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# Development of fabrication technology and investigation of properties of steel-to-bronze joints suggested for ITER HHF components

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ABSTRACT

When developing fabrication process for ITER High Heat Flux components, special attention shall be paid to the production of reliable joints between heat sink material made of CuCrZr bronze and support structure made of austenitic steel. Four different techniques have been proposed and tried: hot isostatic pressing (HIP), HIP-assisted brazing, furnace-assisted brazing, and casting. Investigation of joint structure and properties shows that HIP and casting give better results than other technologies. However, HIP is relatively expensive, and a big furnace is required to manufacture full-size components, which is not available in Russia now. Therefore, casting was selected as reference fabrication technique in Russia for the primary wall of ITER modules. The paper summarizes the outcome of the production effort for bronze-to-steel joints and the findings of the investigations into the properties of such joints.

## 1. Introduction

ITER High Heat Flux components are designed to use CuCrZr bronze as heat sink material and 316L(N)-IG austenitic steel as structural material in the supporting frame of the heat sink components and in the shielding part of the FW module. This calls for provision of reliable joints between CuCrZr and austenitic steel. The ITER Home Team tried several manufacturing techniques and has selected hot isostatic pressing as reference technology because it provided joints of acceptable quality [1]. However, HIP technique has several shortcomings. There are no large HIP furnaces to fabricate the real-size components; there are special requirements for surface preparation; it is difficult to provide high-quality uniform joints; quality control is difficult, and so on. The high strength of CuCrZr bronze can be maintained only by quenching presumed by fast cooling and ageing heat treatment. The experience shows that the cooling rate shall be greater than 1–3 °C/s, which is impossible at the existing facilities. Alternative techniques were tried in an attempt to avoid the above weaknesses.

## 2. Joint fabrication techniques

The following techniques have been used to join CuCrZr bronze-to-steel:

- Hot isostatic pressing (HIP),
- HIP-assisted brazing,[1]
- Furnace-assisted brazing,
- Casting.[2]

CuCrZr bronze and 08X18H10T type austenitic steel (Russian analogue of AISI 321 steel) have been used in the development of joining technique. PM-17 braze material has been used for the HIP-assisted brazing. The chemical composition of PM-17 is given in Table 1.

Preliminary investigations have shown that nickel interlayer improves the CuCrZr-to-steel joints (makes them stronger). In fact, the fracture of tensile specimens always occurred in joint area.

Specimens to be joined by HIP technique were placed into the vacuum can. The specimen surfaces were thoroughly cleaned, polished and plated with a layer of nickel approximately 6 micron thick. HIP continued for 2.5 h at temperature 1035–1040 °C and pressure 175 MPa.

The same HIP parameters were used in the furnace-assisted brazing. In addition to common HIP technology, the brazed material PM-17 in a 0.1 mm thick foil was inserted between the surfaces to be joined.

In the furnace-assisted brazing, the specimens to be joined were polished up to the surface roughness of 2.5 microns, then plated

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[1] HIP has been performed at the Rocket and Space Corporation ‘Energia’.

[2] Casting has been performed at D.V.Efremov Research Institute.

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**Table 1**
Chemical composition of PM-17 braze material.

| Cu | Ni | Mn | Fe | Si | Sn | B | Impurities, no more than | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | C | Pb | Al | Total amount |
| Base | 12.5–14.0 | 15.0–17.0 | 1.0–2.0 | 0.2–0.6 | 5.0–6.0 | 0.15–0.3 | 0.04 | 0.02 | 0.025 | 0.8 |

with a 3 micron layer of nickel. A foil (0.1 mm) was put between the bronze and steel. This assembly was put in a vacuum can and annealed at the temperature of ~950 °C. Pumping was provided while the can remained in the furnace. The residual pressure did not exceed 7–27 Pa. The specimens were under compression during brazing due to a special facility around the can. This facility provided specimen compression owing to the difference in the thermal expansion of the facility components.

The can with the specimens was cooled by forced air to provide a quenching-like heat treatment of CuCrZr and austenitic steel. After that, the specimens were aged at 500 °C for 4 h. The ageing temperature served to strengthen CuCrZr and did not lead to deterioration of the steel properties.

A special mold was manufactured for HHF component fabrication by casting, to introduce the primary wall design. The mold was made of the X18H10T steel. The bronze was melted in a vacuum electron beam furnace and the mold was filled with bronze. The temperature of the liquid metal was about 1200 °C. The cooling was arranged so that the solidification went from the interface area to the outer surface. After solidification, the primary wall components (including the bronze-to-steel joints) were heat treated to strengthen CuCrZr. The specimens were water quenched under 980–1000 °C (after ~1 hr exposure) and annealed (ageing for CuCrZr) at the temperature 480 °C for 3 h.

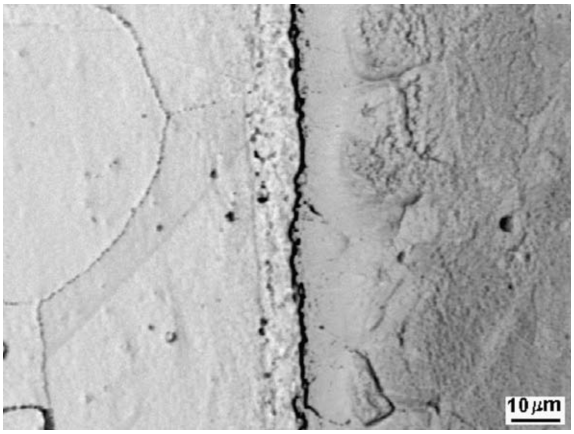

**Fig. 1.** Microstructure of a HIP-produced joint with nickel interlayer (backscattered electrons).

## 3. Microstructure investigation

It is known that microstructure defines the joint properties. Hence, a special emphasis was made on investigating the structure of bronze-to-steel joints.

The microstructure was investigated using the Axioplan optical microscope and the Cam-Scan scanning electron microscope with EDS and WDS. The distribution of the alloying elements through the interface was studied along with the microstructure details.

### *3.1. HIP joints*

The microstructure of the HIP-produced bronze-to-steel joints is presented in Fig. 1. Nickel diffusion in steel was revealed in the microstructure. Steel components (iron and chromium) diffused into the nickel interlayer. The thickness of the nickel interlayer was about 9–10 microns. This interlayer prevents copper diffusion to steel. Nevertheless, the nickel interlayer was enriched with copper. The total thickness of the diffusion zone (including Ni interlayer) was about 38 microns (see Fig. 1).

### *3.2. Joints produced by HIP-assisted brazing*

Fig. 2 shows the microstructure of a joint produced by the HIP-assisted technique using PM-17 braze material. The braze material components easily interacted with steel and diffused into it. The total thickness of the joint area was estimated to be about 60 microns. The chemical composition of braze material (PM-17) changed significantly under the brazing process. The content of nickel decreased from 12.5% to 14.0% to ~5%, of manganese – from

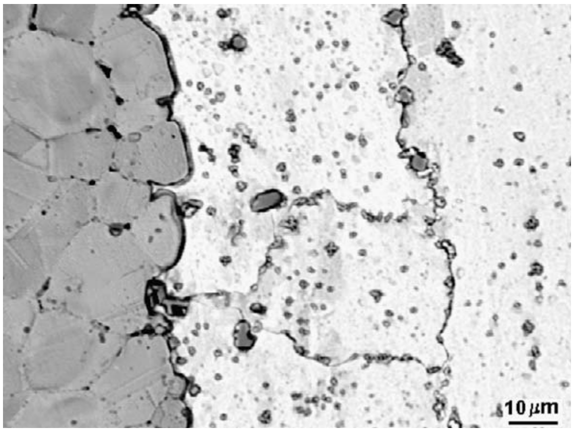

**Fig. 2.** Microstructure of a joint produced by HIP with PM-17 brase material (backscattered electrons).

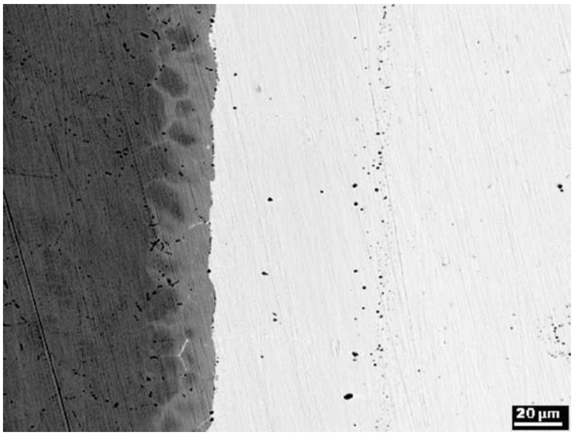

**Fig. 3.** Microstructure of a CuCrZr-to-steel joint produced by way of furnace-assisted brazing (backscattered electrons).

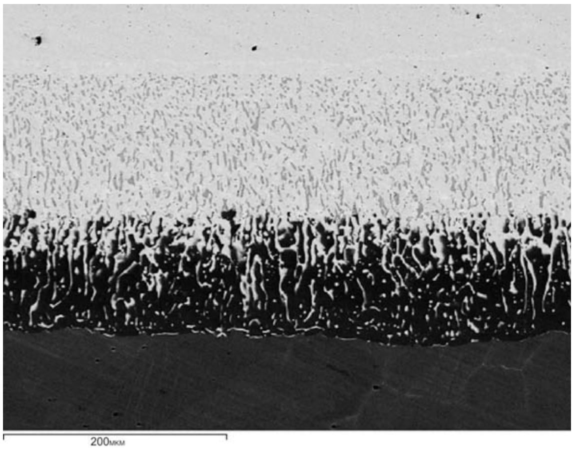

**Fig. 4.** Microstructure of a bronze-to-steel joint produced by way of casting.

15–17% to 4–5%. Small particles distributed in the interface and containing iron, chromium and carbon, can be observed in the microstructure. Most probably, these are carbides of iron and chromium.

### 3.3. Furnace-assisted brazing

The typical microstructure of a CuCrZr-to-steel joint produced by furnace-assisted brazing is presented in Fig. 3. There was no major difference in the alloying elements distribution as compared with HIP-assisted brazing. Only carbides content was lower than in case of the HIP-produced specimens. Also, some local defects (not shown in the Figure) were found in the interface area and were attributed to the non-perfect brazing (not jointed areas).

The big advantage of the furnace-assisted brazing is heat treatment (see the technique description above) which enhances the bronze strength.

### 3.4. Casting

A steel-bronze mixture with interpenetrations was formed during the bronze fusion pouring. A typical structure of the joint is shown in Fig. 4. The interpenetrated “pieces” of metal (see Fig. 4) were identified as bronze and steel with the composition modified due to the interaction between the alloys. The steel pieces were enriched with copper, and bronze was enriched with iron, chromium and nickel, i.e., with steel components.

## 4. Tensile properties

Round specimens with the diameter 5–10 mm were used for the tests. Some results of the tensile tests are presented in Table 2. The fracture of all specimens was ductile, but fracture location was different in different joints.

The fracture of HIP-produced specimens occurred in the joint with a relatively low tensile strength.

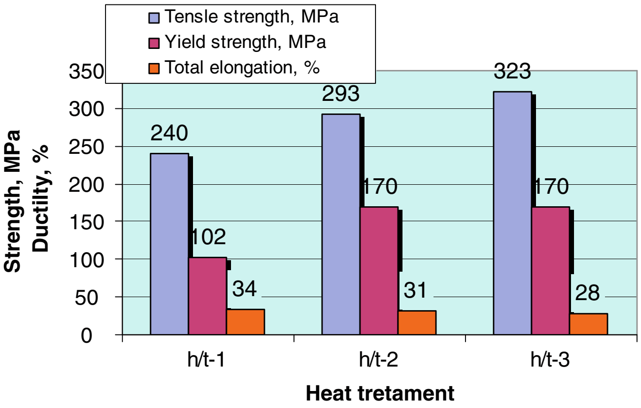

**Fig. 5.** Tensile properties of the bronze-to-steel joints produced by casting followed by different heat treatments. Where h/t-1 – casting (without heat treatment), h/t-2 – casting, water quenching at 980 °C and ageing at 480 °C during 4 hrs., h/t-3 – casting, water quenching at 1020 °C and ageing at 550 °C during 6 h.

In case of the HIP-assisted brazing, specimens fractured during the tensile tests in the area of bronze, because of the lower strength of bronze as compared with braze material (specimens without strengthening due to solution annealing and ageing).

The specimens manufactured by furnace-assisted brazing, failed in the joint (braze material), but showed a greater strength. Probably, that was due to the bronze strengthening after solution annealing and ageing. The interface (braze material) is in the weak area in these specimens.

The fracture of specimens manufactured by way of casting always occurred in the bronze part, with acceptable strength characteristics. However, the joint strength was lower than of the CuCrZr alloy after the reference heat treatment [1]. The specimens strength depend on the specimens heat treatment. Some tensile properties of the specimens after casting and different heat treatments are presented in Fig. 5. The higher temperatures of solution annealing and ageing (see h/t-3) provided the greater strength of the specimens and a slightly lower ductility.

## 5. Conclusion

Four different fabrication techniques were tried for the CuCrZr bronze-to-steel joints:

- HIP,
- HIP-assisted brazing,
- Furnace-assisted brazing,
- Casting.

The joint structure governs the joint properties.

Interlayer nickel coatings and braze material improve joint structure and properties. These interlayers change their composition during the joining process because of the interdiffusion of the alloying elements. Nickel present in interlayer diffuses in steel, initially through grain boundaries and later in grain body.

**Table 2**
Room temperature tensile properties of the joints produced by different techniques.

| Type of joint | Materials | Surface conditions | Tensile strength (min–max) | Fracture location |
|---|---|---|---|---|
| HIP | CuCrZr/Ni/steel | Electrochemical polishing/Ni coating ~6 microns | 153–160 | Joint |
| HIP-assisted brazing | CuCrZr/PM-17/Ni/steel | Electrochemical polishing/Ni coating ~6 microns | 204–230 | Bronze |
| Furnace-assisted brazing | CuCrZr/PM-17/Ni/ steel | Electrochemical polishing/Ni coating ~3 microns | 241–401 | Joint |
| Casting | CuCrZr/steel | Electrochemical polishing | 240–371[a] | Bronze |

[a] with different heat treatments after casting (see Fig. 5).

Casting shows several advantages in comparison with other technologies and provides acceptable joints. Moreover, this method is the most simple and cheap in comparison with other investigated techniques. It is also possible to get higher strength of CuCrZr due to appropriate heat treatment after casting. So, casting was selected by the Russian Home Team as reference technique for manufacture of HHF components

## Reference

[1] Materials Assessment Report. (MAR), § 1.4. Selection of Copper Alloys and § 3.2. SS/Cu Joining Technologies. IDoMS G 74 MA 10 01-07-11 W0.2.