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Armor and heat sink materials joining technologies development for ITER plasma facing components

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Abstract

An extensive program on the development of the joining technologies between armor (beryllium, tungsten and carbon fibre composites) and copper alloys heat sink materials for ITER plasma facing components (PFCs) has been carried out by ITER home teams. A brief review of this R&D program is presented in this paper. The critical problems related to these joints are described. Based on the results of this program and new requirements on the reduction the manufacturing cost of ITER PFC, reference technologies for use in ITER have been selected and recommended for further development. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

The design of the ITER plasma facing components (PFCs) includes various combinations of joints between armor and Cu alloy heat sink materials [1]. The joints must withstand the thermal, mechanical and neutron loads and the cyclic mode of operation and operate under vacuum, while providing an acceptable design lifetime and high reliability. The PFC operating conditions for the ITER final design report (FDR) design during the basic performance phase (BPP) are presented in Table 1. These conditions are similar for new design called ITER-FEAT (Fusion Energy Advanced Tokamak). Additional requirement raised with new design is the reduced cost of manufacturing.

During ITER EDA R&D program significant progress has been achieved in the developments of the joining technologies between Cu alloys and beryllium, tungsten and carbon fiber composites (CFC). This paper summarizes the most relevant results of the R&D program carried out by the ITER Home Teams.

2. Be/Cu-alloy joining technologies

The main problem of bonding Be to Cu alloys is that Be reacts with almost all metals at moderate and high temperatures and forms brittle intermetallic phases that are detrimental for the joint reliability and the fatigue lifetime. The direct interaction and reactivity of Be with Cu is very high in comparison with other metals. Recent studies [2,3] have demonstrated that intermetallic phases are already formed at 350–400°C and with temperature increasing the rate of interaction increases significantly. It should be noted that only few metals do not form stable beryllides below 760°C, i.e., Al, Si, Zn, Ag and Ge.

To solve this problem, the following approaches have been used:

- The use of materials as fillers or interlayers between Be and Cu alloy which do not form intermetallic phases with Be (e.g. Al, Ge, Si, AlSi or AlBeMet). The use of Si and Ge as bonding aid between Be

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Table 1
Operational conditions for the joints in ITER PFCs

Components: joints		Heat flux (MW/m^2)	Number of pulses	Neutron fluence ($MW a/m^2$)	Damage armour/Cu (dpa)	Maximum temperature of joints (°C)	
						Steady state	Transient
First wall	Be/Cu	0.25–0.5	10,000	0.3	1/3	230	∼<600
Limiter	Be/Cu	(3.4–8)[a]–0.5	10,000[b]	0.3[b]	1[b]/3	350–200	∼<600
Baffle	Be/Cu	1–2	10,000	0.17	0.6/1.7	280	∼<600
	W/Cu	1.5–3	10,000	0.15	0.5/1.5	280	∼<600
Divertor	CFC/Cu	10–20	∼3000	0.06[b]	0.3[b]/0.6	300	∼<500
	W/Cu (VT,D)	1–5	∼3000	0.18[b]	0.16[b]/0.5	300	∼<600
	W/Cu (L)	0.1–0.7	∼3000	0.15[b]	0.1[b]/0.4	250	–

[a] During start-up/shut-down.
[b] Without planned replacement. VT – vertical target, *D* – dome, *L* – liner.

and AlBeMet, and HIP at 570–700°C as a joining method has produced joint tensile strengths of 135 MPa at 400°C [4]. The room temperature strength of the joint with pure Al interlayer is 120 MPa with ductile fracture inside the Al layer. For the AlBeMet-150 interlayer, the RT tensile strength increased between 195 and 100 MPa at 300°C [5]. Application of combined Al/Mo interlayer and HIP joining procedure has been studied in [6], the shear strength of bonds was ∼55 MPa with good quality of joints.

- Use as diffusion barrier materials with less affinity to the formation of beryllide intermetallics. Different types of this barrier have been studied: Ti [7–9], Cr, Ti/Ni, Al/Ni [9], Ti/Cu, Al/Ti/Cu, Cr/Cu [10]. Typically for this type of joint, HIP is used as joining procedure at temperature range 500–850°C. Use of Ti interlayer with HIP at 850°C has been studied in [8]. Several types of intermetallic layers with total thickness ∼50 μm as $TiBe_{12}$, $TiBe_2$, Ti_2Cu, TiCu etc. have been observed. The shear strength of Be/Cu joints has been measured at room temperature ∼108 MPa. The application of Cr, Ti/Cu, Al/Ti/Cu interlayers also seems promising, specially because with this element HIP temperature could be reduced up to ∼550°C, [9,10].
- Brazing with Ag- or Cu-based brazing alloys. It is clear, that at brazing temperature more than 700°C (which is typical for this type of brazing alloy) BeCu intermetallic formation occurs. However, the proved way to reduce this process is the reducing of the reaction time. As example, in [11] the Be/Cu joint quality after conventional furnace heating and induction heating with Ag–Cu brazing alloy has been studied and it was concluded that the quality of joints is much better after induction brazing. The good quality of the Be/Cu joints produced by induction brazing with use Ag–Cu (InCuSil-ABA) brazing alloy has been reported in [12]. The shear strength at optimal brazing temperature which has been determined as ∼720°C, was ∼160–120 MPa in the temperature range 20–500°C. However, the use of silver-based alloys has been forbidden for ITER application due to the cadmium transmutation during neutron irradiation. Different types of silver-free brazing technologies have been developed for ITER application. CuMnSnCe alloy has been proposed in [13], CuMn, TiZr, CuInSnNi alloys have been studied in [14,15]. All these alloys have been applied together with 'fast' heating technologies (via induction brazing or heat by e-beam). Nevertheless the metallurgical quality and, more important, high heat flux performance are acceptable.
- Direct bonding of Be to Cu alloy during short time at moderate temperature (∼500–700°C) e.g., explosion bonding [14,16], joint rolling [14], vacuum plasma spray [17,18], or joining of Cu interlayer to Be at low temperature (e.g., electroplating) and next joining to Cu alloy by low temperature HIP [19,20]. Plasma spray, initially developed as a repair method, is also able to produce thick (>10 mm) beryllium coatings with almost expectable thermal conductivity and can therefore be considered for the initial manufacture of PFCs.

Based on the result of the heat flux tests of the representative mock-ups, which are summarized in [21,22] (see Fig. 1), the following Be/Cu joining technologies have been determined for the further more detailed development:

- For high heat flux components (baffle and port limited): fast brazing with CuInSiNi alloy [15] and HIP at 625°C with AlBeMet interlayer [5]. These technologies demonstrated the best thermal durability performance: fast brazing resisted 4500 cycles at 12 MW/m^2, HIPed mock-up survived 1000 cycles at 5 and 10 MW/m^2. The drawbacks (HIP with AlBeMet

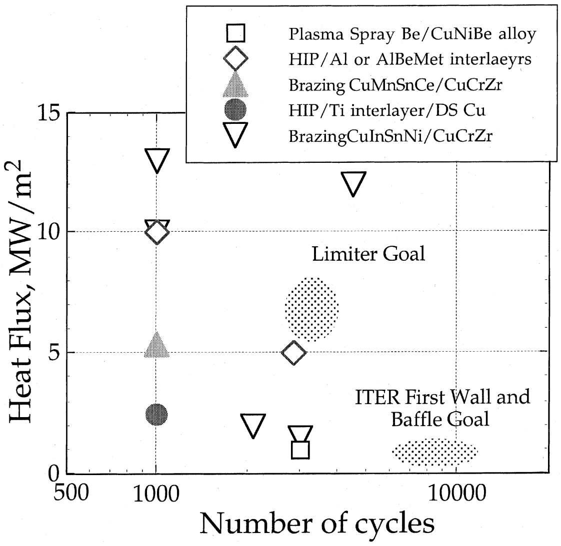

Fig. 1. Some results of the high heat flux tests of Be/Cu mock-ups with indication of the used joining technologies.

required sophisticated diffusion barriers, fast brazing requires special surface preparation and loading tools) restrict the application of these technologies to highly loaded components and for limited surface area.

- For large areas with low heat flux as ITER first wall two main technologies have been selected: HIP at 850°C with Ti interlayer [7] and Be plasma spray [18]. Both technologies have demonstrated the satisfactory performance at heat flux 1–2.5 MW/m^2.

Further developments are still needed with goal to improve the reliability and final selection has to be done taking into account the estimation of the input of these technologies on cost of the components.

3. W/Cu-alloy joining technologies

The main problem in the development of W/Cu joints is the large difference in the coefficient of thermal expansion (CTE) and of elastic modulus. With a conventional flat tile geometry, this difference creates very large stresses at the interface. From the engineering point of view, the solution is to use brush-like (rectangular or rod) or lamella type of the W armor design. The advantages of the brush structure are that the stresses at the W/Cu interface may be reduced, the single elements are free to expand under the heat flux, reducing the thermal stresses.

The problem of the joining of W and Cu could be solved by different methods. One of the studied technologies is the casting of pure Cu onto W [23–25]. This process consists of casting a soft compliant layer of pure copper onto the activated/or not activated surface of W. The good joining during casting is based in high wettability and high creep relaxation ability of pure Cu. The yield tensile strength of W/Cu joint is typically higher than yield strength of pure Cu and equal ~100–120 MPa [23]. The copper layer is then joined by different methods as e-beam welding, brazing or HIP to the actively cooled copper alloy heat sink. The low cycle fatigue cracking and further neutron irradiation resistance of the large grained cast pure Cu are issues which have to be studied.

The brazing technology also has been studied [25–27]. The use of CuMn base brazing alloy demonstrated a good tensile strength of joint ~200 MPa with failure in Cu alloy near the brazed joint [26].

Three methods for joining W-rods (1.6–3.2 mm dia) to CuCrZr heat sinks have been studied. In method 1 plasma sprayed OFHC is applied to the tips of W rods and then diffusion bonded to CuCrZr at 450°C. Method 2 is the same as method 1, except the cast OFHC is used in place of plasma sprayed OFHC. Method 3 uses direct diffusion bonding to push the W-rod tips directly into the OFHC base at 450°C. Tensile strength at 280°C has been found to be 140 MPa for plasma sprayed OFHC, 175 MPa for direct diffusion bonding, and >400 MPa for Cu-casting [28].

The joining of W directly to pure Cu or DS Cu by HIP without interlayers and with Ni interlayer have been studied in [29,30], consequently. The tensile properties of W/Cu joints have been similar to properties of the pure Cu, the direct bonding of W to DS Cu was not successful because the residual stresses have not been relaxed, [29]. High heat flux tests of mock-up described in [30] revealed that the durability of the joint is ~6 MW/m^2 which is significantly less than for casting and brazing technologies.

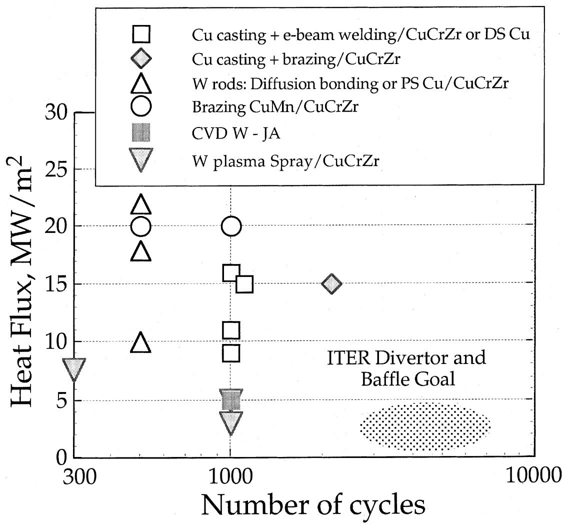

Fig. 2. Some results of the high heat flux tests of W/Cu mock-ups with indication of the used joining technologies.

The use of chemical vapor deposition (CVD) of W onto Cu produces also good joints [31]. The use of W plasma spray gives also good joining with Cu alloy heat sink [32]. Both these methods have been successfully applied for manufacturing of the components with curved surfaces. However, these technologies could be applied only for components with low and moderate heat flux.

The most relevant results of the high heat flux tests of the representative mock-ups are shown in Fig. 2 and compared with the ITER requirements. Few technologies (casting, brazing, direct diffusion bonding of W into Cu) provide excellent high heat flux durability performances of the W/Cu joints.

4. CFC/Cu-alloy joining technologies

The problem in the development of CFC/Cu joints is the same as that discussed for the W/Cu joint, i.e. the even larger difference in the CTE of the materials to be joined, but more reliant properties of armor. For providing the high quality of CFC/Cu joints there are few general requirements, which have to be fulfilled: the surface of CFC has to be activated to increase the wettings (e.g. special coatings, etc.) and the compliant layers between CFC and cu alloy heat sink is needed to relieve the residual stresses during manufacturing. Several joining technologies have been developed and studied:

- Active metal casting (AMC®) technology, originally developed for Tore Supra limiters [33]. This technology includes the special laser treatment of the CFC's surface which produces large number of the closed conical holes (dia ~50–500 μm, depth ~100–750 μm). This provides the increasing of the surface interface in joints and additional crack growth resistance, [34]. The next fabrication steps are the casting of the pure Cu onto CFC's treated surface, machining and final joining with Cu alloy heat sink. The properties of joints have been described in [35,36]. It was shown that tensile strength of joints produced by AMC® technology is ~30 MPa which is less than strength of CFCs, whereas the shear strength is ~40–50 MPa. For the monoblock configuration, theAMC® Cu can be joined to Cu alloys by brazing or HIP, for flat tiles, the same joint could be obtained by e-beam welding. AMC® technology was applied to different CFC grades (SEP N11, SEP N31, etc.).
- Brazing with silver-free alloys, CuMn [37], CuSiAlTi [38], and HIP assisted brazing with CuMn and CuTi alloys, [30].

Some results of the high heat flux tests of the representative mock-ups are shown in Fig. 3. Few technologies (AMC® and brazing with CuMn) provide the required high heat flux durability performances of the CFC/Cu joints.

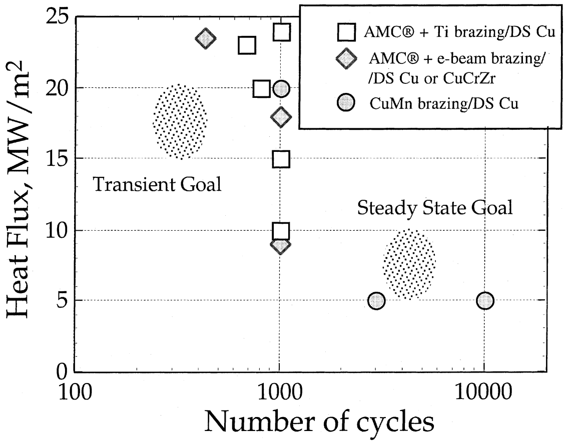

Fig. 3. Some results of the high heat flux tests of CFC/Cu mock-ups with indication of the used joining technologies.

5. Conclusion

As a result of ITER R&D the reference technologies have been selected for the manufacturing of the ITER PFCs:

Be armored components: HIP at ~850°C and Plasma Spray have been identified as the most promising methods for the large surface and low heat flux components, such as the Primary First Wall modules; for high heat flux components the fast brazing and HIP with AlBeMet combined with a variant of brush-like armor satisfy the thermal fatigue lifetime design requirements.

W armored components: Brush or lamella W armor joined by casting of pure Cu or brazing to the heat sink is selected. W rods with diffusion bonding are also a promising solution.

CFC armored components: Active metal casting and brazing with CuMn are the preferred options.

These technologies could be used for the ITER-FEAT design, additional developments with goal of the increasing reliability and reduction of costs are still required.

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References

[1] ITER Technical Basis for the ITER Final Design Report, Cost Review and Safety Analysis, ITER EDA Documentation Series No. 16, Vienna, 1998.

[2] B.C. Odegard Jr., C.H. Cadden, N.Y.C. Yang, Fus. Eng. Design 39&40 (1998) 63.

[3] H. Kawamura, M. Kato, in: Proceedings of the 2nd IEA Workshop on Beryllium Technology for Fusion, Jackson Lake Lodge, WY, Sept. 1995, p. 204.

[4] D.E. Dombrowski, in: Proceedings of the 3rd IEA Workshop on Beryllium Technology for Fusion, Mito, Japan, Oct. 1997, p. 129.

[5] B.C. Odegard, C.H. Cadden, in: Proceedings of the 3rd IEA Workshop on Beryllium Technology for Fusion, Mito, Japan, Oct. 1997, p. 123.

[6] F. Saint Antonin, Development and characterization of Be/Cu alloy HIP Joints, Note Technique D.E.M/S.G.M N 03/96, CEA, CEREM, January 1996.

[7] F. Saint Antonin, G. Bangeois, G. Le Marouis et al., Small scale testing of FW/BS modules, Note Technique D.E.M/S.G.M N 64/96, CEA, CEREM, Dec. 1996.

[8] F. Saint Antonin, D. Barberi, G. Le Marouis, A. Laille, J. Nucl. Mater. 258–263 (1998) 1973.

[9] T. Kuroda, T. Hatano, M. Enoeda et al., J. Nucl. Mater. 258–263 (1998) 258.

[10] T. Hatano, T. Kuroda, T. Iwadachi et al., in: Proceedings of the 20th Symposium on Fusion Technology, Marseille, Sept. 1998, p. 97.

[11] E. Frankoni, G.C. Ceccottiand, L. Magnoli, J. Nucl. Mater. 191–194 (1992) 493.

[12] C.M. Ibott, H.D. Falter, P. Meurer et al., in: Proceedings of the 18th Symposium on Fusion Technology, Karsruhe, Aug. 1994, p. 431.

[13] J.H.Vincent et al., Development of procedure for attaching Beryllium tiles onto CuCrZr testpieces and divertor mock-ups plates, GEC-Markoni Materials technology, Report MS/20416, November 1995.

[14] A. Gervash, R. Giniatulin, V. Komarov et al., Fus. Eng. Design 39&40 (1998) 543.

[15] R. Giniatulin, I. Mazul, A. Gervash et al., in: Proceedings of the 3rd IAE Workshop on Beryllium Technology for Fusion, Mito, Japan, Oct. 1997, p. 113.

[16] D.J. Butler, D. Dombrowski, in: Proceedings 2nd IEA Workshop on Beryllium Technology for Fusion, Jackson Lake Lodge, WY, Sept. 1995, p. 212.

[17] R.G. Castro, A.H. Bartlett, K.E. Elliott, K.J. Hollis, The structure and thermal properties of plasma-sprayed beryllium for ITER, in: Proceedings of the 9th National Thermal Spray Conference, Cincinnati, Ohio, 1996.

[18] R.G. Castro, P.W. Stanek, K.E. Elliot et al., Phys. Scripta T 64 (1996) 77.

[19] R.D. Watson, SNLA, 1996, private communication.

[20] B. Riccardi, ENEA, 1997, private communication.

[21] Materials Assessment Report, ITER Document G A1 DDD 1 98-05-28 W 0.3.

[22] V. Barabash, G. Kalinin, R. Matera, in: Proceedings of the 20th Symposium on Fusion Technology, Marseille, Sept. 1998, p. 215.

[23] F. Brossa, P. Ghiselli, G. Tommei et al., Fus. Technol. 1 (1982) 491.

[24] Ch. Friedrich et al., The manufacturing of the ITER divertor small scale mock-up, Plansee Report TZ 2076, 1996.

[25] A. Makhankov, I. Mazul, V. Safronov, N. Yablokov, in: Proceedings of the 20th Symposium on Fusion Technology, Marseille, vol. 1, Sept. 1998, p. 267.

[26] V. Barabash, V.F. Khorunov, S.V. Maksimova, Weld. Int. 9 (1) (1995) 47.

[27] M. Akiba, JAERI, 1998, private communication.

[28] B.C. Odegard Jr., C.H. Cadden, K.T. Slattery, R.D. Watson, J. Nucl. Mater. 258–263 (1998) 329.

[29] S. Saito, Kfukaya, S. Ihiyama et al., in: Proceedings of the 20th Symposium on Fusion Technology, Marseille, vol. 1, Sept. 1998, p. 113.

[30] G. Le Marois, P. Revirand, F. Saint-Antonin, Baffle small-scale mock-ups manufacturing using solid HIP technique, Note Technique D.E.M. 10/97, CEA, CEREM, March 1997.

[31] I. Smid, E. Kny, M. Akiba, K. Nakamura, G. Leichtfried, L. Ploechl, J. Nucl. Mater. 258–263 (1998) 160.

[32] B. Riccardi, A. Pizzuto, L. Bertamini, M. Diotallevi, G. Vieider, Development of W coatings for ITER divertor components, in: Proceedings 17th Symposium on Fusion Engineering, San Diego, US, 6–9 Oct. 1997.

[33] P. Chappuis et al., in: Proceedings of the 15th Symposium on Fusion Technology, Utrecht, The Netherlands, vol. 1, 1988, p. 879.

[34] N. Reheis, M. Witwer, G. Kneringer et al., in: Proceedings of the 17th Symposium on Fusion Technology, Rome, vol. 1, Sept. 1992, p. 344.

[35] T. Huber, L. Ploechl, N. Reheis, in: Proceedings of 16th Symposium on Fusion Engineering, Illinois, vol. 1, Sept.–Oct. 1995, p. 716.

[36] L. Moncel, J. Schlosser, R. Mittenau, L. Ploechl, in: Proceedings of the 20th Symposium on Fusion Technology, Marseille, vol. 1, Sept. 1998, p. 133.

[37] M. Akiba, S. Suzuki, Fus. Eng. Design 39&40 (1998) 219.

[38] H. Ise, S. Satoh, S. Yamazaki et al., Fus. Eng. Design 39&40 (1998) 513.