FABRICATION OF THE FULL SCALE SEPARABLE FIRST WALL OF ITER SHIELDING BLANKET

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Fabrication of the Full Scale Separable First Wall of ITER Shielding Blanket

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Shielding blanket for ITER-FEAT applies the unique first wall structure which is separable from the shield block for the purpose of radio-active waste reduction in the maintenance work and cost reduction in fabrication process. Also, it is required to have various types of slots in both of the first wall and the shield block, to reduce the eddy current for reduction of electro-magnetic force in disruption events. Such unique features of blanket structure required technological clarification from the technical base of the previous achievement of the blanket module fabrication development.

Previously, within the EDA Task T216+, a prototype for the #4 Primary Wall Module of the ITER Shield Blanket with integrated first wall has been manufactured by forging and drilling and the first wall has been manufactured and joined to the shield block by Hot Isostatic Pressing (HIP) in one step process. This work has been performed to clarify the remaining R&D issues which have not been covered in the previous R&D. This report summarizes the demonstrative fabrication of the real scale separable first wall for ITER shielding blanket designed for ITER-FEAT, together with the essential technology developments such as, the slit grooving of the first wall with beryllium armor and SS shield block and fabrication of a partial mockup of beryllium armored first wall panel with built-in cooling channels. This work has been performed under the task agreement of G 16 TT 95 FJ (T420-1) in ITER Engineering Design Activity Extension Period.

By the demonstration of the Be armor joining to the first wall panel, the joining technique of Be and DSCu developed previously, was shown to be applicable to the realistic structure of first wall panel. Also, the slit grooving by an end-mill method and an electron discharge machining method have been applied to the first wall mockup with Be armor tiles and demonstrated the applicability within the design tolerance. As the slit grooving technique for SS block, water jet method was demonstrated to be applicable to the complicated slit structure required in the shield block fabrication. Also, the fabrication of full scale FW panel was performed. By the destructive observation of the test pieces of HIP joints, the soundness of the fabrication was clarified. In conclusion, essential fabrication technology for the full scale separable first wall panel has been established by this work.

Key words;
ITER Shielding Blanket, Full Scale Separable First Wall, Joining Technique, Be, DSCu, SS, Slit Grooving
ITER 適蔽プランケット用の実規模分離型第一壁パネルの製作

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ITER-FEATの適蔽プランケットでは、放射性廃棄物量の低減と製作コスト低減のために分離第一壁型の構造を採用している。さらに、ディスラプションの際の渦電流を低く抑え電磁力を低減するために、多様なスリット構造を必要とする。このような特徴を有する構造体を製作する場合の基本的な製作技術は、これまでの開発成果を踏まえて、新たに技術開発を行う必要がある。

ITER EDA期間中のタスクT216+では第一壁体型適蔽プランケットのプロトタイプを製作した。一体型プランケットプロトタイプは、適蔽ブロックを鍛造とドリル穴加工で形成し、第一壁部を高温等方加工法（HIP法）で一体化し、製作した。本研究では、これまでのR&Dで解決されていない新たな技術課題について、R&Dを実施し、Be/DSCu/SS第一壁パネル及びSS適蔽ブロックへのスリット加工技術の技術開発、及びベリリウムの第一壁パネル部分モックアップへの接合実証、それらの成果を用いた実規模の分離型第一壁パネルの製作実証を行ったので、その結果を報告する。本研究は、ITER EDA延長期間中の、分離第一壁型適蔽プランケットの製作技術開発を目的としたタスク取り決めG16TT95EJ(T420-1)に基づいて行われたものである。

本研究により、これまでに開発したBeアーマーの接合条件が第一壁パネルの構造体への接合にも有効であることを実証した。また、Be/DSCu/SS第一壁パネルへのスリット加工法としては、エンドミル法、放電加工法の双方で、設計仕様を満たすスリット加工が可能であることを示した。また、ステンレス鋼の適蔽ブロックへのスリット加工としては、ウォータージェット法で、設計で要求される複雑なスリット形状の加工が可能であることを示した。実規模の分離型第一壁パネルの製作を行い、模擬端部の破壊試験により接合の良好性、製作寸法が良好であることを確認した。これ研究の成果として、ITER 適蔽プランケットの分離第一壁パネルの製作技術を確立した。
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1 Introduction

Shielding blanket for ITER-FEAT applies the first wall which is separable from the shield block for the purpose of radio-active waste reduction in the maintenance work and cost reduction in fabrication process. Also, the shielding blanket is required to have various types of slits in both of the first wall panel and the shield block, to reduce the eddy current for reduction of electro-magnetic force in disruption events. Such unique features required clarification of the feasibility with the technical base of the previous achievement of the blanket module fabrication development.

Within the EDA Task T216+, a prototype for the #4 module of the shield blanket with integrated first wall has been manufactured previously by forging and drilling and the first wall has been manufactured and joined to the shield block by Hot Isostatic Pressing (HIP) in one step process. This work has been performed to clarify the remaining R&D issues which have not been covered in the past R&D. This report summarizes the demonstrative fabrication of the real scale separable first wall for shielding blanket designed for ITER-FEAT, together with the essential technology developments such as, the slit grooving of the first wall with beryllium armor and SS shield block and fabrication of a partial mockup of beryllium armored first wall panel with built-in cooling channels. The general missions in the task are:

1. to further develop a suitable joining technique for the beryllium armor and a castellation method of the shielding blanket modules for ITER-FEAT;
2. to develop an improved fabrication method for the shielding blanket based on the ITER-FEAT updated design, and in particular to improve reliability of all the joints (Cu-alloy/SS and SS/SS).

Major technical issues, which are unique in the design of the shielding blanket for ITER-FEAT, are

1) separable first wall panel of Be/Cu alloy/SS plate to reduce the radioactive waste of replacement,
2) slits in first wall panel and shield block to reduce the electro-magnetic force,
3) requirement of fabrication cost reduction and increase of the database of HIP joint mechanical properties under irradiation, and
4) complicated rear side configuration to withstand the external manifolds on VV concepts for coolant water supply.

In this report, basic issues of 1) and 2), which is essential to the feasibility of the separable FW blanket, are summarized from the achievement from the R&D task performed under the agreement of G 16 TT 95 FJ (T420-1) in ITER Engineering Design Activity Extension Period.

With respect to the issue 2), development of slit grooving technique were performed for SS block, DSCu/SS panel, Be/DSCu/SS HIP block. Also, the Be armored first wall mockup with
built-in cooling channels was fabricated by using developed slit grooving techniques. The optimized HIP condition for Be/DSCu, task T508-3 was performed separately. The result of task T508-3 was reflected to the fabrication of the Be armored first wall mockup. With respect to the issue 1), the fabrication of a full scale FW panel was demonstrated.

With respect to the development of slit grooving technique, three mock-ups were fabricated: 1) a HIP-bonded Be/DSCu/SS mock-up without coolant channels to investigate the basic applicability of candidate methods and also the bondability of Be/DSCu by HIP, 2) a SS shield block mock-up without coolant channels to investigate the method for deep slotting and gouging of massive SS block, and 3) HIP-bonded Be/DSCu/SS block with FW coolant tubes embedded within DSCu to examine and demonstrate the methods developed in 1) to be applied within the fabrication procedure of the FW. For the SS block slit grooving, water jet method was applied and the optimized condition was obtained. For the DSCu/SS HIP part, electron discharge machining (EDM) was applied. For penetrating grooving of Be/DSCu/SS, EDM, end mill, and circular saw were compared. The result showed the effectiveness of the EDM method for thin width slits with curved configuration.

By the fabrication of the full scale first wall panel mockup, it was demonstrated that the fabrication technique and procedure developed by the trial fabrication of the half length FW mockup is applicable to the fabrication of the actual first wall panel. The inspection to verify the fabrication process was performed. As the non-destructive inspection, visual inspection, dimensional test, pressure test, He leak test, penetration defect test, radiographic tests, ultrasonic test and the HIP condition record check were performed. All test results showed satisfactory data. The destructive test were performed for dimensional measurement of the SS cooling channels, macroscopic observation, optical micro-graph observation, SEM/EPMA observation, hardness measurement for DSCu and SS HIP joint. As the results of destructive tests, the soundness of HIP joints has been confirmed around the curvature of top and bottom edges and front access holes of the FW panel. The dimension inspection certified the sound dimension control between coolant channels and the diameters of the coolant channels. The support leg of the first wall panel was attached by the electron beam welding. The soundness of the EB welding was inspected by ultrasonic testing method.
2 Objectives and R&D Conditions

2.1 General Description

The general missions of R&D task, G 16 TT 95 FJ (T420-1), were
- Demonstration of the fabrication method for the ITER-FEAT shielding blanket module
design including the beryllium armor and its castellation, and
- Improvement of the mechanical properties of the joining interface.

In order to demonstrate the manufacturing feasibility of the ITER-FEAT shielding blanket module
design, partial mock-ups has been fabricated using the solid HIP method. Metallurgical
observation has been performed with fabricated mock-ups. Additionally, mechanical properties of
the non-irradiated and irradiated DSCu/SS, DSCu/DSCu and SS/SS HIP bonded joints have been
obtained. The task had been divided into two sub-tasks, in correspondence with the above
mentioned missions. This report contains the results of the former subtask. The R&D
summarized in this report contains two items. The followings are the brief definitions of each
R&D item.

(1) Element technology development of Be armor FW and SS shield block mock-ups with slits

In order to develop and demonstrate the manufacturing methods of the first wall with slits,
mock-ups consisting of Be armor/DSCu heat sink/SS shield block will be fabricated. Solid HIP
will be applied for Be/DSCu (and DSCu/SS) joining. According to the design progress for the
RTO/RC ITER, a mock-up of SS shield block with slits will also be fabricated. The slit
grooving method and procedure applied for the first wall panel will be selected taking into
account the fabrication cost as well as the technical soundness. To enable this, three types of
mock-ups will be fabricated: 1) a HIP bonded Be/DSCu/SS mock-up without coolant channels,
2) a SS shield block mock-up without coolant channels, 3) a HIP bonded Be/DSCu/SS mock-up
with FW coolant tubes embedded within DSCu.

(2) Fabrication of a full scale first wall panel

- According to the design progress, a shielding blanket prototypical mock-up with the first wall
  and the penetration hole but without Be armor tiles will be fabricated using the solid HIP
  and/or other alternative methods.
- Metallurgical observations will be performed to confirm the soundness of the joining interface.
2.2 Fabrication and Test Conditions

Fabrication and test conditions in each item are as follows.

(1) Be armor bonded FW and SS shield block mock-ups with castellation and slots

Type 1
Test piece size : 100 mm(l) x 60 mm(w) x 100 mm(t)
Number of test piece : one
Configuration : Be (10 mm)/DSCu (~40 mm)/SS (~50 mm)
without coolant channel in DSCu nor SS block
Depth of castellation : 10 mm in toroidal and ~45 mm or penetrating
through in poloidal directions
HIP conditions : 1050°C/150 MPa/2 hrs for DSCu/SS (first step)
TBD for Be/DSCu (second step) by Task T508-3
Inspection/Test : Destructive tests, metallurgical observation, dimension
measurement, hardness measurement

Type 2
Test piece size : 300 mm(l) x 250 mm(w) x 350 mm(t)
Number of test piece : one
Configuration : SS block without coolant channel
Depth of slots : 250 mm

Type 3
Test piece size : up to 500 mm(l) x 100 mm(w) x 100 mm(t)
Number of test piece : one
Configuration : Be (10 mm)/DSCu (2~40 mm)/SS (~50 mm)
Flat FW with top or bottom corner with coolant channels
Depth of slots : 10 mm in toroidal, and ~45 mm or penetrating through in
poloidal directions
HIP conditions : 1050°C/150 MPa/2 hrs for DSCu/SS (first step) and
555°C/150 MPa/2 hrs for Be/DSCu (second step) [7,8].
Inspection/Test : Destructive tests, metallurgical observation, dimension
measurement, hardness measurement
(2) Shielding blanket mock-up with the first wall

Mock-up size : 1000 mm x 1000 mm (first wall area)
FW configuration : poloidally flat with castellated surface, separable structure
Depth of slots : ~100 mm
FW/SS shield block : 85 mm/355 mm (with embedded SS coolant tubes in DSCu)
HIP conditions : 1050°C/150 MPa/2 hrs for DSCu/SStube/SS plate (single step)
Number of mock-ups : one
Inspection/Test : destructive tests, metallurgical observation, dimension measurement, hardness measurement
3 Element Technology Development of Be Armor FW and SS Shield Block Mock-ups with Castellation and Slits

In order to develop and demonstrate the manufacturing methods of the first wall (FW) with castellation and slots, three mock-ups were fabricated:

1) a HIP-bonded Be/DSCu/SS mock-up without coolant channels to investigate the basic applicability of candidate methods and also the bondability of Be/DSCu by HIP,

2) a SS shield block mock-up without coolant channels to investigate the method for deep slotting and gouging of massive SS block, and

3) HIP-bonded Be/DSCu/SS block with FW coolant tubes embedded within DSCu to examine and demonstrate the methods developed in 1) to be applied within the fabrication procedure of the FW.

The last mock-up possesses coolant headers and external coolant pipes to be ready for thermo-mechanical testing.

3.1 HIP-bonded Be/DSCu/SS Mock-up without Coolant Channels

3.1.1 Mock-up Design

For the investigation on the castellation of Be armor and the slotting through Be/DSCu/SS structure, a mock-up simulating the FW top (or bottom) end was designed as schematically shown in Fig. 3-1. As this mock-up consisted of the three FW materials, i.e., Be, DSCu and SS, the influence of fabrication process, especially heat treatments according to DSCu/SS and Be/DSCu HIP bonding, could be incorporated. Since the influence of the DSCu/SS HIP was included by the bonding of the heat sink and the backing plate, SS coolant tubes were not embedded within DSCu. The mock-up was initially fabricated in dimensions of ca. 60 mm\(^W\) x 130 mm\(^H\) x 95 mm\(^T\) as shown in Fig. 3-1. Then a half of the mock-up was cut and destructively examined. The final dimensions of the mock-up are shown in Fig. 3-2.

3.1.2 Mock-up Fabrication

Materials used for the mock-up were S65C-grade Be for the armor, GlidCop\textsuperscript{\textregistered} AL-25-IG1 for the heat sink and SS316L for the backing plate.

The fabrication route was divided into two main procedures, i.e., the HIP-bonding of
DSCu/SS and also the HIP-bonding of Be/DSCu. Both of the HIP conditions were determined based on previous investigations, namely at 1050 °C under 150 MPa for two hours for DSCu/SS [1-6] and at 555 °C under 150 MPa for 2 hours for Be/DSCu [7, 8]. For the latter, the assembly was kept at 425 °C for 4 hours on the cooling way from the HIP temperature as shown in Fig. 3-3. This heat treatment was performed anticipating the reduction of residual stress at the bonded interface since the S65C grade Be shows the highest elongation at this level of temperature. However, the effectiveness and necessity of this heat treatment are not fully confirmed yet and need further investigation. In addition for the latter, the interlayer between Be and DSCu was applied also based on the previous investigation [7, 8]. The interlayer materials employed for this mock-up were 0.75-mm-thick Al coated by vacuum plasma spray (VPS) on Be, 0.12-mm-thick Al foil containing Mg and Si inserted between Be and DSCu, and 10-μm-thick Al, 15-μm-thick Ti and 7-μm-thick Cu coated by physical vapor deposition (PVD) on DSCu. This composition of the interlayer materials is schematically shown in Fig. 3-4. Overall fabrication steps are summarized as follows:

**DSCu/SS HIP**

1) Machining of DSCu and SS parts
   - Measured roughness of the surface to be HIP-bonded: \( R_z \leq 3.2 \, \mu m \)
2) Degassing the DSCu parts by heating up to 800 °C for 2 hours with evacuation down to \( 1 \times 10^{-5} \) Torr
3) Cleaning the surfaces to be HIP-bonded by acetone
4) Assembling and canning of the DSCu and SS parts
   - Canning material: thin plate of SS304
5) Pressure test at 0.49 MPa for 0.5 hour, He leak test and seal welds penetrant testing of the canned assembly
6) Degassing of the assembly internals by heating up to 500 °C for 2 hours with evacuation down to \( 1 \times 10^{-5} \) Torr
7) Pinching, seal welding and penetrant testing of the evacuation pipe
8) HIP treatment at 1050 °C and 150 MPa for two hours
9) Cutting and penetrant testing of the root of the pinched evacuation pipe
10) Machining for eliminating the canning plates, shaping the DSCu/SS part and preparing the HIP bonding of Be/DSCu
   - Measured surface roughness of DSCu to be HIP-bonded to Be: \( R_z \leq 2.7 \, \mu m \)
Be/DSCu HIP

11) Machining of Be blocks to be HIP-bonded onto DSCu
   - Prepared block size for assembly (Fig. 3-5)
     64 mm x 74.25 mm x 10 mm$^3$ for curved block
     64 mm x 63.5 mm x 10 mm$^3$ for flat block

12) VPS coating of Al on Be surface
   - Measured coating thickness
     0.70 mm on flat block
     0.70 mm at flat region of curved block
     0.64 mm at curved region of curved block

13) PVD coating on DSCu
   - Figure 3-6 shows an appearance before coating with jigs for coating thickness measurement on both sides (top and bottom in the figure) of the DSCu/SS structure.
   - An appearance after PVD coating and coating thickness distribution on the DSCu surface are shown in Figs. 3-7 and 3-8, respectively. Almost uniform coating of each material was obtained. Slight decrease of the thickness at the curved region was observed but would be acceptable for the bonding.

14) Assembling the VPS-coated Be blocks, Al (containing Mg and Si) foil and the PVD-coated DSCu/SS structure

15) Canning of the assembly by thin SS304 plates and their seal welding

16) Pressure test, He leak test and degassing of the assembly internals with heating and evacuation

17) Pinching, seal welding and penetrant testing of the evacuation pipe

18) HIP treatment at 555 °C and 150 MPa for 2 hours and post-heat treatment at 425 °C for 4 hours

19) Cutting and penetrant testing at the root of the pinched evacuation pipe

20) Machining for eliminating the canning plates and finishing the outward shape except for cutting off the piece for destructive testing

21) Castellation of Be armor by means of end mill (two toroidal lines) and electrical discharge machining (EDM), and slotting of Be/DSCu/SS structure also by means of EDM
   - The end-milling, the tool and the castellation machined by the end mill are shown in Fig. 3-9.

22) Finally, cutting of the piece for destructive testing

Appearance of the mock-up before cutting the piece for destructive testing and the final appearance are shown in Figs. 3-10 and 3-11, respectively.
3.1.3 Destructive examination

With the cut piece from the fabricated Be/DSCu/SS HIP-bonded structure, destructive examination including macroscopic and microscopic observations and EPMA analysis shown in Fig. 3-12 was performed. Figure 3-13 compares bottom shapes of the castellation performed by three methods. Though the most ideal shape was obtained by EDM with shaped Cu plate, smooth shapes were also obtained by other two methods. No cracks initiated from the bottom and/or propagated through the bonded interface were observed. Roughness of the surface cut by EDM (R1-R7) was 1.5-3.5 μm. On the other hand, roughness of the surface cut by the end mill (R8) was smoother, i.e., 0.8 μm. Micrographs of Be/DSCu HIP-bonded interface are shown in Fig. 3-14 (same location, Mi1, with different magnification). The location Mi1 corresponds to the end of the DSCu curved region as seen in Fig. 3-12. Although the thickness of Ti and Al PVD-coated on DSCu decreased, no voids were observed at the interface, and thus good bonding was obtained. Similar bonding aspects were also observed at other HIP-bonded interfaces. Results of EPMA analysis on the same location (E1) are shown in Fig. 3-15. Mg seems to have functioned well to reduce oxygen in Al though it still remained. Segregation of Si at the interface was observed, which might cause a reduction of joint strength. Therefore, optimization of Mg and Si contents in the Al foil might be needed for further investigation.
Fig. 3-1 Be/DSCu/SS mock-up without coolant channels

Fig. 3-2 Final dimensions of Be/DSCu/SS mock-up without coolant channels
Fig. 3-3 HIP and succeeding heat treatment process for Be/DSCu

Fig. 3-4 Interlayer materials for HIP bonding of Be/DSCu
Fig. 3-5 Prepared Be blocks for HIP assembly

Fig. 3-6 DSCu/SS structure with jigs for thickness measurement before PVD-coating
Fig. 3-7 PVD-coated DSCu/SS structure

Fig. 3-8 Thickness profile of PVD-coated materials on DSCu
Fig. 3-9 End mill for castellation of Be armor

Fig. 3-10 Appearance of mock-up before cutting the piece for destructive examination
Fig. 3-11 Final appearance of Be/DSCu/SS mock-up without coolant channels
Fig. 3-12 Destructive examination of HIP-bonded Be/DSCu/SS structure
Fig. 3-13 Bottom shape of castellation

Fig. 3-14 Micrographs of Be/DSCu HIP-bonded interface (Mi 1)
Fig. 3-15 EPMA analysis around Be/DSCu HIP-bonded interface (E 1)
3.2 SS shield block mock-up without coolant channels

3.2.1 Mock-up design

The design of the SS shield block of the shielding blanket proclaims that slots have to be provided in order to reduce the electromagnetic force acting on the blanket by cutting the eddy current circuits induced during the plasma disruption. These slots must not obviously interfere with coolant channels and manifolds within the shield block. To investigate the fabrication method of the slot to satisfy these requirements, a SS mock-up schematized in Fig. 3-16 were designed. The mock-up represents the slots in one-to-one scale to the design, i.e., 200 mm in depth and 250 mm in length. The mock-up was initially manufactured in dimensions of ca. 170 mm\(^W\) x 350 mm\(^L\) x 300 mm\(^T\) to include three slots. Afterwards, one of the slots was cut off and destructively examined. The final dimensions of the mock-up are shown in Fig. 3-17.

![Mock-up diagram](image-url)
3.2.2 Mock-up Fabrication and Destructive Examination

The material used for the mock-up was SS316L. The method applied for sloting (gouging) was water jet with conditions summarized in Table 3-1 and illustrated in Fig. 3-18. The nozzle was inclined by 5° (injection angle 85°) to help water and abrasive flow out of the mock-up. This nozzle inclination caused the delay distance ("L" in Fig. 3-18), which was about 30 mm in the case of this mock-up. To prevent crack initiation from the gouged end, a hole of 6 mm in diameter was drilled as shown in Fig. 3-17. A hole was also drilled at the bottom of the slots. The diameter of the bottom hole was 30 mm for inserting protection materials to prevent the shield block around the bottom from being damaged by the injected water and abrasive. The protection materials applied here were 4.5-mm-thick SS pipe (19 mm in outer diameter) and 9-mm-square cemented carbide rod. They were inserted into the 30-mm-diameter hole as shown in Fig. 3-18. Under these conditions, water jet gouging was performed with the rate of 1 mm/min. It should be noted that there was a region remained uncut at the end in the nozzle moving direction near the bottom due to the delay distance mentioned above. The method to eliminate the uncut region, including an inclination of the 6-mm-diameter hole and reduction of the bottom hole, needs to be investigated.
Table 3-1 Water jet conditions

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Water pressure</td>
<td>294.2 MPa</td>
</tr>
<tr>
<td>Water nozzle diameter</td>
<td>0.33 mm</td>
</tr>
<tr>
<td>Abrasive nozzle diameter</td>
<td>1.2 mm</td>
</tr>
<tr>
<td>Abrasive material</td>
<td>garnet sand #80</td>
</tr>
<tr>
<td>Abrasive supply rate</td>
<td>0.4 kg/min</td>
</tr>
<tr>
<td>Stand-off distance</td>
<td>2 mm</td>
</tr>
<tr>
<td>Nozzle moving velocity</td>
<td>1 mm/min</td>
</tr>
<tr>
<td>Injection angle</td>
<td>85°</td>
</tr>
<tr>
<td>Bottom protection</td>
<td>SS pipe and cemented carbide rod</td>
</tr>
</tbody>
</table>

Fig. 3-18 Gouging of SS block by water jet

The appearance of the fabricated mock-up is shown in Fig. 3-19. Measured slot widths were 1.25-2.4 mm as listed in Table 3-2 together with the measured location indicated in Fig. 3-17. Though the slot width tends to be narrower at the top and wider at the bottom, the width ranging from 1.25 mm to 2.4 mm could be acceptable in terms of the design.

Table 3-2 Measured slot widths

<table>
<thead>
<tr>
<th>Location</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
<th>T6</th>
<th>T7</th>
<th>T8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slot width [mm]</td>
<td>1.3</td>
<td>1.25</td>
<td>1.35</td>
<td>2.4</td>
<td>1.6</td>
<td>1.65</td>
<td>1.56</td>
<td>1.78</td>
</tr>
</tbody>
</table>
The SS surface gouged by water jet was observed from the cut piece for destructive examination. The surface appearance is shown in Fig. 3-20. A wavy pattern is observed on the surface, with which measured surface roughness (Rmax) was 33-102 μm. As the cut surface is not fairly smooth, its influence on the shield block performance needs to be examined. The inside views of the bottom holes are shown in Fig. 3-21. As seen from the figure, bottom region seemed to be protected well by the above protection materials. Since the protection might be too sufficient, further investigation on reducing the bottom hole diameter will be required.
Fig. 3-20 SS surfaces gouged by water jet

Fig. 3-21 Inside view of bottom holes
3.3 HIP-bonded Be/DSCu/SS mock-up with FW coolant tubes embedded within DSCu

3.3.1 Mock-up design

Based on the R&D results described in the previous Section, a Be/DSCu/SS mock-up more relevant to the ITER FW design was considered, namely a mock-up with FW coolant tubes embedded within DSCu. Figure 3-22 shows the design of this mock-up. The overall size of the mock-up, about 100 mm$^W \times 230$ mm$^L \times 95$ mm$^H$, was determined taking the possibility to be tested in a heating facility into account. The coolant supply and return pipes were also prepared in this sense.

Fig. 3-22 Be/DSCu/SS mock-up with FW coolant tubes embedded within DSCu
3.3.2 Mock-up fabrication

Materials used for this mock-up were the same as those for the Be/DSCu/SS mock-up without coolant channels, namely S65C-grade Be for the armor, GlidCop® AL-25-IG1 for the heat sink and SS316L for the backing plate. In addition to these, SS316L was also used for the FW coolant tube (12 mm in outer diameter and 1 mm in thickness) and for the coolant supply and return pipes.

Similarly to the previous mock-up, the fabrication route was divided into two main procedures, i.e., the HIP-bonding of DSCu/SS and the HIP-bonding of Be/DSCu. The HIP conditions for DSCu/SS were exactly the same as those for the previous mock-up, i.e., at 1050 °C under 150 MPa for 2 hours. On the other hand, different HIP conditions were selected for Be/DSCu. Two candidates for the Be/DSCu HIP conditions, especially in terms of HIP temperature and interlayer materials, had been discussed and recommended from previous research experience [7, 8] as follows:

- 555 °C, 150 MPa, 2 hours with VPS-Al (on Be), Al foil, PVD-Al/PVD-Ti/PVD-Cu (on DSCu) interlayer
- 620 °C, 150 MPa, 2 hours with PVD-Cu (on DSCu) interlayer

The former had shown higher mechanical strength and also higher durability in thermal fatigue testing at e-beam heat flux facility. Therefore it was applied to the previous mock-up without coolant channels. The latter is advantageous in lower fabrication cost. Though the mechanical properties of the latter were not as high as those of the former, they might be satisfactory for the FW application. Besides, the feasibility of the former would be demonstrated by the results of the previous mock-up. Therefore, it would be beneficial to investigate the feasibility of the latter HIP conditions to the FW structure this time. The interlayer was PVD-coated Cu, 20 μm in thickness, onto DSCu surface. The stress-relief treatment at 425 °C for 4 hours after the HIP treatment was also performed. The temperature evolution is schematized in Fig. 3-23. Fabrication steps are also similar to the previous mock-up as summarized in the following:
**DSCu/SS HIP**

1) Machining of DSCu and SS parts including semi-circular grooves to mate with the coolant tubes, and bending of SS tubes
   - Roughness of the surface to be HIP-bonded: $R_{\text{max}} \leq 1.6 \ \mu\text{m}$

2) Degassing the DSCu parts by heating up to 800 °C for 2 hours with evacuation down to $1 \times 10^{-5}$ Torr

3) Cleaning the surfaces to be HIP-bonded by acetone

4) Assembling and canning of the DSCu and SS parts, and coolant tubes
   - Canning material: thin plate of SS304
   - DSCu parts and SS coolant tubes, DSCu and SS parts on the way of assembling are shown in Fig. 3-24 and 3-25, respectively.

5) Pressure test at 0.49 MPa for 20 minutes, He leak test and seal welds penetrant testing of the canned assembly

6) Degassing of the assembly internals by heating up to 500 °C with evacuation down to $1 \times 10^{-5}$ Torr

7) Pinching, seal welding and penetrant testing of the evacuation pipe

8) HIP treatment at 1050 °C and 150 MPa for 2 hours

9) Cutting and penetrant testing of the root of the pinched evacuation pipe

10) Machining for eliminating the canning plates, drilling of coolant channels and preparing coolant headers in SS backing plate

11) Welding of header cover plates and plugs

12) Final machining including finishing of DSCu surface

13) Welding of coolant supply/return pipes and penetrant test of the welds including those in step 11

14) Pressure test at 6 MPa for 0.5 hour
15) He leak test
- leak rate: $\leq 1 \times 10^{-7}$ Torr•liter/sec

![Fig. 3-24 DSCu parts to be assembled](image1)

![Fig. 3-25 SS tubes, DSCu heat sink and SS backing plate on the way of assembly](image2)

**Be/DSCu HIP**
16) Machining of Be blocks to be HIP-bonded onto DSCu
- Prepared block size for assembly (Fig. 3-26)
  - 49.5 mm x 73.8 mm x 10.7 mm$^3$ for curved block
  - 99 mm x 63.5 mm x 10.7 mm$^3$ for flat block
17) PVD coating on DSCu
- Figure 3-27 shows the appearance after PVD coating on DSCu. Measured coating thickness was within the range from 22.5 $\mu$m in the curved region to 32.6 $\mu$m near the end of flat region. The intention to secure the target thickness in the curved region where the coated thickness was reduced in the fabrication of the previous mock-up resulted in the thicker coating above.
18) Assembling the VPS-coated Be blocks, Al (containing Mg and Si) foil and the PVD-coated DSCu/SS structure
19) Canning of the assembly by thin SS304 plates and their seal welding
20) Pressure test, He leak test and degassing of the assembly internals with heating up to 450 °C for 2 hours and evacuation down to $1 \times 10^{-5}$ Torr
21) Pinching, seal welding and penetrant testing of the evacuation pipe
22) HIP treatment at 620 °C and 150 MPa for 2 hours and post-heat treatment at 425 °C for 4 hours
   - The canned and instrumented (with thermocouple) assembly is shown in Fig. 3-28.
23) Cutting and penetrant testing at the root of the pinched evacuation pipe
24) Machining for eliminating the canning plates and finishing the outward shape of the mock-up
25) Castellation and slotting by means of electrical discharge machining (EDM) in the following order:
   i) Be armor castellation in the direction perpendicular to the FW coolant tube (toroidal direction in the ITER FW) by wire EDM
   ii) Be armor castellation in the direction parallel to the FW coolant tube (poloidal direction in the ITER FW) by EDM with shaped-Cu plate
   iii) Be/DSCu/SS slotting in the direction perpendicular to the FW coolant tube (toroidal direction in the ITER FW) by wire EDM
   - Castellation process by EDM with shaped-Cu plate was shown in Fig. 3-29.
   - Methods applied for the castellation and slotting are summarized in Fig. 3-30.
26) Wet honing for surface cleaning

   The appearance of the fabricated Be/DSCu/SS mock-up with FW coolant tubes embedded within DSCu is shown in Fig. 3-31. The fabrication was successful, which can be resulted in demonstrating the feasibility of manufacturing the structure relevant to the ITER FW including the built-in coolant tubes, Be armor bonding even on the curved DSCu and the castellation and slotting. As for the castellation and slotting, EDM was consequently the most convenient taking the presently available facility. The end mill and even the water jet might be applicable by the modification of the facility to handle Be though it might be costly. For further investigation, thermo-mechanical testing of the fabricated mock-up and demonstration of larger scale (dimensions) mock-up, e.g., to optimize the initial Be block size and to show the feasibility to fabricate the FW panel with the support beam, would be remained.
a) curved Be block

b) flat Be block

Fig. 3-26 Prepared Be blocks for HIP assembly

Fig. 3-27 PVD-Cu coated DSCu/SS structure

Fig. 3-28 Canned and instrumented assembly in HIP basket (before HIP)
Fig. 3-29 castellation by EDM with shaped-Cu plate

Fig. 3-30 Methods applied to castellation and slotting
3.4 Conclusions of this section

A series of mock-up fabrication was performed to investigate the methods of the castellation and slotting of the Be/DSCu/SS FW panel and the massive SS shield block including the confirmation on the HIP bondability of Be armor onto the DSCu heat sink. Through the investigation, the following conclusions were derived:

1) The HIP-bonded Be/DSCu/SS mock-up without coolant tubes was successfully fabricated with DSCu/SS HIP at 1050 °C under 150 MPa for 2 hours and succeeding Be/DSCu HIP at 555 °C under 150 MPa for 2 hours.
2) For the Be/DSCu HIP, the interlayer composed of VPS-Al (on Be), Al foil and PVD-Al/PVD-Ti/PVD-Cu (on DSCu) worked well for the bonding though the optimization of
Mg and Si contents in the Al foil would be required.

3) The HIP-bonded Be/DSCu/SS mock-up with FW coolant tubes embedded within DSCu was also successfully fabricated with the same HIP conditions for DSCu/SS but HIP conditions at 620 °C under 150 MPa for 2 hours for Be/DSCu.

4) For the Be/DSCu HIP of the latter mock-up, the interlayer of PVD-Cu on DSCu was applied. Though this interlayer had shown lower mechanical strength and lower thermal fatigue durability than the interlayer applied to the former mock-up, the strength would be enough for the application to the FW. This should be confirmed by further testing including thermo-mechanical test of the fabricated mock-up.

5) Castellation and slotting of Be/DSCu/SS FW mock-up was mainly performed by electrical discharge machining (EDM) either with wire or shaped-Cu plate. End mill was also applied to the castellation of Be armor. Consequently, EDM revealed to be presently the most convenient method for the castellation and slotting. Dry cutting, e.g., by end mill or circular saw, took long time for machining, and then it might not be so cost-effective. Cutting with fluid including water jet could be also applied, but it needs facility modification to handle Be, that might be costly.

6) For further investigation of Be/DSCu/SS FW, above-mentioned thermo-mechanical testing of the mock-up with coolant tubes and the fabrication of larger mock-up to demonstrate the feasibility for the FW panel with the support beam would be remained.

7) For SS shield block, basic applicability of water jet gouging was shown.

8) The slot width gouged by water jet was kept well within the range 1.25-2.4 mm.

9) The gouged surface revealed wavy pattern with the roughness (Rmax) of 33-102 μm.

10) Further investigation required for the water jet gouging are accommodation to the uncut region due to the delay distance, examination of the effects and/or reduction of the wavy gouged surface, and possibility on the reduction of the bottom hole diameter.
4. Fabrication of shielding blanket mock-up with the first wall

4.1 Design of shielding blanket mock-up with the first wall

Figure 4.1-1 shows the design of FW panel mockup, which is dedicated to show feasibility of full scale SS/DSCu HIP joining technique in real scale FW panel. Figure 4.1-2 shows the shielding blanket mockup with full scale FW panel mockup. Figure 4.1-3 to 4.1-5 shows the detailed fabrication steps of each fabrication processes with important control values. Important fabrication steps are,

(1) HIP of DSCu/SS of FW
(2) Slit grooving of the FW panel

These critical fabrication conditions and parameters were researched in the fabrication of the partial first wall mockup in chapter 1 of subtask 1 in this task (T420-1). Also, the condition of the most important fabrication step, HIP process for DSCu/SS of FW panel, was also optimized in subtask 2 of this task (T420-1). The major objective of "the fabrication of the shielding blanket mockup with the first wall" is to demonstrate the basic feasibility of the real scale first wall panel with clarified conditions and technique until now.
Fig. 4.1-1  Design of shielding blanket FW panel mockup

Fig. 4.1-2  Sketch of shielding blanket mockup with the first wall
Fig. 4.1-3 Fabrication procedure before HIP of DSCu/SS of first wall mockup

Fig. 4.1-4 Fabrication procedure of HIP process of DSCu/SS of first wall mockup
Fig. 4.1-5 Fabrication procedure of post-HIP process of DSCu/SS of first wall mockup
4.2 Fabrication Process

Figures 4.2-1 to 4.2-7 show the photograph of the mockup after major critical fabrication process. Figure 4.2-1 shows DSCu material plates preparation for FW, including shearing of raw material plates and machining of clad. Figure 4.2-2 shows SS316L material preparation for FW. Figure 4.2-3 shows grooving of DSCu plate for setting the FW cooling channel SS tubes. Figure 4.2-4 shows surface finish of SS basement of FW panel for HIP process. Figure 4.2-5 shows completed status of de-canning and machining after DSCu/SS HIP process. Figure 4.2-6 shows machining of upper and lower FW headers from SS basement side. Figure 4.2-7 shows the process of finish polish of the rear side of the FW panel before EB welding of the support leg. Figure 4.2-8 shows the "tab" welding at the upper and lower edges of FW panel, after header plug welding, before slit grooving and EB welding of support leg. Deformation was suspected because of the residual stress after welding of header plugs at the edges of the FW. By this tabs, the deformation during the slit grooving and the EB welding of the support legs were avoided. Figure 4.2-9 shows the status just after EB welding. EB welding of the support leg was performed with assistance parts to avoid deformation of the leg. Figure 4.2-10 shows the final photograph of full scale FW panel after fabrication completed.
Fig. 4.2-1  DSCu material plates preparation for FW (shearing and machining of clad)

Fig. 4.2-2  SS316L material preparation for FW
Fig. 4.2-3  Grooving of DSCu plate for setting the FW cooling channel SS tubes

Fig. 4.2-4  Surface finish of SS basement of FW panel for HIP process
Fig. 4.2-5 Decanning and machining completed after DSCu/SS HIP process

Fig. 4.2-6 Machining of Upper and lower FW headers from SS basement side
Fig. 4.2-7  Finish polish of the rear side of the FW panel before EB welding of the support leg

Fig 4.2-8  Tab welding at the upper and lower edges of FW panel, after header plug welding, before slit grooving and EB welding of support leg
Fig. 4.2-9  EB welding was completed with assistance parts

Fig. 4.2-10  Completion of fabrication of full scale FW panel
4.3 Inspections and destructive examinations

In the course of the fabrication progress, important critical processes of fabrication have been inspected to control the soundness of fabrication. For this purpose, various inspections were performed, such as material check, surface roughness measurement, and HIP process control. The most critical point is HIP condition control, deformation by heat treatment of HIP process and destructive tests as the post fabrication test. After HIP process, the edge part of the FW panel was sampled for destructive testing to examine the soundness of HIP process. By destructive tests, metallurgical evaluation was performed.

4.3.1 Fabrication process control

Material
DSCu

As the heat sink material, DSCu GlidCop AL25 was used. The material of DSCu was purchased from OMG. Table 4.3-1 sows the material data sheet.

<table>
<thead>
<tr>
<th>Table 4.3-1 Material data sheet of DSCu</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOT number</td>
</tr>
<tr>
<td>Heat number</td>
</tr>
<tr>
<td>Dimension</td>
</tr>
<tr>
<td>Chemical composition</td>
</tr>
<tr>
<td>Copper</td>
</tr>
<tr>
<td>Aluminum</td>
</tr>
<tr>
<td>Iron</td>
</tr>
<tr>
<td>Lead</td>
</tr>
<tr>
<td>Boron</td>
</tr>
<tr>
<td>Mechanical properties</td>
</tr>
<tr>
<td>UTS</td>
</tr>
<tr>
<td>YS</td>
</tr>
<tr>
<td>Elongation</td>
</tr>
<tr>
<td>Apparent hardness</td>
</tr>
<tr>
<td>Conductivity</td>
</tr>
</tbody>
</table>

Stainless steel

For the base plate of the FW, stainless steel SUS 316L was used. SUS 316L was manufactured by NKK corporation. Table 4.3-2 shows chemical composition of the raw material.
Table 4.3-2 Material mill sheet of SUS 316L

<table>
<thead>
<tr>
<th>Chemical composition</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>balance</td>
</tr>
<tr>
<td>C</td>
<td>0.006%</td>
</tr>
<tr>
<td>Si</td>
<td>0.006%</td>
</tr>
<tr>
<td>Mn</td>
<td>0.008%</td>
</tr>
<tr>
<td>P</td>
<td>0.0003%</td>
</tr>
<tr>
<td>S</td>
<td>0</td>
</tr>
<tr>
<td>Ni</td>
<td>12.26%</td>
</tr>
<tr>
<td>Cr</td>
<td>17.37%</td>
</tr>
<tr>
<td>Mo</td>
<td>2.09%</td>
</tr>
</tbody>
</table>

Surface roughness finish of HIP boundary before HIP

As the preparation of HIP process, surface machining is the most important. Table 4.3-3 summarizes the final surface roughness of the HIP interfaces. The measured surface roughness was within the range of smaller than 3 μm.

Table 4.3-3 Surface roughness on the HIP interface surfaces

<table>
<thead>
<tr>
<th>Location</th>
<th>Measured values (μm)</th>
<th>average (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper DSCu</td>
<td>3.0 3.0 2.8 2.6 2.6 2.6</td>
<td>2.77</td>
</tr>
<tr>
<td>Lower DSCu (a)</td>
<td>3.0 2.8 2.6 2.6</td>
<td>2.75</td>
</tr>
<tr>
<td>Lower DSCu (b)</td>
<td>2.8 2.8 3.0 2.8</td>
<td>2.85</td>
</tr>
<tr>
<td>Lower DSCu (c)</td>
<td>2.6 2.6 3.0 3.0</td>
<td>2.8</td>
</tr>
<tr>
<td>DSCu bent</td>
<td>2.8 2.8 3.0 2.8 3.0 2.8</td>
<td>2.87</td>
</tr>
<tr>
<td>SS base plate</td>
<td>1.8 2.0 2.0 1.8</td>
<td>1.9</td>
</tr>
<tr>
<td>SS pipe</td>
<td>2.0 2.0 1.8 2.0 2.0 1.8</td>
<td>1.93</td>
</tr>
</tbody>
</table>

HIP temperature and pressure control

In the course of Be HIP process, the temperature and the pressure in the HIP furnace was controlled to 1050 ± 10 °C and 1500 ± 10 kgf/cm². Figure 4.3-1 shows the record of a representative temperature of the mockup in HIP process (not the control history). As can be seen from this figure, control was successfully achieved.
4.3.2 Destructive tests

Destructive tests consists of six kinds of tests, dimension measurement of the SS cooling channels, macroscopic observation, optical micro-graph observation, SEM observation, EPMA analysis and material hardness measurement. Test pieces of the destructive tests were sampled from a part of the FW panel mockup marked in Fig. 4.3-2. Figure 4.3-3 shows the location of the test pieces sampled from the part shown in Fig 4.3-2. In Fig. 4.3-3, TP numberings are given. Table 4.3-4 shows the list of the TP number and tests. Figure 4.3-4 shows the photographs of sampled test pieces in this work.

<table>
<thead>
<tr>
<th>Test content</th>
<th>TP #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension measurement</td>
<td>#1 to #5, #7 to #14</td>
</tr>
<tr>
<td>Macroscopic observation</td>
<td>all TP cross section of channel</td>
</tr>
<tr>
<td>Microscopic observation</td>
<td>#1 to #6 at all HIP joints</td>
</tr>
<tr>
<td>SEM observation</td>
<td>#1, #2, #5, #6 at all HIP joints</td>
</tr>
<tr>
<td>EPMA analysis</td>
<td>#2 at all HIP joints</td>
</tr>
<tr>
<td>Hardness measurement</td>
<td>#1 and #2 at all HIP joints</td>
</tr>
</tbody>
</table>
Fig. 4.3-2  Location of the sample part of destructive tests
Fig. 4.3-3 Location of test piece sampling
Fig. 4.3-4  Test pieces sampled in this work

a) Dimension measurement of the SS cooling channels

Table 4.3-5 shows the measured results. As can be seen from the table, the bent part of the SS cooling channel tubes at upper and lower edge of the FW, the tube dimensions tends to deviate in such ways as the horizontal diameter become larger and vertical diameter smaller. On the other hand, the dimension of measured in straight parts didn't show clear dependency.
Table 4.3-5  Measured value of dimension of the SS cooling channels
(measured by universal projector in x 10)

<table>
<thead>
<tr>
<th>TP #</th>
<th>inner diameters</th>
<th>outer diameters</th>
<th>distance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a</td>
<td>b</td>
<td>a'</td>
</tr>
<tr>
<td>1</td>
<td>left</td>
<td>10.5</td>
<td>11.55</td>
</tr>
<tr>
<td></td>
<td>right</td>
<td>11.57</td>
<td>11.56</td>
</tr>
<tr>
<td>2</td>
<td>left</td>
<td>10.09</td>
<td>10.29</td>
</tr>
<tr>
<td></td>
<td>right</td>
<td>10.29</td>
<td>10.5</td>
</tr>
<tr>
<td>3</td>
<td>left</td>
<td>9.96</td>
<td>10.23</td>
</tr>
<tr>
<td></td>
<td>right</td>
<td>10.27</td>
<td>10.58</td>
</tr>
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<td>4</td>
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<td>10.05</td>
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<td>10.24</td>
<td>10.68</td>
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<td>10.07</td>
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</tr>
<tr>
<td></td>
<td>right</td>
<td>11.52</td>
<td>10.55</td>
</tr>
<tr>
<td>8</td>
<td>left</td>
<td>10.04</td>
<td>10.32</td>
</tr>
<tr>
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<td>11.31</td>
<td>11.39</td>
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</table>

For locations of dimensions, refer the following figure.

![Diagram](image)

b) Macroscopic Observation

Figure 4.3-5 shows typical macroscopic photograph of TP 1, 2 and 6. No visible failure was observed in any test pieces.
(a) TP1

(b) TP2

(c) TP6

Fig. 4.3-5 Typical macroscopic observation (TP 1, 2 and 6)
c) Optical Micro-graph Observation

Optical observation was performed to show the soundness of all combinations of HIP joints (DSCu/SS tube, DSCu/SS base, SS base/SS tube). Figure 4.3-6 shows the typical microscopic photograph of TP1, 2 and 5. As can be seen from this figure, sound joining is obtained even at the rounded part of the front access holes or upper and lower headers, including the TIG welded part between SS tubes and SS base.

Fig. 4.3-6  Example of microscopic photograph (TP1, 2 and 6)
d) SEM/EPMA Observation

SEM observation and EPMA analysis were performed to verify the chemical species distribution near HIP joint. Figure 4.3-7 (a), (b) and 4.3-8 (a), (b) show typical results of SEM observation and EPMA analyses. In EPMA analysis, O, Al, and Cu, Cr and Fe were analyzed. The distribution showed the typical chemical form for DSCu/SS joint.

Fig. 4.3-7 (a)  SEM image of the HIP joint of TP2 in different enlargement

Fig. 4.3-7 (b)  SEM image of TP6 in 3 different enlargement
Fig. 4.3.8 (a) EPMA analysis result of TP 2
Fig. 4.3.8 (b)  EPMA analysis result of TP 6
e) Hardness Measurement

Table 4.3-6 shows the obtained bending strength. Measurements were performed in room temperature. The value of hardness were almost the same as the typical values for both of HIP-boinded DSCu and SS parts.

<table>
<thead>
<tr>
<th>Material</th>
<th>Distance from HIP interface</th>
<th>Hardness [HV] (Load=2492 mN)</th>
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</thead>
<tbody>
<tr>
<td>SS tube</td>
<td>-0.8</td>
<td>160</td>
</tr>
<tr>
<td>SS tube</td>
<td>-0.6</td>
<td>156</td>
</tr>
<tr>
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<td>158</td>
</tr>
<tr>
<td>SS tube</td>
<td>-0.2</td>
<td>166</td>
</tr>
<tr>
<td>DSCu</td>
<td>0.5</td>
<td>123</td>
</tr>
<tr>
<td>DSCu</td>
<td>1.5</td>
<td>123</td>
</tr>
<tr>
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<td>127</td>
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<td>125</td>
</tr>
<tr>
<td>DSCu</td>
<td>5.5</td>
<td>126</td>
</tr>
</tbody>
</table>

Measurement location is as follow:

![Diagram of DSCu/SS HIP interface part]
4.4 Conclusions of this section

The fabrication technique of the shielding blanket mock-up with the first wall mockup was demonstrated in this work from the aspect of the following issues by HIP condition control, and destructive tests including coolant channel dimension measurement, macroscopic observation, optical micro-graph observation, SEM observation, EPMA analysis and hardness measurement.

1) Feasibility of HIP joining in the curvature around top and bottom and front access holes of the real scale FW panel.
2) Soundness of HIP joining between DSCu heat sink and SS coolant tubes and SS base.
3) Dimension control between coolant channels and the diameters of the coolant channels
4) Demonstration of EB welding of the support leg
5. Conclusions

The achievement in this work can be concluded as follows.

1) The HIP-bonded Be/DSCu/SS mock-up without coolant tubes was successfully fabricated with DSCu/SS HIP at 1050 °C under 150 MPa for 2 hours and succeeding Be/DSCu HIP at 555 °C under 150 MPa for 2 hours, or at 620 °C under 150 MPa for 2 hours by using different interlayer treatment.

2) Castellation and slotting of Be/DSCu/SS FW mock-up was mainly performed by electrical discharge machining (EDM) either with wire or shaped-Cu plate. End mill method was also applied to the castellation of Be armor. Consequently, EDM revealed to be presently the most convenient method for the castellation and slotting. Dry cutting method, e.g., by end mill or circular saw method, took long time for machining, and then it might not be so cost-effective. Cutting with fluid including water jet could be also applied, but it needs facility modification to handle Be, that might be costly.

3) For SS shield block, basic applicability of water jet gouging was shown with the slot width within the range 1.25-2.4 mm with the roughness (Rmax) of 33-102 μm.

4) The fabrication technique of the shielding blanket mock-up with the first wall mockup was demonstrated in this work from the aspect of the following issues by HIP condition control, and destructive tests including coolant channel dimension measurement, macroscopic observation, optical micro-graph observation, SEM observation, EPMA analysis and hardness measurement.
Acknowledgement

The authors wish to express sincere appreciation to Dr. Masahiro Seki, Dr. Hideyuki Takatsu and Dr. Shogo Seki for their continuous encouragement. Also, the authors wish to express special gratitude to Dr. Kimihiro Ioki and Dr. Antonio Cardella of ITER JCT for their guidance of R&D items. The authors acknowledge the tremendous contributions by Kawasaki Heavy Industries, Ltd. and NGK Insulators, Ltd. to accomplish this work.

References

国際単位系 (SI) と換算表

### 表1 SI基本単位および補助単位

<table>
<thead>
<tr>
<th>量</th>
<th>名称</th>
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<td>長さ</td>
<td>メートル</td>
<td>m</td>
</tr>
<tr>
<td>質量</td>
<td>キログラム</td>
<td>kg</td>
</tr>
<tr>
<td>時間</td>
<td>秒</td>
<td>s</td>
</tr>
<tr>
<td>電気</td>
<td>アンペア</td>
<td>A</td>
</tr>
<tr>
<td>電気強度</td>
<td>ケルビン</td>
<td>K</td>
</tr>
<tr>
<td>物質量</td>
<td>モル</td>
<td>mol</td>
</tr>
<tr>
<td>光度</td>
<td>キラルデルタ</td>
<td>cd</td>
</tr>
<tr>
<td>平面角</td>
<td>ラジアン</td>
<td>rad</td>
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<tr>
<td>立体角</td>
<td>ステラジアン</td>
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### 表2 SIと併用される単位

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<thead>
<tr>
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<th>名称</th>
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</tr>
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<tbody>
<tr>
<td>分、時、日</td>
<td>min、h、d</td>
<td></td>
</tr>
<tr>
<td>度、分、秒</td>
<td>°、′、″</td>
<td></td>
</tr>
<tr>
<td>リットル</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>トン</td>
<td>t</td>
<td></td>
</tr>
<tr>
<td>電子ボルト</td>
<td>eV</td>
<td></td>
</tr>
<tr>
<td>原子質量単位</td>
<td>u</td>
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</tr>
</tbody>
</table>

1 eV = 1.60218 × 10^-19 J
1 u = 1.66056 × 10^-27 kg

### 表3 固有の名称をもつSI補助単位

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<thead>
<tr>
<th>量</th>
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<th>記号</th>
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<td>周波数</td>
<td>ヘロツ</td>
<td>Hz</td>
</tr>
<tr>
<td>压力、応力</td>
<td>ニュートン</td>
<td>N</td>
</tr>
<tr>
<td>エネルギー、仕事、熱量</td>
<td>ジョール</td>
<td>J</td>
</tr>
<tr>
<td>工率</td>
<td>ワット</td>
<td>W</td>
</tr>
<tr>
<td>電気量、電荷</td>
<td>クローノン</td>
<td>C</td>
</tr>
<tr>
<td>電位、起電力</td>
<td>ボルト</td>
<td>V</td>
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<td>静電容量</td>
<td>ファラド</td>
<td>F</td>
</tr>
<tr>
<td>電気抵抗</td>
<td>オーム</td>
<td>Ω</td>
</tr>
<tr>
<td>コンダクタンス</td>
<td>ジーメンス</td>
<td>S</td>
</tr>
<tr>
<td>磁束</td>
<td>ワブ</td>
<td>Wb</td>
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<td>チュリガラム</td>
<td>T</td>
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<td>インダクタンス</td>
<td>ヘンリー</td>
<td>H</td>
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<td>セルシウス度</td>
<td>°C</td>
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<td>ルーゲン</td>
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<td>イクス</td>
<td>m/s</td>
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<tr>
<td>放射能</td>
<td>ベクレル</td>
<td>Bq</td>
</tr>
<tr>
<td>吸収線量</td>
<td>グレイ</td>
<td>Gy</td>
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<tr>
<td>線量当量</td>
<td>シーベルト</td>
<td>Sv</td>
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### 表4 SI単位をもとに慣用的に導入される単位

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<td>パー</td>
<td>b</td>
<td></td>
</tr>
<tr>
<td>ガル</td>
<td>G</td>
<td></td>
</tr>
<tr>
<td>キュリ</td>
<td>Ci</td>
<td></td>
</tr>
<tr>
<td>レントゲン</td>
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<td></td>
</tr>
<tr>
<td>レム</td>
<td>rem</td>
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</tbody>
</table>

1 A = 0.1 nm = 10^-9 m
1 b = 100 fm = 10^-14 m
1 bar = 0.1 MPa = 10^5 Pa
1 Gy = 1 cm = 10^-2 m^3
1 Ci = 3.7 × 10^10 Bq
1 R = 2.58 × 10^-2 C/kg
1 rad = 1 cGy = 10^2 Gy
1 rem = 1 cSv = 10^2 Sv

### 単位換算表

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<tr>
<th>量</th>
<th>MPa = 10 bar</th>
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<th>mmHg (Torr)</th>
<th>lbf/in² (psig)</th>
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### 質量

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### 積分

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<tr>
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<th>J(10⁶ erg)</th>
<th>kgf.m</th>
<th>kW.h</th>
<th>cal(計量法)</th>
<th>Btu</th>
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### 放射能

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### 電気

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<td>rem</td>
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(86年12月26日現在)