Recent Progress of Dissimilar Material Bonding Technique with Spark Plasma Sintering Method for High Heat Load Plasma Facing Components in Reactor-relevant Devices

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In NIFS, dissimilar material bonding technique using Spark Plasma Sintering (SPS) method has been developed to join the high heat load armor to the heat sink in target plates of the divertor. Various combinations of materials, i.e., tungsten (W), copper ally (CuCrZr), molybdenum alloy (TZM), stainless steel (SS), graphite or carbon fiber reinforced composite (C/CFC), etc., were tried to bond, according to the required conditions. Up to now, the W-CuCrZr bonded divertor for LHD succeeded in the heat load test with e-beam of 23 MW/m^2 quasi steady-state (10 min.) and of 15 MW/m^2, 10 sec, 100 times cyclic (duty cycle = 50 %). In order to evaluate the bonding performance, diagnostics with SEM/EDS at the bonding surface, together with the shear stress test were performed. In this paper, recent progress of research and development for dissimilar material bonding with SPS are overviewed.

In future DEMO or reactor-relevant devices, e.g., ITER, tungsten is the most promising material for the armor of the high heat load plasma facing components (PFCs). On the other hand, effective heat removal from the armor to the heat sink made of high heat conductivity materials, e.g., copper or copper alloy, is crucial [1]. To realize such ideal PFCs, it is necessary to join armor to heat sink with high performance bonding technique in strength and heat conductivity. In LHD, coated tungsten or mechanically joined molybdenum has been utilized for inertially cooled divertor target plates or ECH and NBI protection tiles. However, it is obvious not to be able to use such armor for higher power and steady-state devices. Recently in NIFS, actively cooled divertor target plates with bulk tungsten armor have been developed, aiming for future DEMO or reactor-relevant devices. To join the tungsten armor to copper alloy heat sink, advanced multi-step brazing technique is employed [2]. In parallel with the brazing, a new bonding method with the Spark Plasma Sintering (SPS) has also been developed.

In the SPS process, the two dissimilar materials are bonded with the thin interlayer which mitigates thermal stress caused between two materials, under high one-dimensional pressure of several tens MPa and high pulsed current of several kA. The Joule heating and the periodic electric field move ions and electrons, which results in the stiff bonding between two dissimilar materials. The advantage of the SPS bonding method over other methods, e.g., diffusion bonding, brazing, etc., is that the process can be performed in relatively low temperatures with a single and simple procedure, which leads to the reduction of the time and the cost in mass production. Additional advantage of the SPS method is the variety of the combination of materials to be bonded, for example, tungsten can be bonded to graphite [3].

In NIFS, various combinations of dissimilar materials have been tried to bond, according to each requirement. After the intensive parameter survey for the optimal SPS processing with small test pieces, bonding of W-CuCrZr was first succeeded with the interlayer made of W and CuCrZr (20/80 mixed powder). The SPS process was conducted at the temperature of 900 degree C for 30 minutes in hydrogen atmosphere to avoid oxidization of tungsten. According to the microscopic diagnostics including SEM/EDS, as shown in Fig. 1, severe defect and formation of tungsten oxide were not detected. Interesting point is that no diffused atom of bonding partner material was detected neither in W-side nor CuCrZr-side. In the sheer strength test, it showed favorable result of more than 120 MPa. After the inspection of physical properties with small test pieces, a prototype of the actively cooled divertor target plate was fabricated, aiming for the LHD experiment, which consists of a 20mm wide x 150mm long x 5mm thick W-armor and CuCrZr-heat sink. Before installing in LHD, the heat load test was carried out using the electron beam irradiation facility ACT-2. It was confirmed that the divertor could withstand quite high heat flux more than 23 MW/m^2 in quasi steady-state (10 minutes). The surface temperature at 15MW/m^2 was about 1200 degree C. In order to apply the divertor to DEMO or reactor relevant devices, it should withstand not simply high heat load, but its repetitive load. For this requirement, the cyclic heat load test was also performed in ACT-2. The 10 sec electron beam pulse was successfully irradiated 20mm x 60mm area on divertor target plates 100 times with duty cycle of 50 %, which satisfies the most severe requirement of JT-60SA (15 MW/m^2 x 5 sec x 100 cycles). Based on this success, a larger scale prototype is being developed, aiming for JT-60SA tungsten divertor. Preliminary results from the heat load test are shown in Table 1.

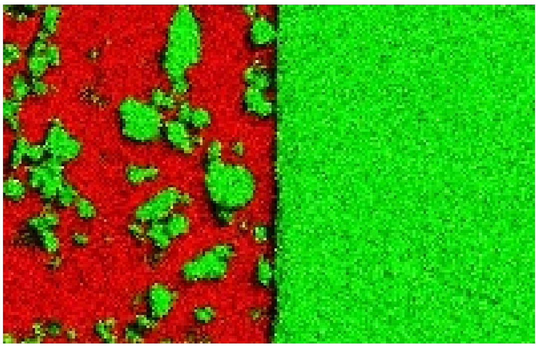

Fig. 1. SEM/EDS image at transition surface between Cu/W-interlayer (left) and bulk-W (right).

Other material combinations for different purposes in different devices are tried to bond. For example, W-SS bonding, aiming for the vacuum vessel wall of the QUEST tokamak in Kyushu University succeeded, after introducing multi or graded interlayer. This kind of technique should contribute to the bonding between tungsten and the reduced activation ferritic/martensitic (RAFM) steel for the fusion reactor blanket.

Research and Development results so far in NIFS are summarized in Table 1. Finally, we would like to thank Toho Kinzoku Co., LTD. and Anaori Carbon Co., LTD. for their great contributions.

Table 1. Present status of R&D for SPS bonding in NIFS

Target	Divertor LHD	Divertor JT60-SA	Divertor JT60-SA	Divertor JT60-SA	NB target JT60-SA	Divertor LHD	First wall QUEST
Heat flux	high	high	high	high	high	low	quite low
Armor	W	W	W	C	CFC / C	W	W
Heat sink	CuCrZr	CuCrZr	CuCrZr	TZM	CuCrZr	C	SS
Base	SS	SS	-	SS	SS/-	-	-
Cooling	active	active	active	active	active	inertial	inertial
Shear strength	120MPa	120MPa	120MPa	10MPa	1.2MPa	-	-
Heat load (pulse)	23MW/m^2 600sec	15MW/m^2 100sec	15MW/m^2 100sec	not yet	not yet	-	-
Heat load (cyclic)	15MW/m^2 10s x 100	not yet	15MW/m^2 10s x 100	not yet	not yet	-	-

References

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