

CONFERENCE PRE-PRINT**RECENT PROGRESS OF DISSILAR MATERIAL
BONDING TECHNIQUE WITH SPARK PLASMA
SINTERING METHOD FOR HIGH HEAT LOAD
PLASMA FACING COMPONENTS IN
REACTOR-RELEVANT DEVICES**

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Abstract

In National Institute for Fusion Science (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 component in fusion experimental devices. Tungsten (W) which is the first candidate of the divertor armor material in fusion reactors has been tried to bond to various heat sink materials, i.e., copper alloy (CuCrZr), molybdenum alloy (TZM), stainless steel (SS), graphite or carbon fiber reinforced composite (C/CFC). Up to now, the W-CuCrZr bonded divertor tile for LHD succeeded in the heat load test with e-beam of 23 MW/m², quasi steady-state (10 minutes) and of 15 MW/m², 10 sec, 100 times cyclic (duty cycle = 50 %). In order to evaluate the bonding performance, diagnostics with SEM/EDS on the bonding surface, together with the shear stress test were performed. In the paper, recent progress of research and development for dissimilar material bonding with SPS are overviewed.

1. INTRODUCTION

In future DEMO or reactor-relevant devices, e.g., ITER, tungsten is the first candidate material for the armor of the high heat load plasma facing components (PFCs), e.g., divertor tile, vacuum vessel or blanket wall. 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 the armor to the heat sink with high performance bonding technique in strength and heat conductivity.

In LHD, tungsten coated graphite tiles and bulk molybdenum plates, mechanically joined to the cooling tubes, have been utilized for the divertor component and the ECH/NBI protection system, respectively. 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 has been developed [2]. In parallel with the brazing, a new bonding method with the Spark Plasma Sintering (SPS) has also been developed.

2. SPARK PLASMA SINTERING (SPS)

The SPS processing was originally invented in Japan as “Electric-discharge sintering” in 1960s. It has been developed mainly in industry for sintering, bonding, surface treatment and synthesis [3-6]. Today, the SPS process is widely used in many countries around the world for the research and development of various advanced new materials such as nanomaterials, fine ceramics, functionally graded materials, and thermoelectric conversion materials. The advantage of the SPS bonding method over other conventional methods, e.g., diffusion bonding, brazing, etc., is that the process can be performed at 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 bond.

In NIFS, the tungsten divertor for LHD has been developed, employing the SPS method to bond bulk tungsten (W) plate to copper alloy (CuCrZr) heat sink. Figure 1 shows the SPS processing chamber for W-CuCrZr bonding, together with the enlarged bonding area on the right.

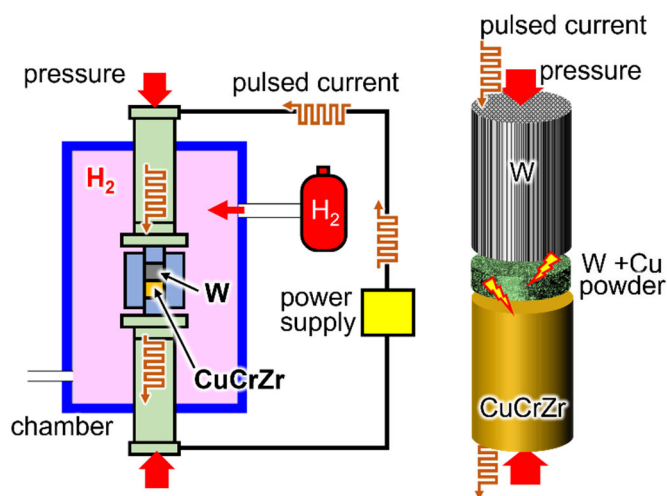


FIG. 1. SPS process chamber and external setups. Bonding area is enlarged on the right.

In the vacuum chamber, the two dissimilar materials are bonded, applying the high one-dimensional pressure of several tens MPa and the high frequency 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. Hydrogen gas is introduced to avoid oxidization of tungsten during the SPS process under Joule-heated environment.

In common bonding process, it is frequent to use interlayer(s) between dissimilar materials to be bonded. To mitigate thermal stress arising between two materials, NIFS and a collaborating private company have developed a new interlayer made of metallic powder. After the intensive parameter survey with small test pieces for the optimization of the SPS condition, bonding of W-CuCrZr was first succeeded with the interlayer made of W and CuCrZr (20/80 mixed powder, 900 degree C for 30 minutes). With this technique, the conventional SPS has been greatly improved, and is patented as "Powder Solid Bonding".

3. MICROSCOPIC AND MECHANICAL INSPECTIONS

With test pieces, the SPS bonding performance was inspected from the viewpoint of mechanical and material properties. Concerning the mechanical strength of the bonding boundary, the shearing strength was measured and compared to that of brazing. It is clearly shown in Fig. 2 that the performance of the SPS bonding is about 1.7 times higher than that of brazing. Interesting point is that the SPS processing even in vacuum shows poor performance, which suggests the fact that the deoxidization by hydrogen is more effective compared to the evacuation of oxygen.

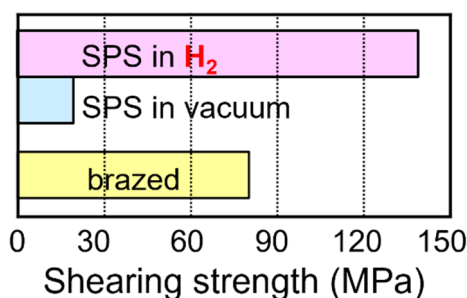


FIG. 2. Shearing strength of bonding boundary.

This result is supported by the ultrasonic inspection, i.e., the void ratio at the SPS bonded boundary is much smaller (0.05 %) than that of brazing (12.8 %).

According to the microscopic diagnostics including SEM/EDS, as shown in Fig. 3, formation of tungsten oxide was not detected, and no diffused atom of bonding partner material was detected neither in W-side nor CuCrZr-side.

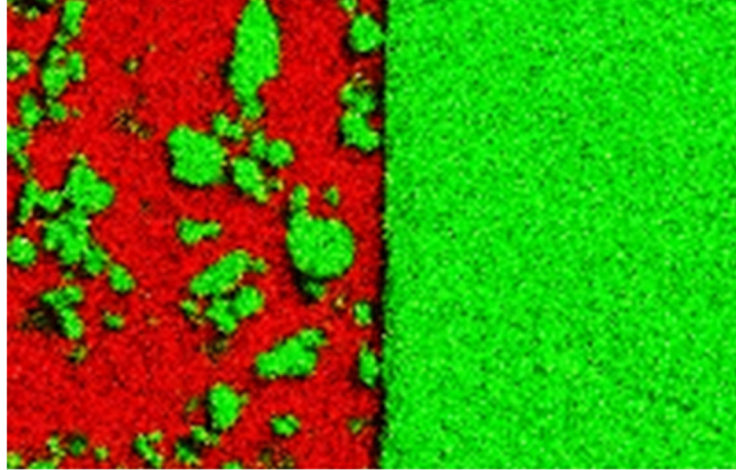


FIG. 3. SEM/EDS image at transition surface between Cu/W-interlayer (left) and bulk-W (right).

After the inspection of physical properties with small test pieces, a prototype of the actively cooled divertor element was fabricated, aiming for the LHD experiment, which consists of a 20mm wide x 150mm long x 5mm thick W-armor and a CuCrZr-heat sink, as is shown in Fig. 4. The W-armor is formed to be castellated to mitigate the thermal stress.

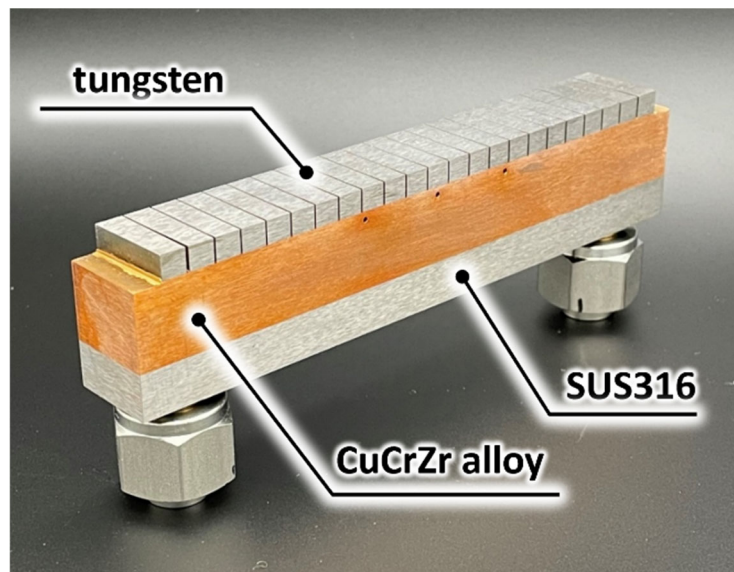


FIG. 4. W-CuCrZr divertor target element for LHD

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 15 MW/m^2 was about 1200°C . In order to apply the divertor to DEMO or reactor-relevant devices, it should withstand not only high heat loads, but also repetitive loads. For this requirement, the cyclic heat load test was also performed in ACT-2. A $20 \text{ mm} \times 60 \text{ mm}$ area on the divertor target plate was successfully irradiated 100 times with a 10 sec electron beam pulse at a duty cycle of 50 %, which satisfies the most stringent requirement of JT-60SA ($15 \text{ MW/m}^2 \times 5 \text{ sec} \times 100 \text{ cycles}$). Experimental results together with setup are shown in Fig. 5.

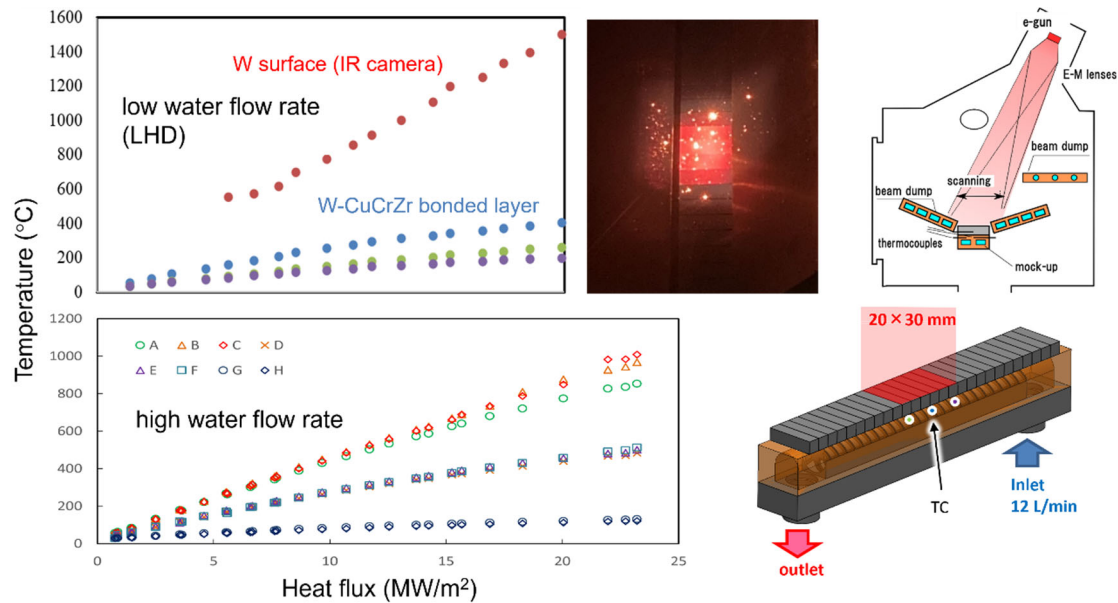


FIG. 5. Tungsten surface and heat sink temperature of LHD divertor element in the function of heat flux. Note that surface temperature was only measured in the case with low water flow. Overall ACT-2 setup and position of thermocouples are also depicted.

Based on this success, a larger-scale prototype is being developed, aiming at the JT-60SA tungsten divertor, which has the same cross section as an actual divertor element, although its length along water channel is about one third. Three mockups with different water channel designs, tungsten thickness were fabricated. For one of them, a heat load test was also carried out in ACT-2. In the test, it succeeded in relatively long-duration irradiation of 100 seconds at 15 MW/m^2 , and in 100 cycles of irradiation at 15 MW/m^2 with a duty cycle of 50% (10 sec. ON, 10 sec. OFF), which is the requirement of the JT-60SA tungsten divertor, as mentioned earlier.

In order to investigate the thermal performance of the JT-60SA divertor manufactured with SPS, the high-power irradiation test is also performed in the HADES device [7] in CEA Cadarache, which has been utilized to test the JT-60SA tungsten divertor developed and procured by Europe. Before the HADES test, the SATIR test [8] is performed, which is a nondestructive inspection to detect primary defects by using the infrared thermography. The first series of the SATIR test followed by the HADES test in CEA has been completed and the experimental data is now being analyzed.

Material combinations tailored for diverse applications across different devices have been evaluated for bonding feasibility. In LHD, a 1 mm thick tungsten plate was bonded to a graphite tile [9] for the inertially cooled helical divertor. Compared to the tungsten coating on the graphite tiles, the fabrication cost is relatively low.

For the QUEST device, which is a medium-sized spherical tokamak at Kyushu University, a bonding technique using SPS to attach tungsten armor to a 5 mm-thick stainless steel heat sink has been developed, targeting applications in the divertor plate and the vacuum vessel wall. Two combinations of different tungsten thicknesses (1 mm and 0.1 mm) and different interlayers were tested for bonding. In the case of 1 mm tungsten, it was

necessary to mitigate thermal stress between the tungsten and stainless steel. To address the problem, a relatively thick (1 mm) multilayer or graded interlayer was introduced, consisting of W-Cu mixed powder, a Cu sheet and Cu powder. With this technique, a 50 mm x 50 mm x 1 mm tungsten plate could be bonded to the stainless steel heat sink, although a slight warp remained. This technique is expected to contribute to the bonding between tungsten and the reduced activation ferritic/martensitic (RAFM) steel for the fusion reactor blanket. Recently, the bonding 0.1 mm tungsten to 5 mm stainless steel succeeded with 0.1 mm thick nickel film as an interlayer.

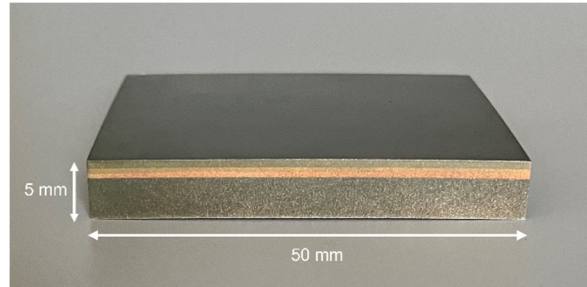


FIG. 6. W-SS bonding for QUEST VV wall. Thickness of both W and interlayer is 1 mm. Graded interlayer is inserted between W and SS.

Preliminary results from the heat load test, along with research and development outcomes to data at NIFS, are summarized in Table 1.

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	-	-

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