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Development of joining technology for Be/Cu-alloy and Be/SS by HIP

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Abstract

Joining of Be/DSCu and Be/SS by using HIP technique with and without various interlayers were investigated as a screening test for selecting optimum joining method and conditions. Metallurgical observation and shearing tests were performed for basic characterization of the bonded joints. For Be/DSCu, the use of Ag interlayer with 700°C HIP temperature would be a prime candidate if Cd formation under neutron irradiation would not seriously affect plasma operation and joint performance. Other than the Ag interlayer, a Cr/Cu interlayer gave relatively high joint strength in the present screening test. The lower HIP temperature, 550°C, for this joint contributes to prevent sensitization of stainless steel (SS) structural material. As for Be/SS, the highest joint strength was obtained with a Ti interlayer. The HIP temperature of 800°C or a little higher would be applied for this joint to avoid SS sensitization.

1. Introduction

Beryllium (Be) has been proposed for a plasma facing armor of the first wall in the ITER design [1]. For effective removal of heat loads to the Be armor, the armor is to be metallurgically bonded to the heat sink made of alumina dispersion strengthened copper (DSCu) in the case of the shielding blanket, or to the first wall structural material, type 316LN stainless steel (SS), in the case of the breeding blanket. Brazing can be a method to join these materials based upon industrial experiences. However, the integrity of the brazed joint under severe neutron irradiation would be insufficient, and uniform joining by brazing onto rather large first wall surface area of the blanket module would be very difficult. Trials of Be/Cu-alloy joining by diffusion bonding [2] or by hot isostatic pressing (HIP) [3–5] and testing have been extensively conducted. Although high heat flux test results on some of the joints were found to be promising to be used as the first wall armor joining structure [3–5], characterization of the joints and further optimization of the joining processes are still underway. Here, HIP technique for joining Be/DSCu and basic performance of the bonded joints in mechanical strengths have been investigated. In addition to the Be/DSCu joints, HIP bonding of Be/SS has also been investigated.

2. Be/DSCu joints

2.1. Materials

For Be and DSCu materials, the grade S-65C hot-pressed block and GlidCop® AL-25 were used, respectively. Joining of these materials was tried with and without various interlayer materials insertion as shown in Table 1. Beryllium, being chemically active, tends to

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Table 1
Inter layer material and HIP conditions for Be/DSCu joints

Bonded material	Method to provide interlayer	HIP condition		
		Temperature (°C)	Pressure (MPa)	Hold time (h)
Be/DSCu		500	140	2
		600	140	2
		700	140	2
Be/Ag/DSCu	Foil	300	140	4
		500	140	4
		700	140	4
Be/Al/DSCu	Foil	300	140	4
		500	140	4
Be/BeCu/DSCu	Foil	500	140	2
		600	140	2
		700	140	2
Be/Ti/DSCu	Foil	500	140	2
		600	140	2
		700	140	2
Be/OFCu/DSCu	Foil	500	140	2
		600	140	2
		700	140	2
Be/Cu/DSCu	PVD	550 [a]	140	2
Be/Cu/DSCu	e-plating	550 [a]	140	2
Be/Ti/Ni/DSCu	Foil	800 [a]	140	2
		850 [a]	140	2
Be/Ti/Ni/Cu/DSCu	PVD	800 [a]	140	2
Be/Al/Ti/Cu/DSCu	PVD	550 [a]	140	2
Be/Al/Ni/Cu/DSCu	PVD	550 [a]	140	2
Be/Al/Mo/Cu/DSCu	PVD	550 [a]	140	2
Be/Cr/Cu/DSCu	PVD	550 [a]	140	2

[a] annealed at 425°C for 4 h on the way of cooling after HIP.

form intermetallic compounds with most of metals. Beryllium has high solubility into Cu at high temperature and forms intermetallic compounds in γ- and δ-phases, which are known to be rather brittle. Therefore, an interlayer to prevent this formation would be required. From the brazing experiences, silver (Ag) is known to be a good interlayer material for Be/DSCu joining. Silver forms no intermetallic compounds with Cu under 760°C. Aluminum (Al) forms no intermetallic compounds, but an eutectic alloy with Be, which is presumed to be more ductile. On the other hand, Al has high solubility into Cu and forms presumably brittle intermetallic compounds. A Cu-alloy, BeCu, is expected to have affinity with both Be and DSCu because it already contains both Be and Cu as constituents. Titanium (Ti) can be used as a diffusion barrier layer due to low Be diffusivity through Ti. Chromium (Cr) can also be used as a diffusion barrier, but the thickness should be limited to allowable level because the formed Cr compounds are brittle. With pure Cu, lower HIP temperature could be applied, resulting in minimizing the formation of intermetallic compounds. Pure Cu is also expected to effect as a compliant layer between hard DSCu and Be. Based on these considerations, interlayer materials and their material combinations were selected as listed in Table 1. Thicknesses of the interlayer materials shown in Table 1 were 50 μm for foil insertion, 20 μm for PVD coatings and electro-plating, with exceptionally 0.5–0.8 μm for Cr PVD coating.

2.2. HIP conditions

Fabrication conditions for HIP process are also summarized in Table 1. Especially, the HIP temperatures, from 300°C to 850°C, were investigated. In the fabrication process of the ITER blanket module, the bonding of Be armor would be in the final step. Therefore, SS structural material of the blanket would be subjected to the same heat treatment as the Be/DSCu HIP process. The above HIP temperature conditions were chosen to include the lower, 350–600°C, and the higher, 800–850°C, for prevention of SS sensitization during the process. The HIP pressure was fixed to be at 140 MPa. Although 2 and 4 h were tried for the holding time, 2 h was found to be sufficient. The longer holding time would effect too much reaction between the materials in some cases.

2.3. Testing methods

Shearing test, which could be effective to evaluate the integrity of the surface-to-surface bonded joints such as HIP, was chosen for characterization and comparison of the joint bondability. The shearing test was performed at room temperature, 200°C and 400°C for each joint using a testing jig and specimen illustrated in Fig. 1. In addition to the joint specimens, bare Be and DSCu specimens with the same heat treatment as the HIP process were also tested for comparison.

Although Charpy impact test was also performed, the absorbed energies of the joints were dominated by Be, which is very low (0.1 J/cm^2), and significant difference among the joints was not observed.

2.4. Test results

Test results are shown in Fig. 1. At HIP temperatures lower than or equal to 500°C, all specimens were insufficient in joining, or, in some cases, even not joined at all. With Ag interlayer at HIP temperature of 700°C, high shearing strength almost comparable to that of Be base metal were obtained. If cadmium (Cd) formation from Ag through transmutation under neutron irradiation be turned out to be allowable by more detail examination, joining with Ag interlayer would be a prime candidate. The joint bonded at HIP temperature of 700°C without interlayer also showed relatively high strength.

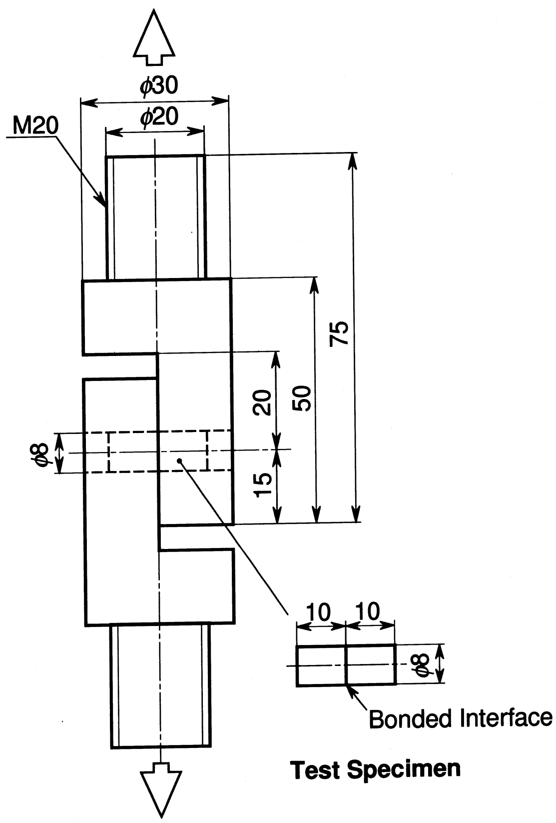

Fig. 1. A schematic for the shearing test of bonded joint.

Among the joints with lower HIP temperatures, the joint with Cr/Cu interlayer bonded at 550°C showed relatively high strength. The joints bonded at HIP temperature of 550°C with Cu coated by PVD or electroplating also showed similar joint performance. Shearing strengths of the other joints were lower in comparison with these joints.

2.5. Discussion

Although the joint strength with Al foil insertion was low, those with PVD-Al coating and additional material layers, i.e., Ti/Cu, Ni/Cu or Mo/Cu, were higher in this investigation. However, those joints tend to fracture at Al interface, or even at Al itself, especially at elevated temperatures.

With Ti foil insertion and at HIP temperature of 700°C, relatively high strength was obtained at low test temperature. However, the strength degraded remarkably at elevated temperature. In this case, fracture occurred at Ti/DSCu interface, and an intermetallic compound was observed at the interface by EPMA analysis. Trials of Ni insertion between Ti and DSCu to prevent this intermetallic compound formation and PVD-Ti coating with additional interlayer materials gave no improvement in the joint strength. In these cases, fracture occurred at Be/Ti interface.

With BeCu interlayer, high strength as expected was not obtained. This would be due to high hardness of BeCu which would not work as a compliant layer.

Relatively high strength was obtained by direct bonding of Be and DSCu at HIP temperature of 700°C (Fig. 2). Also high strengths were obtained for the joints with PVD-coated and electro-plated Cu interlayers. For the latter joints, brittle intermetallic compounds, Be_2Cu and BeCu, were not observed, at least by microscopic observation, at Be/Cu interfaces, presumably due to the lower HIP temperature of 550°C. The PVD-Cu coating would be desirable in terms of the prevention of oxide formation on surfaces to be bonded and possible strict impurity control.

To assure of avoiding the Be_2Cu and BeCu formation and growth, Cr insertion between Be and Cu were tried. With Cr/Cu interlayer, relatively high strength was also obtained. Microscopic observation and EPMA result of this joint interface are shown in Fig. 3. A smooth transition of the materials via Cr insertion is observed in the EPMA result. The 20 μm thick PVD-coated Cu layer is not clearly observed at the bonded interface. The fracture did not occur at the interface but in DSCu. This also suggests the good bondability of this joint.

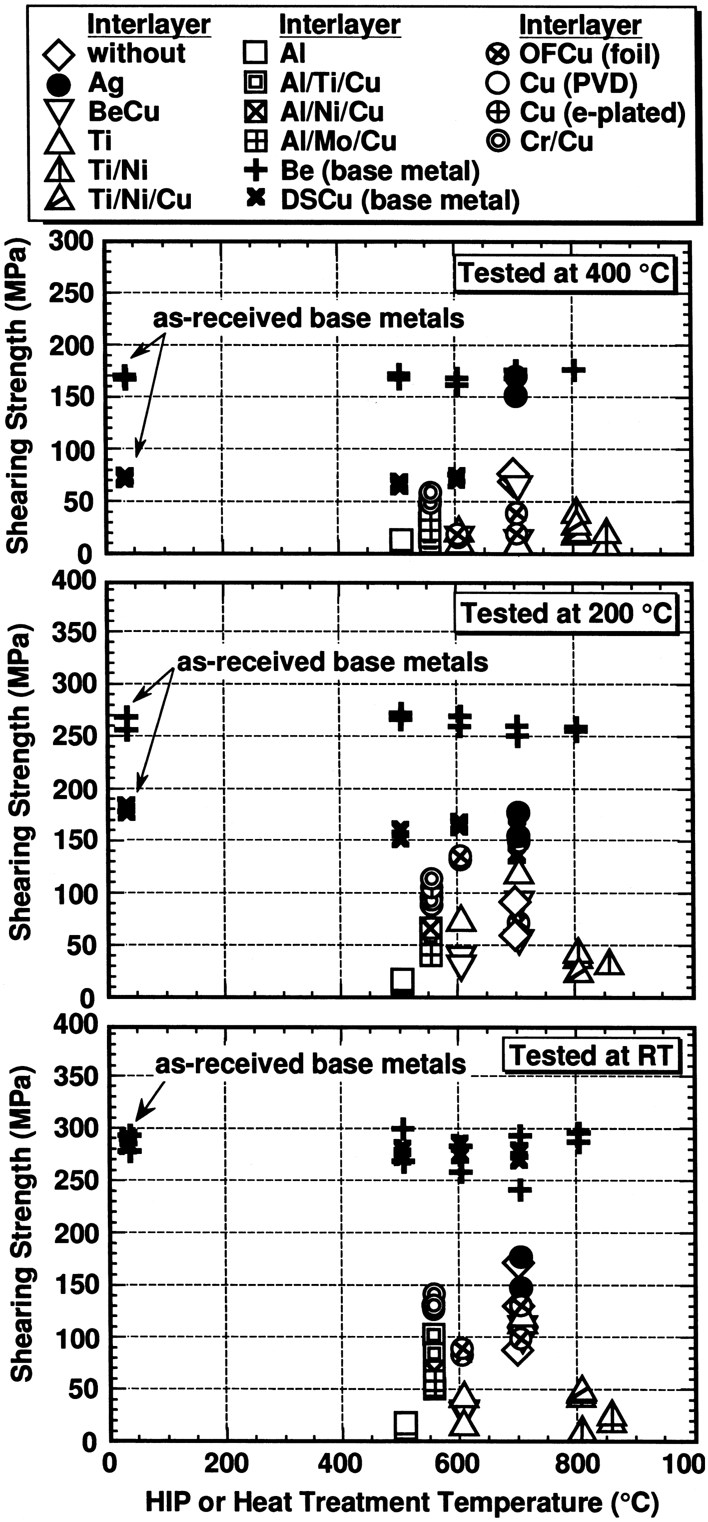

Fig. 2. Shearing strength of HIP bonded Be/DSCu joints and base metals.

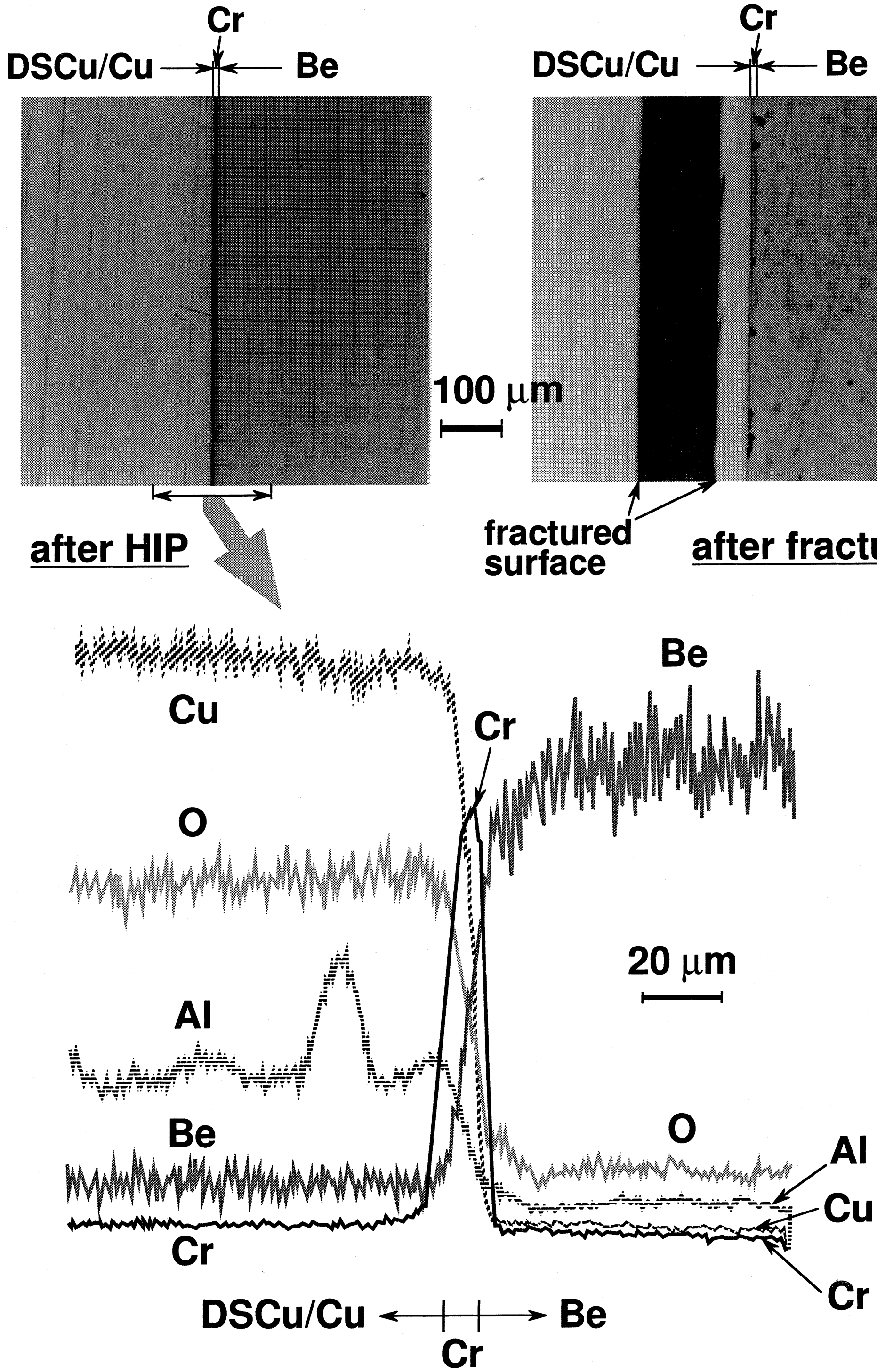

Fig. 3. Microscopic observation and EPMA results of Be/DSCu joint interface with Cr/Cu interlayer.

It should be noted that the joint strength with Cu interlayer is slightly reduced at elevated temperatures due to the degradation in the mechanical strength of Cu. Therefore, limit on operating temperature should be investigated together with the investigation of required strength for ITER operation conditions.

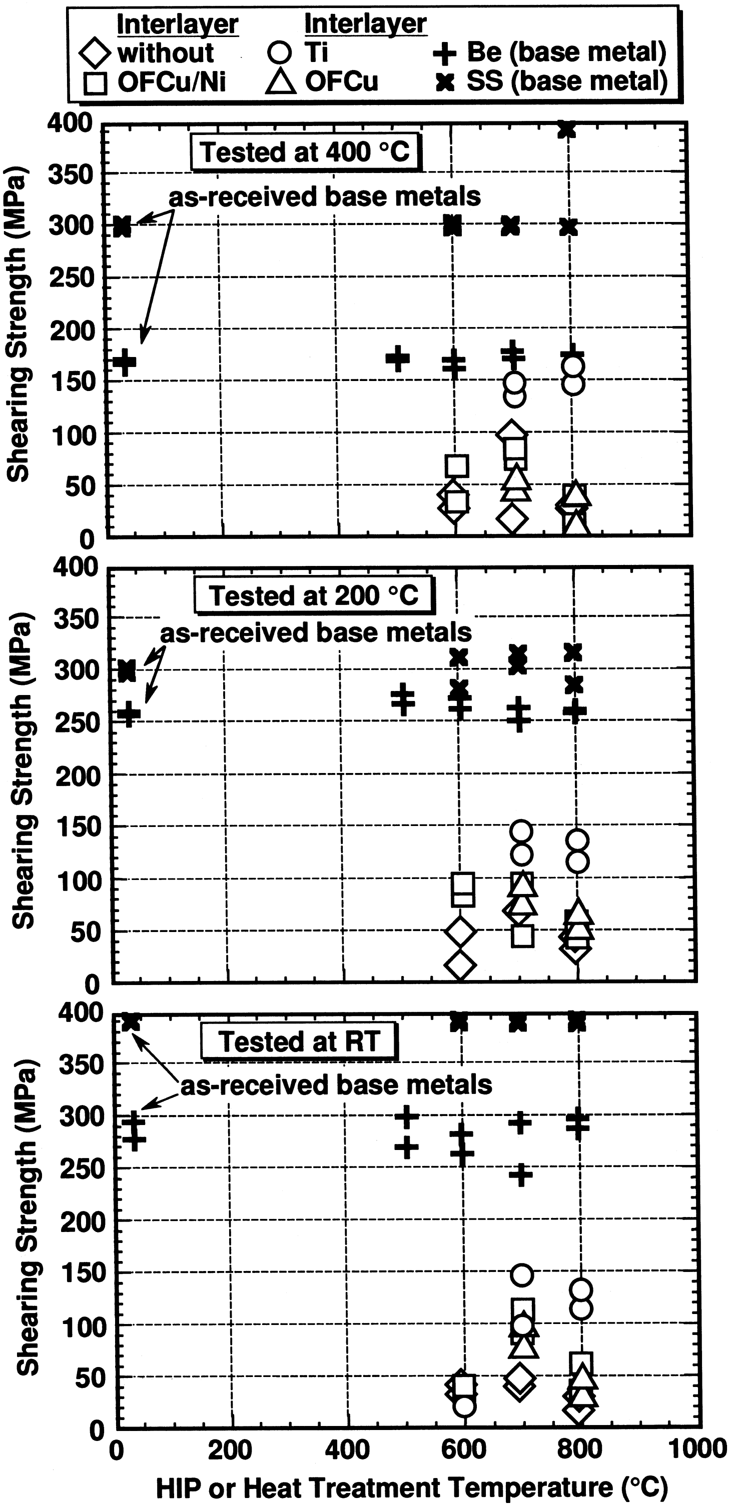

Fig. 4. Shearing strength of HIP bonded Be/SS joints and base metals.

Table 2
Interlayer material and HIP conditions for Be/SS316L joints

Bonded material	Method to provide interlayer	HIP condition		
		Temperature (°C)	Pressure (MPa)	Hold time (h)
Be/SS316L		600	140	2
		700	140	2
		800	140	2
Be/OFCu/Ni/SS316L	Foil	600	140	2
		700	140	2
		800	140	2
Be/Ti/SS316L	Foil	600	140	2
		700	140	2
		800	140	2
Be/OFCu/SS316L	Foil	600	140	2
		700	140	2
		800	140	2

3. Be/SS joints

The grade S-65C hot-pressed Be and type 316L SS were used for the joining test of Be/SS. HIP temperatures of 600–800°C with and without interlayers were examined as listed in Table 2. Interlayer materials taken for this joint were Ti as a diffusion barrier and OFCu as a compliant material. In the case of OFCu interlayer, two cases, i.e., with and without pre-electro-plating of Ni on SS, were tried. Shearing test results are shown in Fig. 4. Highest shearing strengths, among the joints tested, were obtained by the joints bonded at 700–800°C HIP temperatures with Ti interlayer. For the joints with OFCu and OFCu/Ni interlayers, shearing strengths were relatively high with HIP temperatures of 700°C. However, they were still lower than the joints with Ti interlayer and reduced at elevated temperatures. Therefore, for the Be/SS joints, the use of Ti interlayer seems promising. In terms of preventing the SS sensitization, HIP temperature of 800°C or even a little higher will be adopted.

4. Conclusion

Joining of Be/DSCu and Be/SS by means of HIP with and without various interlayers were investigated, and mechanical strengths of the bonded joints were tested. The following conclusions were derived:

1. For Be/DSCu joint, the use of Ag interlayer with HIP temperature of 700°C would be a prime candidate if Cd formation under neutron irradiation would not seriously affect plasma operation and the joint performance.
2. The Be/DSCu joint with an interlayer of PVD-coated Cr/Cu or even only Cu also seems promising. The lower HIP temperature, 550°C, for this joint is advantageous to prevent sensitization of SS structural material.
3. As for Be/SS, the highest joint strength was obtained by the use of Ti interlayer. The HIP temperature of 800°C or even a little higher would be applied, in this case, to avoid SS sensitization.

References

[1] Technical Basis for the ITER Interim Design Report, Cost Review and Safety Analysis, ITER EDA Documentation Series No. 7, IAEA, Vienna, 1996.
[2] E. Visca, E. Di Pietro, G. Ceccotti, G. Mercurio, Fusion Technol. 30 (1996) 689.
[3] P. Lorenzetto, G. Le Maroi, F. Saint Antonin, M. Rödig, W. Dänner, A. Cardella, Fourth International Symposium on Fusion Nuclear Technology, Tokyo, Japan, 1997.
[4] Y. Severi, P. Chappuis, L. Giancarli, Y. Poitevin, M. Rödig, J.F. Salavy, G. Vieider, Fourth International Symposium on Fusion Nuclear Technology, Tokyo, Japan, 1997.
[5] M. Rödig, R. Duwe, J. Linke, A. Schuster, B. Wiechers, Fourth International Symposium on Fusion Nuclear Technology, Tokyo, Japan, 1997.