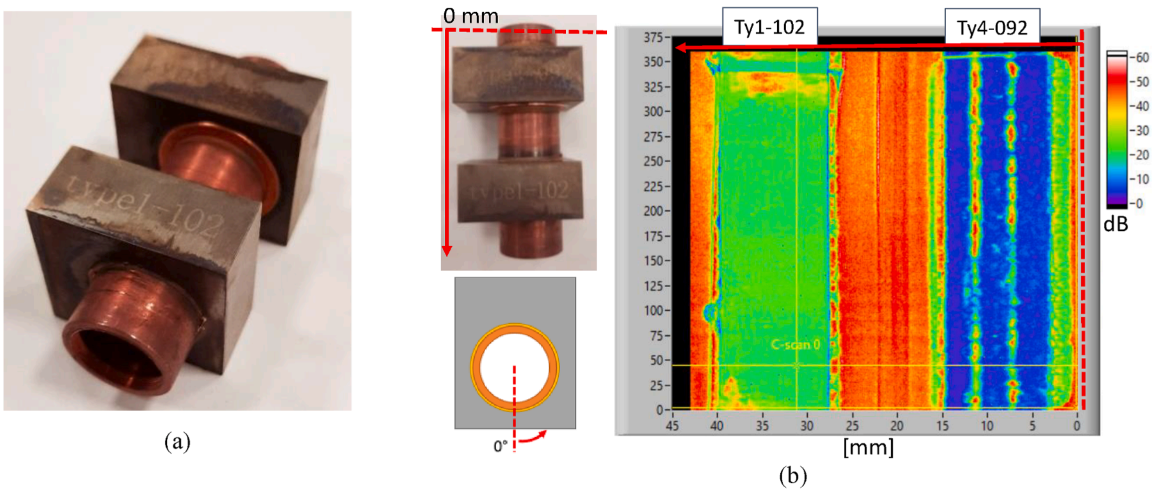


Fig. 10. View of the sample Braz04 (a) joined with Nicumn23 alloy and C-scan of the UT on sample Braz04 (b).

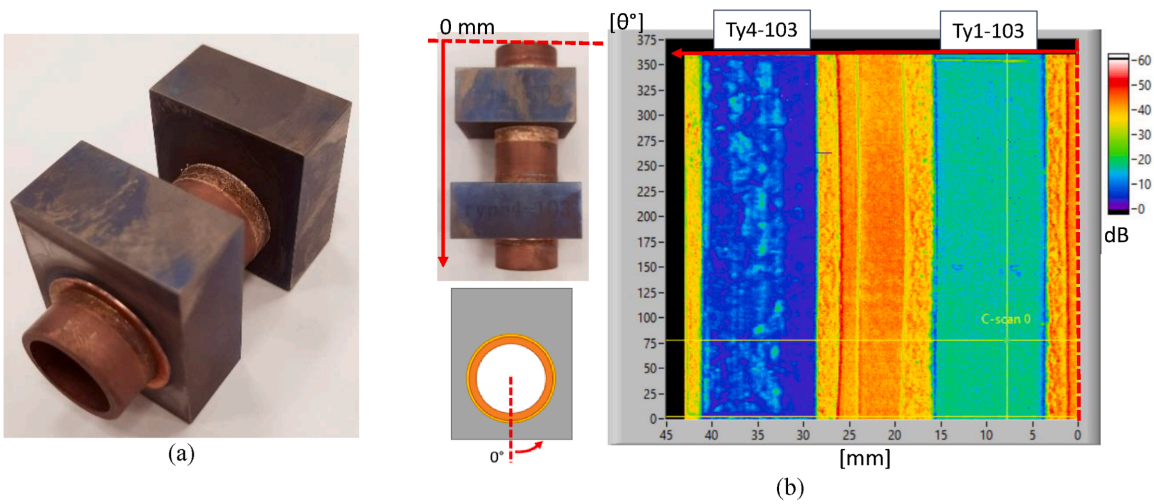


Fig. 11. View of the sample Braz05 (a) joined with Gemco alloy and C-scan of the UT on sample Braz05 (b).

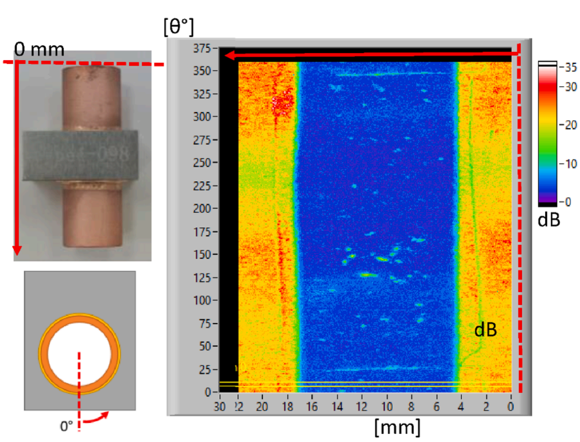


Fig. 12. View of the sample Braz10 joined with Gemco alloy and C-scan of the UT.

5. Conclusions

In the framework of the DEMO EUROfusion Programme for the development of the Divertor, a research activity has been addressed to the R&D of the target PFCs technology. In particular, a dedicated study has been carried out at ENEA aiming at finding alternative technological solutions for joining the pipe with the W-monoblocks in order to reduce the use of high activation materials, as well as materials whose properties degrade under neutron irradiation. This objective has been pursued by means of a joining characterization through a preliminary brazing alloy screening activity consisting in wettability tests on joint base materials (i.e., W and Cu) and the fabrication of samples using selected brazing alloys.

In particular, the samples fabricated using Gemco and Nicuman23 joining the W monoblocks (with and without Cu interlayer) on CuCrZr pipes showed good results, with an almost complete attachment. The fabrication of the sample with W monoblocks joined with Wf-Cu pipes demonstrated that monoblock joined with Gemco and Nicuman23 were attached for about half of the surface. Regarding the TiCuNi sample, the monoblock surface presented large areas not attached to the pipe. This not correct attachment could be mainly due to a poor quality of the Wf-Cu pipe external surface, causing a not uniform penetration and distribution of the alloys through the W fibers, as well as to the low thermal expansion coefficient of the Wf-Cu pipe, which makes more difficult to recover the assembly free gap.

Further studies are ongoing on Wf-Cu pipes to solve main issues: i.e., improvement of the tube manufacturing and optimization of the W fibers percentage, as a compromise between thermal expansion and mechanical characteristics of the composite pipes. The fabrication of Wf-Cu pipes is an activity currently ongoing within the EUROfusion tasks. Currently, the manufacturing technology is improving to fabricate new tubes having ad-hoc dimensions for their use without further machining. This means that the next batch of tubes for joining experiments will have uniform surface with no defects. The joining test activity presented in this paper will continue in the next future, when new batches of improved Wf-Cu pipes will be available, in order to extend the results obtained, improving the experimental database.

In conclusion, the activity presented is a preliminary screening in order to identify a suitable alloy for the brazing technology for targets. The results of the sample fabrication and the related UT examinations demonstrated that Gemco and Nicuman23 brazing alloys are suitable for joining monoblocks with and without pure copper interlayer. In particular, Gemco brazing alloy has a lower Ni percentage than Nicuman23, thus a lower neutronic activation. For this reason, Gemco will be considered as the first candidate for the applications in target PFC fabrication and used in the near future to the manufacturing of small and medium-scale mock-ups intended for qualification by HHF thermal fatigue.

CRediT authorship contribution statement

P. Lorusso: Conceptualization, Data curation, Formal analysis, Investigation, Software, Visualization, Writing – original draft, Writing – review & editing. **E. Martelli:** Conceptualization, Data curation, Formal analysis, Investigation, Software, Visualization, Writing – original draft, Writing – review & editing. **E. Cacciotti:** Formal analysis, Investigation, Methodology, Software. **V. Cerri:** Formal analysis, Investigation, Methodology, Software. **L. Verdini:** Methodology, Software. **S. Roccella:** Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Validation, Visualization, Writing – review & editing. **M. Sánchez Martínez:** Formal analysis, Investigation, Methodology. **J.H. You:** Funding acquisition, Project administration, Supervision.

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.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (grant agreement no 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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