FABRICATION AND TESTING OF SMALL SCALE MOCK-UPS
OF ITER SHIELDING BLANKET

December 1998

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Fabrication and Testing of Small Scale Mock-ups of ITER Shielding Blanket

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(Received November 18, 1998)

Small scale mock-ups of the primary first wall, the baffle first wall, the shield block and a partial model for the edge of the primary first wall module were designed and fabricated incorporating most of the key design features of the ITER shielding blanket. All mock-ups featured the DSCu heat sink, the built-in SS coolant tubes within the heat sink and the SS shield block. CFC tiles was used as the protection armor for the baffle first wall mock-up. The small scale shield block mock-up, integrated with the first wall, was designed to have a poloidal curvature specified in the ITER design.

Fabrication routes of mock-ups were decided based on the single step solid HIP of DSCu/DSCu, DSCu/SS and SS/SS reflecting the results of previous joining techniques development and testing. For attaching the CFC tiles onto DSCu heat sink in the fabrication of the baffle first wall mock-up, a two-step brazing was tried. All mock-ups and the partial model were successfully fabricated with a satisfactory dimensional accuracy.

The small scale primary first wall mock-up was thermo-mechanically tested under high heat fluxes of 5-7 MW/m² for 2500 cycles in total. Satisfactory heat removal performance and integrity of the mock-up against cyclic high heat flux loads were confirmed by measurement during the tests and destructive examination after the tests. Similar high heat flux tests were also performed with the small scale baffle first wall mock-up under 5-10 MW/m² for 4500 cycles in total resulting in sufficient heat removal.

+ Office of ITER Project Promotion
capability and integrity confirmed by measurements during the tests.

Keywords: ITER, Shielding Blanket, First Wall, Small Scale Mock-up, HIP, Brazing, Thermal Cycle Test
ITER遮蔽ブランケット小型モックアップの製作と試験

日本原子力研究所那珂研究所核融合工学部

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黒田 敏公・渡辺 幹男・高津 英幸*・小原 祥裕

(1998年11月18日受理)

ITER遮蔽ブランケットの製作性を確認すると共に実負荷試験による特性評価を行うことを目的として、一般第一壁及びパッフル第一壁、遮蔽ブロックと第一壁端コーナー部の小型モックアップを作製した。これらモックアップはITERでの設計に基づいて、鋼合金の熟シンクにステンレス鋼の冷却管を内蔵し、その背後にステンレス鋼の遮蔽体が配置される構造とした。また、遮蔽ブロックモックアップは第一壁と一体型であり、横断方向に曲曲する構造とした。これらのモックアップは、従来より実施してきた接合技術開発の成果を反映し、鋼合金／鋼合金、鋼合金／ステンレス鋼、ステンレス鋼／ステンレス鋼を同時に接合する熱間加圧（HIP）法を用いて製作した。この基材部のHIP接合に加え、パッフル第一壁では鋼合金の熟シンク上にアーマータイプとして炭素繊維複合材を一定厚付を適用して接合した。いずれのモックアップも精度良く製作することができ、モックアップ端部の破壊観察から健全な接合が得られていることを確認した。モックアップの熱機械的性能を評価するため一般第一壁とパッフル第一壁モックアップを用いて高温負荷試験を行った。一般第一壁モックアップでは熱負荷5〜7MW/m²で2500サイクル、パッフルでは熱負荷5〜10MW/m²で4500サイクルの試験を行い、いずれも熱解析により予想した除熱性能と良い一致を示すと共に、サイクル試験中の除熱性能劣化は観察されなかった。試験後の金相観察においてモックアップ内部にき裂などの欠陥は見られず、製作した構造体の健全性を確認した。
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1. Introduction

During the Basic Performance Phase, the ITER blanket will be comprised of integrated first wall/shield modules supported on a back plate that has structural shell. Blanket modules can be replaced with modules with a function of breeding for the Enhanced Performance Phase. A cross section of the ITER is shown in Fig. 1 and main parameters of the blanket are summarized in Table 1.1.

Table 1 Parameters of the blanket system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Flux, Average (Max.)</td>
<td>0.25 (0.5) MW/m²</td>
</tr>
<tr>
<td>Limiter</td>
<td>~2.4 (~5) MW/m²</td>
</tr>
<tr>
<td>Baffle</td>
<td>~1 (~3) MW/m²</td>
</tr>
<tr>
<td>Neutron Wall Loading</td>
<td>2</td>
</tr>
<tr>
<td>Average Neutron Fluence</td>
<td>0.92 (1.2) MW/m²</td>
</tr>
<tr>
<td>Number of Blanket Module</td>
<td>520/120/100</td>
</tr>
<tr>
<td>First Wall Materials</td>
<td></td>
</tr>
<tr>
<td>Plasma Facing Material</td>
<td>Be</td>
</tr>
<tr>
<td>Limiter</td>
<td>Be or CFC</td>
</tr>
<tr>
<td>Baffle</td>
<td>Be or CFC (upper), W (lower)</td>
</tr>
<tr>
<td>Heat Sink</td>
<td>Copper alloy</td>
</tr>
<tr>
<td>Cooling Tube</td>
<td>316LN</td>
</tr>
<tr>
<td>Coolant Conditions</td>
<td></td>
</tr>
<tr>
<td>Coolant</td>
<td>Water</td>
</tr>
<tr>
<td>Inlet Pressure/Temperature</td>
<td>4 MPa/140 °C</td>
</tr>
<tr>
<td>Normal ΔT/ΔP/Flow rate</td>
<td></td>
</tr>
<tr>
<td>PM &amp; Inboard Baffle</td>
<td>51 °C/0.5 MPa/6,700 kg</td>
</tr>
<tr>
<td>Outboard Baffle &amp; Limiter</td>
<td>34 °C/0.7 MPa/3,500 kg</td>
</tr>
</tbody>
</table>

Each blanket module will be integrated structure of a first wall and a shield part, which are provided by 740 modules. The cross section of the module at the inboard mid plane is shown in Fig. 1.2. Blanket modules are distinguished three type of modules including of primary module, limiter and baffle, by a function of first wall. The first wall of the primary module shown in Fig. 1.3 is a layered assembly of 10 mm thick Be armor and 20 mm thick copper alloy heat sink with built-in stainless steel (SS) cooling tubes of 10 mm inner diameter and 1 mm thick. For the limiters and baffles, ~0.2 mm thick, will be used in place of SS. Bird view of a baffle module which is similar to the primary module is shown in Fig. 1.4. The plasma facing material for the primary modules will be beryllium (Be). Be is also considered as the primary candidate material for the limiters. However, carbon fiber composite (CFC) is being considered as an alternate. Tungsten will be used in the lower baffle region subject to high erosion.
Small scale primary first wall and baffle module mock-ups have been fabricated and tested aiming at conforming the fabrication technology and qualifying the fabricated dispersion strengthened copper (DSCu)/SS structure for ITER operation conditions. The aim of the shield block fabrication is also to qualify the manufacturing techniques of the curved shield block with internal coolant channels and the bonding method of the first wall to the shield block.
Fig. 1.1 In-Vessel Components
Fig. 1.2 Cross Section of Inboard Midplane Blanket Module
Fig. 1.3 Detail of Primary First Wall

- Shield
- First Wall

Dimensions:
- Unit: mm

Materials:
- Beryllium
- Copper
- Stainless Steel
- SS-Tube

Dimensions:
- 1
- 22
- 11
- 10
- 20
- 24

Symbols:
- φ12
- φ10
2. Design of Mock-ups

2.1 Primary First Wall Mock-up

The design of the small scale primary first wall mock-up was developed based on the shielding blanket design in ITER [1]. A cut-away-view and a detailed drawing of the mock-up are shown in Figs. 2.1.1 and 2.1.2, respectively. The principal design features are as follows:

a) Flat shape with 20 mm thick DSCu (GlidCop® AL-25) heat sink, 20 mm thick SS316L end plates, and 7 mm thick SS316L backing plate
b) Six SS316L circular tubes, 1 mm thick and 10 mm in inner diameter, embedded within the DSCu heat sink and SS316L and plates
c) Minimum DSCu thickness of 5 mm from the surface to the SS316L coolant tube
d) Coolant tube pitch of 22 mm
e) Overall dimensions of the flat first wall mock-up approximately 130 mm wide, 300 mm long (including 200 mm long DSCu), and 27 mm thick
f) Coolant water inlet/outlet headers and supply/return pipes (SS304) welded at both ends of the first wall mock-up
g) Nine thermocouples attached (Fig. 2.1.3) for measuring temperatures in the mock-up during high heat flux test

This small scale mock-up incorporates the following key features essential to the fabrication technology development relative to the shielding blanket design:

a) Joining of DSCu/DSCu (The DSCu heat sink is divided into two plates with semi-circular grooves to sandwich the SS316L coolant tube. See Section 3.1 for detail.)
b) Joining of DSCu/SS316L (heat sink/coolant tube, heat sink/shield block and heat sink/top and bottom walls: The shield block and the top/bottom wall are simulated by the backing plate and end plates, respectively, in this mock-up fabrication.)
c) Joining of SS316L/SS316L (coolant tube/top and bottom wall)
The mock-up was fabricated in larger size than the above-mentioned overall dimensions for leaving surrounding parts around the test specimen. The surrounding parts are to be cut off and to be destructively examined in terms of HIP bonded interface quality.

Materials used in the present fabrication are basically the same as specified in the shielding blanket design though SS316L instead of SS316LN-IG and GlidCop Al-25 instead of Al-25-IG were used because of the materials availability at this stage.

The only one missing issue, relative to the shielding blanket design, is the joining of Be protection armor to the DSCu surface.
Fig. 2.1.1 A cut-away view of small scale Primary first wall mock-up
Fig. 2.1.2  Detailed drawing of small scale primary first wall mockup.
Fig. 2.1.3 Location of thermocouple attachment.
2.2 Baffle First Wall Mock-up

The design of the small scale baffle first wall mock-up was developed based on the baffle module design in ITER [2]. An isometric view of the mock-up is shown in Fig. 2.2.1. Detailed dimensions of the mock-up are shown in Figs. 2.2.2 and 2.2.3. The principal design features of this mock-up are as follows:

a) L shape simulating the edge (bottom corner) of the outboard lower baffle module

b) DSCu (GlidCop® AL-25) heat sink of 20 mm in thickness behind the protection armor, and 10 mm thick SS316L backing plate behind the DSCu heat sink simulating the shield block

c) Two SS316L circular tubes of 0.5 mm thick and 10 mm in inner diameter, bent with a radius of 40 mm at the corner, embedded within the DSCu heat sink

d) 18 CFC (CX2002U®) protection armor tiles of the size approximately 24 mm x 24 mm x 20 mm thick each attached onto DSCu

e) Overall dimensions of the mock-up approximately 50 mm wide, 500 mm long, and 50 mm thick

f) 0.5 mm thick OFCu base plate introduced as a compliant layer between CFC and DSCu

g) Coolant water inlet/outlet headers and supply/return pipes (SS316L) welded at both ends of the mock-up

h) Eight thermocouples attached for measuring temperatures in the mock-up during high heat flux test

This small scale mock-up incorporates the key design features essential to the fabrication technology development for the baffle first wall. Materials used in the present fabrication are basically the same as specified in the ITER design though SS316L instead of SS316LN-IG and GlidCop Al-25 instead of Al-25-IG were used because of the materials availability at this stage. For the protection armor, 2-DCFC (CX-2002U®) was used.
Fig. 2.2.1 Isometric view of small scale baffle first wall mock-up
Fig. 2.2.2 Detail dimensions of small scale baffle first wall mock-up
Fig. 2.2.3 Cross-section of small scale baffle first wall mock-up
2.3 Shield Block Mock-up

The design of the small scale shield block mock-up was developed based on the shielding blanket design [1] with the following principal design features:

a) Shield block made of a forged SS316L block with 18 drilled coolant channels of 24 mm in diameter each, arranged in two rows, simulating the front part of the shielding blanket module
b) Overall dimensions of the mock-up approximately 400 mm wide x 500 mm high x 150 mm deep
c) Curved module in the poloidal direction with curvatures of 2000 mm at the first wall
d) Integrated first wall composed of DSCu heat sink and SS316L coolant tubes with rectangular cross-section
e) Poloidal cooling channels both for the first wall and the shield block, which are separately connected to individual coolant inlet and outlet headers at the back
f) Coolant water supply/return pipes (SS304) welded to cover plates of inlet/outlet headers at the back of the shield block

The rectangular cross-section of the first wall coolant tube and the separate coolant flow for the first wall and the shield block are different from the design developed in ITER. However, the key design features essential to the fabrication technology development, i.e., the fabricability of the forged SS shield block with drilled coolant channels and the bondability of the DSCu heat sink with the SS coolant tubes and the SS shield block, can be basically examined with this mock-up fabrication. (The fabricability with SS circular coolant tubes for the first wall was examined as a complementary R&D focusing on an edge part of the module. This complementary R&D is described in the next Section.) A cut-away-view and a drawing for the final shape of the mock-up are shown in Figs. 2.3.1 and 2.3.2, respectively.

The shield block is made of a massive forged block of SS316L with 18 internal coolant channels drilled through the block. The arrangement of the coolant channels was decided based on the ITER design to simulate the front two rows in the shield block. A fabrication drawing of the shield block is shown in Fig. 2.3.2. Until finishing the HIPing stage, this shield block has dummy parts at its edges (55 mm wide each from both sides) for the destructive examination as shown in the figure. This part includes the key elements for the fabrication such as coolant tubes embedded within the first wall and the SS316L block with drilled internal coolant channels. These dummy parts were to be cut off and destructively examined in terms
of HIP bonded interface quality, deformation of the internal coolant channels and any change of the metallurgical quality.

Materials used in the present fabrication are basically the same as specified in the design, though SS316L instead of SS316LN-IG and GlidCop Al-25 instead of Al-25-IG were used because of the materials availability at this stage.
Fig. 2.3.1 A cut-away view of small scale shield block mock-up integrated with first wall.
Fig. 2.3.2 Drawing for final shape of small scall shield block mock-up integrated with first wall
Fig. 2.3.3  Fabrication drawing of shield block mock-up
2.4 Partial Model for Edge of Primary First Wall Module

A partial model using SS circular tubes in the first wall was fabricated as a complementary R&D to the small scale shield block fabrication in which rectangular tubes were used. This partial model simulates the edge of the module, as shown in Fig. 2.4.1, focusing on investigating the HIP bondability of the SS circular tube bent by a small radius to the DSCu heat sink and also the DSCu heat sink to the SS shield block. The design of the partial model was developed with the following design features:

a) A SS316L circular coolant tube embedded within 20 mm thick DSCu (GlidCop® AL-25) heat sink at the first wall
b) The SS316L circular tube dimensions of 1 mm thick, 10 mm in inner diameter and bending radius of 31 mm at the tube center
c) SS316L block, approximately 130 mm x 130 mm x 22 mm, having a round corner to which the first wall elements are bonded
d) Overall dimensions of the partial model approximately 150 mm x 150 mm x 22 mm

Materials used in the present fabrication are GlidCop® AL-25 and SS316L instead of Al-25-IG and SS316LN-IG, respectively, specified in the ITER design because of the materials availability at this stage.

The fabricated model was cut into pieces and destructively examined in terms of HIP bonded interface quality and deformation of the coolant tube.
Fig. 2.4.1 Partial model simulating edge of primary first wall module
3. Fabrication of Mock-ups

3.1 Primary First Wall Mock-up

3.1.1 Fabrication Route and Conditions

For fabricating the small scale primary first wall mock-up, a "single step solid HIP" technique was applied. Namely, the SS316L coolant tubes were sandwiched by semi-circular grooved DSCu plates at the heat sink region and SS316L plates at end regions, then they were simultaneously HIPed. A schematic concept of the single step solid HIP is illustrated in Fig. 3.1.1.

Two DSCu plates were machined into 16 mm (front plate) and 9 mm (rear plate) in thickness and semi-circular grooves on one side each. Two SS316L plates for end regions were machined in the same manner. The SS316 backing plate was machined into 12 mm in thickness. A fine machining with a surface finish in the range of 2 μm was performed for the surfaces to be HIPed. The DSCu heat sink, SS316 end and backing plates, and SS316L coolant tubes were all assembled for HIPing. As shown in Fig. 3.1.2, the HIPed assembly was larger in the size than the mock-up designed in Section 2.1 for leaving surrounding parts. After the HIP process, the surrounding parts were cut off along lines A and B shown in the figure and destructively examined in terms of the bondability at HIPed interfaces. The front DSCu and SS316 plates were also machined into 11 mm in thickness, and the SS316L backing plate 7 mm in thickness, by final machining after HIP in order to provide the specified dimensions in the design.

Before assembling for HIP, all of the elements were cleaned by acetone, and furthermore, DSCu plates were pre-baked in a vacuum furnace at the temperature of 800 °C for 2 hours. Then the assembly was canned by TIG seam-welding of thin SS304 plates all around the assembly, and after checking the seam weld by penetrant and He leak tests, the internal of the assembly was baked for degassing. After reaching the internal pressure down to 10^-5 Torr, the evacuation nozzle was sealed, and then HIP treated.

For the HIP conditions, the temperature of 1050 °C, the pressure of 150 MPa and the holding time of 2 hours were applied based on the selection studies of the optimum HIP conditions applicable to the joints combination of SS316/SS316, SS316/DSCu and DSCu/ DSCu [3-7].
After the HIP process, the surrounding parts for destructive examination were cut, the canning was removed, and final machining was performed. Then finally, coolant inlet/outlet headers and supply/return pipes were welded. A number of thermocouples were mounted on the mock-up for temperature measurement during high heat flux tests. A final appearance of the mock-up after all of the fabrication processes is shown in Fig. 3.1.3.

3.1.2 Measurements and Inspections

Deformation due to the HIP process was measured. Surface undulation of the HIPed assembly measured before removing the canning was shown in Fig. 3.1.4. The undulation was very small, i.e., less than 0.3 mm, for this mock-up. After removing the canning and cutting the surrounding parts, diameters of coolant tubes and distances between the coolant tubes were measured. The results are shown in Fig. 3.1.5. The dimensions were precisely kept within -0 mm/+0.01 mm against the nominal design value of 10 mm for tube inner diameter and -0.1 mm/+0 mm against the nominal design value of 12 mm for distance between the coolant channels.

HIPed interfaces were destructively examined with cut pieces of the surrounding parts at locations shown in Fig. 3.1.6. Figures 3.1.7 through 3.1.9 show microscopic images of the SS316L/SS316L, DSCu/SS316L and DSCu/DSCu HIPed interfaces. Neither internal defects nor voids were observed along all of the HIP interfaces, especially even the HIPed interface was not clearly seen for the DSCu/DSCu joint.

From the above results, sufficient HIP bonding features without any voids and large deformation were confirmed. It should be noted that some-μm-thick interlayer between SS316L and DSCu and precipitation of SS316L elements into DSCu were observed as in the screening tests. A sharp intrusion of DSCu into the gap between SS316L plates were observed at the end region as seen in Fig. 3.1.9. Though no internal defects were observed even at this region, the effects of the sharp DSCu intrusion need to be investigated in terms of mechanical integrity of the joint including crack initiation behavior and fatigue strength.

After TIG welding of the coolant inlet/outlet headers and supply/return pipes to the HIPed and machined specimen, non-destructive examination for pressure boundaries were performed. The results of pressure test with water at 4.5 MPa for 30 min, He leak test, penetrant test and radiographic test showed no water leakage and no excessive deformation, He leakage rate below $2.4 \times 10^{-9}$ Torr l/s (undetectable), respectively, for the first and the second tests, no indication of defects for the third and the last tests.
Fig. 3.1.1 Schematic concept of single step HIP for small scale primary first wall mock-up
Fig. 3.1.2 Size of HIPed assembly
Fig. 3.1.3 Appearance of fabricated small scale primary first wall mock-up
Fig. 3.1.4  Surface undulation of HIPed assembly.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
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<th>G</th>
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<tr>
<td>1</td>
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<td>+0.07</td>
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</table>
Fig. 3.1.5  Results of dimensional measurement after HIP
Fig. 3.1.6  Locations for metalurgical observation

- d-d
- c-c
- e-e
- a-a
- b-b
- g-g
- c-c
- e-e
- a-a
- b-b
- g-g

IAERI-TECH 98-058
Fig. 3.1.7  Microscopic image of HIPed interface (along A-A)
Fig. 3.1.8 Microscopic image of HIPed interface (along B-B)
3.2 Baffle First Wall Mock-up

3.2.1 Fabrication Route and Conditions

The fabrication procedure of the small scale baffle first wall mock-up is schematically shown in Figs. 3.2.1 through 3.2.3.

The SS316L coolant tubes were sandwiched by DSCu plates on which semi-circular grooves were machined. The DSCu plates were divided perpendicular to the shield block (SS316 backing plate) surface in this case to investigate better accommodation of the DSCu plates to the bending along the corner of the module. Actually, the semi-circular grooves were machined after the bending of the DSCu plates, and thus no deformation and precise machining of the grooves were realized.

After the DSCu plates, the SS316L coolant tubes and the SS316L backingplate (simulating shield block) were assembled all together and canned by thin SS plates, they were simultaneously HIP bonded at the temperature of 1050 °C, the pressure of 120 MPa and for the holding time of 2 hours. The HIPed assembly was then machined to remove the canning and also to provide the parts for attaching CFC armors and a coolant header.

After the cover plates of the header and coolant supply/return pipes were welded, CFC armors were attached onto the DSCu heat sink. For the attachment of the CFC armor, a two-step brazing technique was utilized. Bonding surface of the porous CFC was filled with Ti-Cu and Cu coating was made onto the surface for being flat. Then, the CFC armor tile was brazed to a 0.5 mm thick OFCu base plate (the first brazing). The set of CFC tile/OFCu base plate was brazed to the DSCu heat sink (the second brazing). The OFCu base plate works as a compliant layer between CFC and DSCu. For both of the first and second brazing, Ag-free brazing materials were used. Namely, the brazing material and conditions for the first brazing were Cu-Mn at 960 °C for 15 minutes, and Al at 675 °C for 43 minutes for the second brazing. The two-step brazing would be advantageous, by brazing a group of CFC tiles to the OFCu base plate in the first brazing, in assembling and attaching the huge number of small tiles onto the module first wall.

3.2.2 Measurements and Inspections
For observation of CFC/OFCu and OFCu/DSCu joints, test samples were fabricated with same materials, fabrication procedure as those of the mock-up. After the brazing, the test samples were cut to examine the joined interface quality as schematically shown in Fig. 3.2.4. The results of metallurgical observation showed no crack and exfoliation as shown in Figs. 3.2.5 and 3.2.6. From these results, it can be concluded that the bondability of the two-step brazing is confirmed.
(1) Combine vertical division heat sink plates and cooling liners

(2) Combine shield block

Fig. 3.2.1 Fabrication procedure of small scale baffle first wall mock-up (1)
Fig. 3.2.2 Fabrication procedure of small scale baffle first wall mock-up (2)
(7) Welding of cooling tubes

Cooling header (SS316L)

Cooling tubes (SS304)

(8) Brazing of armor tiles

Armor (CFC)

Fig. 3.2.3  Fabrication procedure of small scale baffle first wall mock-up (3)
Fig. 3.2.4  Metallurgical observation point
Fig. 3.2.5 Metallurgical observation of brazed joint (edge)
Fig. 3.2.6 Metallurgical observation of brazed joint (center)
3.3 Shield Block Mock-up

3.3.1 Fabrication Route and Conditions

Fabrication process of the small scale shield block mock-up integrated with first wall was grouped into three steps: a) fabrication of the first wall elements, b) fabrication of the shield block, and c) assembly, HIP process, final machining and welding of header cover plates and water supply/return pipes. For HIP process, the "single step solid HIP" technique was applied as for the fabrication of the small scale primary first wall mock-up (Section 3.1). Note that rectangular coolant tubes were used for this mock-up fabrication, and the coolant tubes were not sandwiched by two DSCu plates as in the small scale primary first wall mock-up but sandwiched by DSCu plate and SS316L shield block.

First Wall Elements

The first wall elements consisted of a DSCu plate for heat sink, SS316L top/bottom plates, SS316L rectangular coolant tubes, a thin SS316L liner plate, and a SS316L rear plate. The thin SS316L liner of 0.5 mm in thickness was inserted in-between DSCu plate and rectangular coolant tubes in order to prevent the sharp intrusion of DSCu into the gaps between adjacent coolant tubes. The SS316L rear plate of 10 mm and 15 mm in thickness at front region and top/bottom regions, respectively, was inserted in-between coolant tubes and the shield block, especially for providing rigid cover plates of top/bottom coolant headers.

DSCu plates delivered were machined from 30 mm thickness down to 8 mm thickness to delete the OFCu cladding, and after fine machining with a surface finish in the range of 2 μm for the surface to be HIPed, they were bent to provide the final curved shape.

SS316L rectangular coolant tubes were bent to provide curvature along the first wall (radius of 2000 mm at first wall surface) and along the top/bottom edges of the mock-up (radius of 52 mm at tube center).

SS316L top/bottom plates were machined into 8 mm in thickness. SS316L liner and rear plate were also machined into the thickness specified above. Their surfaces to be HIPed were finished in the range of 2 μm. After the surface finishing, the liner and the rear plate were bent to provide the specified curvature.

The DSCu and SS316L top/bottom plates were machined into 5 mm in thickness during the final machining process after HIP.
**Shield Block**

SS316L forged block delivered was pre-machined, and then drilled from both ends to provide the internal coolant channels. After the drilling process, the shield block was bent by pressing a SS flat plate against the block at the center without any material inserted into the drilled holes as shown in Fig. 3.3.1. Machining of external surface and header regions and welding of thin (3 mm thick) SS316L header cover plates were then followed. These thin cover plates were to realize the bonding of the rigid cover plates (first wall rear plates) by HIPing.

**Assembly and HIP Treatment**

All of the first wall elements were assembled with the shield block into one assembly. Before assembling, all of the elements were cleaned by acetone, and furthermore, DSCu plates were pre-baked in a vacuum furnace at the temperature of 800 °C for 2 hours. An appearance of the assembly before HIPing is shown in Fig. 3.3.2. The assembly gap was 2 mm at maximum between the first wall rear plate and the shield block at the corner from the first wall to the bottom of the mock-up. This assembly was canned by TIG seam-welding of 3-mm-thick SS304 plates almost all around the assembly. After checking the seam weld by penetrant and He leak tests, the internal of the assembly was baked. While the internal pressure was kept down to lower than 10^-5 Torr, the evacuation nozzle was sealed, and then HIP treated.

For the HIP conditions, the temperature of 1050 °C, the pressure of 150 MPa and the holding time of 2 hours were applied based on the selection studies of the optimum HIP conditions applicable to the combinations of SS316/SS316, SS316/DSCu and DSCu/ DSCu [3-7].

After the HIP process, the edge parts for destructive examination were cut, the canning was removed, and final machining including first wall inlet/outlet headers was performed. Then finally, header cover plates and supply/return pipes were welded from the back of the mock-up. A number of temperature measurement during thermocouples were mounted on the mock-up for the purpose of thermo-mechanical testing. A final appearance of the mock-up after all of the fabrication processes is shown in Fig. 3.3.3.

**3.3.2 Inspections**

With pieces cut from the edge of the HIPed assembly, destructive examination was performed. The appearance of the cut piece is shown in Fig. 3.3.4. Figure 3.3.5 shows macroscopic images at various
HIPed interfaces indicated in Fig. 3.3.4. No excessive deformation of the first wall coolant tube and the internal coolant channel of the shield block was observed. Representative observation locations and microscopic images of DSCu/SS316L and SS316L/SS316L HIPed interfaces are also shown in Figs. 3.3.6 and 3.3.7, respectively. Neither internal defects nor voids were observed along these HIP interfaces. Therefore, sufficient HIP bonding features without any voids and large deformation were confirmed.

After TIG welding of the coolant header cover plates and supply/return pipes, non-destructive examination for pressure boundaries were performed. The results of pressure test with water at 4.5 MPa for 30 min, He leak test, penetrant test and radiographic test showed no water leakage and no excessive deformation, He leakage rate below $3.0 \times 10^{-9}$ Torr:L/s (undetectable), respectively, for the first and the second tests, no indication of defects for the third and the last tests.
Fig. 3.3.1 Bending of shield block
Fig. 3.3.2 Assembled small scale shield mock-up with first wall elements
Fig. 3.3.3 Appearance of fabricated small scale shield block mock-up integrated with first wall
A-E: Location of microscopic observation

Fig. 3.3.4 Appearance of cut piece and location of macroscopic observation
Fig. 3.3.5  Macroscopic observation of cut piece.
Fig. 3.3.6 Location of microscopic observation of cut piece.
Fig. 3.3.7 Microscopic image at HIPed interfaces.
3.4 Partial Model for Edge of Primary First Wall Module

3.3.1 Fabrication Route and Conditions

The "single step solid HIP" technique was also applied to fabricate this partial model. Namely, the SS316L coolant tubes were sandwiched by semi-circular grooved DSCu plates, assembled together with the shield block, then they were simultaneously HIPed.

To simulate the first wall corner at the edge of the blanket module, SS316L coolant tubes were bent with a radius of 31 mm at the center. The dimensions of the SS316L tubes were 10 mm in inner diameter and 1 mm in thickness as specified in the ITER design. Three tubes were used in this model fabrication.

Two DSCu plates were machined into 11 mm (front plate) and 9 mm (rear plate) in thickness and semi-circular grooves on one side each. After the machining, two DSCu plates were bent to be along with the specified curvature at the module edge. The diameter of the semi-circular groove was 13 mm, thus 1 mm larger than the outer diameter of the coolant tube, in order to accommodate the deformation of the groove and also the tube due to their bending. Appearance of the bent SS316L tubes and DSCu plates is shown in Fig. 3.4.1.

A SS316L block was machined into 132 mm x 132 mm x 76 mm thick and to have one round corner with a radius of 22 mm in order to simulate the shield block shape at the edge of the blanket module.

A fine machining with a surface finish in the range of 2 μm was performed for the to-be-HIPed surfaces of semi-circular grooved DSCu plates and SS316 shield block. Also before assembling for HIP, all of the elements were cleaned by acetone, and furthermore, DSCu plates were pre-baked in a vacuum furnace at the temperature of 800 °C for 2 hours. Then the DSCu plates, SS316L coolant tubes and SS316L shield block were all assembled, and the assembly was canned by TIG seam-welding of thin SS304 plates all around the assembly. After checking the seam weld by penetrant and He leak tests, the internal of the assembly was baked for degassing until the internal pressure reached down to 10^-5 Torr. Finally the evacuation nozzle was sealed, and HIP treated. Appearance of the assembled DSCu plates, SS316L coolant tubes and SS316L shield block is shown in Fig. 3.4.2.
HIP conditions were the same as the small scale primary first wall mock-up (Section 3.1) and the small scale shield block mock-up (Section 3.3), i.e., the temperature of 1050 °C, the pressure of 150 MPa and the holding time of 2 hours.

After the HIP process, the fabricated model was cut and examined in terms of the deformation of the coolant tubes and the bondability at the HIPed interfaces.

3.4.2 Inspections

Typical examples of the deformation behavior of the coolant tube and microscopic images at HIPed interfaces are shown in Figs. 3.4.3 through 3.4.5. Though a slight deformation in the cross-sectional shape of the coolant tube is observed at the top of the corner (Fig. 3.4.4), this deformation could be allowed in terms of coolant flow characteristics, e.g., deviation of pressure drop, and also a stress concentration in the SS316L coolant tube. In spite of the slight deformation of the coolant tube at the top of the corner, neither internal defects nor voids were observed along all of the HIPed interfaces. Therefore, sufficient HIP bonding features without any voids and excessive deformation can be concluded from the fabrication of this partial model with SS316L circular coolant tube. The same fabrication technique can be applied to the medium scale primary first wall mock-up [8,9].
Fig. 3.4.1 Appearance of SS316L coolant tubes and DSCu plates after bending.

Fig. 3.4.2 Appearance of assembly before HIPing.
Fig. 3.4.3 Deformation of tube cross-section and microscopic image of HIPed interfaces (1).
Fig. 3.4.4 Deformation of tube cross-section and microscopic image of HIPed interfaces (2).
Fig. 3.4.5  Deformation of tube cross-section and microscopic image of HIPed interfaces (3).
4. Thermo-mechanical Tests of Mock-ups

4.1 Primary First Wall Mock-up

4.1.1 Preparatory Analysis

Thermo-mechanical tests were performed with the fabricated small scale primary first wall mock-up in order to investigate the heat removal performance, the integrity, especially at the HIPed interfaces, fatigue lifetime and fracture behavior of the mock-up under high heat flux [10]. Prior to the testing, preparatory analysis was performed to decide the test conditions and also to predict fracture behavior and fatigue lifetime of the mock-up [11].

A 2-D analysis model shown in Fig. 4.1.1 was developed taking a half width of the mock-up assuming symmetrical boundary condition at one side. The analysis code used was ABAQUS. The out-of-plane condition for thermal stress analysis was generalized plane strain. Material properties of DSCu and SS316L used in the analysis were summarized in Table 4.1.1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature (°C)</th>
<th>Thermal conductivity (W/mK)</th>
<th>Specific heat (J/kgK)</th>
<th>Young's modulus (GPa)</th>
<th>Poisson's ratio</th>
<th>Thermal expansion coefficient (1/K)</th>
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</thead>
<tbody>
<tr>
<td>DSCu (AL-25)</td>
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<td>348</td>
<td>384</td>
<td>134</td>
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<td></td>
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<td>437</td>
<td>83</td>
<td>0.343</td>
<td>19.60</td>
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<td>SS316L</td>
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<td>0.3</td>
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<tr>
<td></td>
<td>100</td>
<td>15.1</td>
<td>486</td>
<td>186</td>
<td>0.3</td>
<td>16.40</td>
</tr>
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<td></td>
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<td>529</td>
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<td>0.3</td>
<td>17.45</td>
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<td>571</td>
<td>153</td>
<td>0.3</td>
<td>18.33</td>
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<td></td>
<td>700</td>
<td>23.7</td>
<td>613</td>
<td>137</td>
<td>0.3</td>
<td>19.05</td>
</tr>
</tbody>
</table>

One of typical results of thermal analysis is shown in Fig. 4.1.2. For this analysis, an average heat flux of 5 MW/m² with Gaussian distribution expected in the test facility was applied. The higher heat flux than the ITER nominal heat flux condition of 0.5 MW/m² was examined for accelerating the fatigue test. Coolant conditions applied were 25 °C, 3 MPa and 7 m/s. With these conditions, thermal steady state was reached within 15 sec from the start of heat flux loading. The maximum temperatures at DSCu front
surface and HIPed DSCu/SS316L interface are 468 °C and 406 °C, respectively. The results of elasto-plastic stress analysis gave the maximum strain of about 1% at the inner surface of the inner-most SS316L coolant tube. The number of cycles to failure with this strain was about 1100 cycles by the evaluation using Manson-Coffin correlation [12].

### 4.1.2 Test Conditions

Based on the preparatory analysis, thermo-mechanical test conditions were selected as shown in Table 4.1.2. The tests consisted of two campaigns. For the first campaign, a surface heat flux of 5 MW/m$^2$ in average was selected so that the maximum strain at the inner surface of the coolant tube was expected to exceed the fatigue lifetime limit based on the design fatigue curve of SS316L at about 1000 cycles. As for the second campaign, a higher heat flux of 7 MW/m$^2$, also in average, was to be applied so that the cumulative fatigue damage at the inner surface of the coolant tube was expected to reach a failure limit based on material test data. These test conditions were plotted in Fig. 4.1.3 together with SS316 fatigue data. These thermo-mechanical tests were performed at JEBIS (JAERI Electron Beam Irradiation Stand).

<table>
<thead>
<tr>
<th>Campaign</th>
<th>Heat flux (MW/m$^2$)</th>
<th>Heat flux loading duration (sec)</th>
<th>Number of cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>5.0</td>
<td>15</td>
<td>1000</td>
</tr>
<tr>
<td>Second</td>
<td>7.0</td>
<td>15</td>
<td>1500</td>
</tr>
</tbody>
</table>

Coolant Conditions (same for first and second campaigns)
Inlet temperature : room temperature
Pressure : 3 MPa
Velocity : 7 m/s

### 4.1.3 Test Results

In the first campaign, no visible changes in the surface appearance including hot spots were observed by VTR and IR camera. Temperature responses at the first and the 1000th cycles measured by a thermocouple
embedded at 3.5 mm deep from the DSCu surface are shown in Fig. 4.1.4. Analysis results are also plotted in the figure. Temperature responses measured at the first and the 1000th cycles agree very well with each other. They also agree well with the analysis result. This indicates no degradation in heat removal capability during the first campaign with the expected maximum strain of 1 % at the inner surface of the SS316L coolant tube.

The test was continued further with higher heat flux of 7 MW/m$^2$ in the second campaign. No visible changes in the surface appearance were also observed in this campaign. Temperature responses measured by thermocouples during the second campaign also agreed well with analysis results. Cracks and any damages were not observed on the surface of the mock-up. A final appearance of the mock-up after all tests is shown in Fig. 4.1.5.

From above test results with 5-7 MW/m$^2$ for 2500 cycles in total, sufficient thermo-mechanical integrity of the primary first wall mock-up fabricated with the single step HIP technique was confirmed.
Heat Flux

Coolant
Temperature : 25°C
Velocity : 7.0 m/sec

Fig.4.1.1 Analysis model for small scale primary first wall mock-up
Fig. 4.1.2  Temperature profile under a heat flux of 5.0MW/m²
Fig. 4.1.3 Fatigue data of SS316L and result of high heat flux test
Fig. 4.1.4 Temperature response under a heat flux of 5.0 MW/m² and thermal analysis result.
Fig. 4.1.5 Appearance of small scale primary first wall mock-up after high heat flux tests.
4.2 Baffle First Wall Mock-up

4.2.1 Preparatory Analysis

Thermo-mechanical tests with the fabricated small scale baffle first wall mock-up were performed at JAERI Electron Beam Irradiation Stand (JEBIS) at JAERI-Naka in order to investigate the heat removal performance, the integrity, especially at the HIPed and brazed interfaces, fatigue lifetime and fracture behavior of the mock-up under high heat flux. Prior to the testing, preparatory analysis were performed to decide the test conditions and also to predict fracture behavior and fatigue lifetime of the mock-up.

A 2-D analysis model shown in Fig. 4.2.1 was developed taking a half width of the mock-up by assuming symmetrical boundary condition at one side. The analysis code used was ABAQUS. The out-of-plane condition for thermal stress analysis was generalized plane strain. Material properties of DSCu, SS316L and CFC used in the analysis were summarized in Table 4.2.1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Temp. (°C)</th>
<th>Thermal conductivity (W/mK)</th>
<th>Young's modulus (GPa)</th>
<th>Specific heat (J/kgK)</th>
<th>Thermal expansion coefficient (1/K)</th>
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<td>700</td>
<td>263</td>
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<tr>
<td>SS316L</td>
<td>20</td>
<td>13.9</td>
<td>192</td>
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<td></td>
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<td>23.7</td>
<td>137</td>
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<td>613</td>
</tr>
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</table>

Thermal analysis under ITER nominal conditions, which are heat flux of 3.0 MW/m², coolant flow of 11 m/sec and temperature of 140 °C, were carried out. From results of thermal analysis, temperature of CFC surface and CFC/OFCu interface were 500 °C and 300 °C, respectively. The higher heat flux than the
ITER nominal heat flux condition of 5.0 MW/m$^2$ was examined for accelerating the fatigue test. Coolant conditions applied were 25 °C, 2 MPa and 10 m/sec, which were available in the high heat flux test. With these conditions, thermal steady state at CFC/OFCu interface was reached within 25 sec from the start of heat flux loading. The maximum temperatures at CFC surface and CFC/DSCu interface are 948 °C and 320 °C, respectively as shown in Fig. 4.2.2. This would be a base case because the temperature at CFC/OFCu interface is in the same level of that under ITER nominal conditions. Higher heat fluxes can be also taken into account for more acceleration of the test. With heat fluxes of 6.0 and 10.0 MW/m$^2$, both for heating duration of 30 seconds, the maximum temperatures at CFC/OFCu interface are 350 °C and 500 °C as shown in Figs. 4.2.3 and 4.2.4, respectively. The 10.0 MW/m$^2$ would be the maximum heat flux available in the test facility because the sublimation of CFC would become considerable and harm the facility under higher heat fluxes than it.

4.2.2 Test Conditions

Based on the preparatory analysis, thermo-mechanical test conditions were selected as shown in Table 4.2.2. The tests consisted of three campaigns. For the first campaign, a surface heat flux of 5 MW/m$^2$ in average was selected so that the temperature at the CFC/OFCu brazed interface simulated the ITER operation condition. As for the second and third campaign, higher heat fluxes of 6 and 10 MW/m$^2$, also in average, respectively were applied.

<table>
<thead>
<tr>
<th>Campaign</th>
<th>Heat flux (MW/m$^2$)</th>
<th>Heat flux loading duration (sec)</th>
<th>Number of cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>5.0</td>
<td>25</td>
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</tr>
<tr>
<td>Second</td>
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<td>600</td>
</tr>
<tr>
<td>Third</td>
<td>10.0</td>
<td>30</td>
<td>3000</td>
</tr>
</tbody>
</table>

Coolant Conditions (same for first, second and third campaigns)

- Inlet temperature : room temperature
- Pressure : 1.8 MPa
- Velocity : 10 m/s

4.2.3 Test Results
In the first campaign, no visible changes in the surface appearance including hot spots were observed by VTR and IR camera. Temperature responses at the first and the 1000th cycles measured by thermocouples and IR camera on the surface are shown in Fig. 4.2.5. Temperature responses at the first and the 1000th cycles agree very well. They also agree well with the analysis result. This indicates no degradation in heat removal capability during the first campaign.

The tests were continued further with higher heat fluxes of 6-10 MW/m² in the second and third campaigns. Temperature responses measured by thermocouples and IR camera in the second and third campaigns are shown in Fig. 4.2.6 and 4.2.7, respectively. No visible changes in the surface appearance and brazing interface were also observed in these campaigns. Temperature responses measured by thermocouples during the second and third campaigns also agreed well with analysis results. Cracks and any damages were not observed on the surface of the mock-up.

From above test results with 5-10 MW/m² for 4600 cycles in total, sufficient thermo-mechanical integrity of the baffle first wall mock-up fabricated with the two-step brazing technique was confirmed.
Heat Flux

- Coolant velocity 10 m/s
- Heat transfer coefficient as a function of wall temperature

Fig. 4.2.1 Analysis model and boundary conditions
Coolant temperature: $25 \, ^\circ\text{C}$

**Fig. 4.2.2** Temperature distribution at heating duration of 25 sec under heat flux of $5.0 \, \text{MW/m}^2$
Coolant temperature: 25 °C

**Fig. 4.2.3** Temperature distribution at heating duration of 30 sec under heat flux of 6.0 MW/m$^2$
Coolant temperature: 25 °C

Fig. 4.2.4 Temperature distribution at heating duration of 30 sec. under heat flux of 10.0 MW/m²
Fig. 4.2.5  Typical temperature responses measured by IR and thermocouple and analyzed with FEM for heat flux of 5.0 MW/m²
Fig. 4.2.6 Typical temperature responses measured by IR and thermocouple and analyzed with FEM for heat flux of 6.0 MW/m²
Fig. 4.2.7 Typical temperature responses measured by IR and thermocouple and analyzed with FEM for heat flux of 10.0 MW/m²
5. Summary

Detailed designs of small scale mock-ups for the primary first wall, the baffle first wall, the shield block and a partial model for an edge of primary first wall module were developed to incorporate most of the key design features. The primary first wall mock-up consisted of DSCu heat sink, built-in SS316L coolant tubes within the heat sink and SS316L backing plate simulating the shield block, and water headers and supply/return pipes for thermo-mechanical testing. The first wall part was flat-shaped and of dimensions approximately 130 mm wide, 300 mm long (200 mm long for DSCu) and 27 mm thick. The baffle first wall mock-up was L-shaped simulating the top corner of the outboard lower baffle module and consisted of DSCu heat sink, SS316L coolant tube (liner, 0.5 mm thick), and SS316L backing plate. CFC armor tiles were attached onto the DSCu heat sink. The size of the mock-up was about 50 mm wide, 500 mm long and 50 mm thick. Coolant headers and supply/return pipes were also provided for thermo-mechanical testing. The shield block mock-up was 400 mm wide, 500 mm high and 150 mm deep, and integrated with the first wall. The shield block part was made of forged SS316L with drilled holes for internal coolant channels. A poloidal curvature with a radius of 2000 mm at the first wall surface was also provided. Though rectangular coolant tubes were used for the first wall, a partial model simulating an edge part of the primary first wall module was designed as a complementary R&D for the application of circular coolant tubes. The size of the partial model was approximately 130 mm x 130 mm x 22 mm.

Though the materials used were SS316L instead of SS316LN-IG and GlidCop® AL-25 instead of AL-25-IG due to the material availability at this stage, this difference in the materials will not affect the fabricability and the performance of the mock-up. The only issue missing in these small mock-ups, relating to the ITER design, is the attachment of the Be protection armor onto the DSCu heat sink.

Fabrication routes of the above small scale mock-ups and the partial model were decided based on the single step solid HIP of DSCu/DSCu, DSCu/SS316L and SS316L/SS316L reflecting the results of previous joining techniques development and testing. The HIP conditions applied were the temperature of 1050 °C, the pressure of 150 MPa and the holding time of 2 hours. For attaching the CFC tiles onto DSCu heat sink in the fabrication of the baffle first wall mock-up, a two-step brazing was tried. First, the CFC armor tile was brazed to an OFCu base plate with Ag-free brazing material of Cu-Mn at 960 °C for 15 minutes, and then the OFCu base plate was brazed to DSCu heat sink also with Ag-free brazing material of Al at 675 °C for 43 minutes.
All mock-ups and the partial model were successfully fabricated with a satisfactory dimensional accuracy. A number of non-destructive and destructive inspections confirmed the satisfactory HIP bondability with neither internal defects nor voids at bonded interfaces. The joining of CFC and DSCu by brazing was also satisfactory.

The small scale primary first wall mockup was thermo-mechanically tested under high heat fluxes of 5-7 MW/m² for 2500 cycles in total. Temperature responses measured during the tests agreed well with analysis results. This indicates no degradation in heat removal performance of the mock-up. The maximum strain estimated under these conditions were 1-1.5 % at the inner surface of the SS316L coolant tube, which was beyond the design fatigue curve of the base metal (SS316L) with the above-mentioned number of cycles. Even with these testing conditions, no crack at the coolant tube surface and delamination of HIPed interfaces were observed by destructive examination of the mock-up after all of the tests. Thus, sufficient integrity of the mock-up against thermal cyclic loads was confirmed.

Also the small scale baffle first wall mockup was thermo-mechanically tested under high heat fluxes of 5-10 MW/m² for 4600 cycles in total. Satisfactory heat removal performance and integrity of the mock-up against cyclic high heat flux loads were again confirmed by measurements during the tests.

Consequently, the fabrication techniques applied in the present study were found to be successful and recommended for the primary first wall and baffle mock-ups.

The two-step brazing applied for the small scale baffle first wall would contribute to ease the attachment of thousands of armor tiles to the baffle module surface by grouping several to tens of armor tiles to be brazed on Cu base plate then the sets of armor tiles/base plates to be brazed on the DSCu heat sink of the module surface.

Acknowledgment

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References


国際単位系 (SI) と換算表

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<th>表 1 SI基本単位および補助単位</th>
<th>表 2 SIと併用される単位</th>
<th>表 3 固有の名称をもつSI基底単位</th>
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</table>

| 量 | 名称 | 記号 | 他のSI単位 による表現 |
|--------------------------------|--------------------------------|--------------------------------|
| 長さ | メートル | m | 1m = 100cm |
| 質量 | キログラム | kg | 1kg = 1000g |
| 時間 | サイクル | s | 1s = 1000ms |
| 電流 | アンペア | A | 1A = 1000mA |
| 熱力学温度 | ケルビン | K | 1K = 1℃ |
| 物質量 | キログラム | mol | 1mol = 6.02214x10^23 |
| 光度 | カン德拉 | cd | 1cd = 6.83x10^14lm |
| 平面角 | ラジアン | rad | 1rad = 57.2958° |
| 立体角 | ステラジアン | sr | 1sr = 4πrad |

| 周波数 | ハertz | Hz | 1Hz = 1s^-1 |
| 力 | ニュートン | N | 1N = 1000gcm/s^2 |
| 力 | パスカル | Pa | 1Pa = 1N/m^2 |
| 磁束密度 | ワット | W | 1W = 1J/s |
| 磁場強度 | クローレン | A | 1A = 1C/s |
| 電位、電圧、電力 | ボルト | V | 1V = 1J/C |
| 静電容量 | フララッド | F | 1F = 1C/V |
| 電気抵抗 | オーム | Ω | 1Ω = 1V/A |
| コンダクタンス | ジェームス | S | 1S = 1A/V |
| 磁束密度 | ワット | Wb | 1Wb = 1V.s |
| 磁場強度 | クローレン | A | 1A = 1C/s |
| 照度 | ルーメン | lm | 1lm = 1cd-sr |
| 光度 | ルックス | lx | 1lx = 1lm/m^2 |
| 放射能 | ベクレル | Bq | 1Bq = 1s^-1 |
| 吸収線 線量 | グレイ | Gy | 1Gy = 1J/kg |
| 線量当量 | シーベルト | Sv | 1Sv = 1J/kg |

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（注）
1. 表 1 - 5 は「国際単位系」第 5 版、国際度量衡局 1985年版によること。ただし、1 eV および 1u の値は CODATA の 1986 年推奨値によった。
2. 表 4 には、音速、密度の等を表す場合に限り表 2 のカタログに記載されているら。
3. barは、JISでは体積の圧力を表す場合に限り表 2 のカタログに記載されているら。
4. EC 制則に基づき、補助単位は bar、barnおよび「血圧の単位」mmHgを表 2 のカタログに記載されている。

換算表

| 力 | N(10^9dyn) | kgf | lbf |
|--------------------------------|--------------------------------|--------------------------------|
| 1 | 0.1019272 | 0.226249 | 1.000000 |
| 9.80665 | 1 | 2.0460 | 4.44822 |

| 粘度 | (N·s/m²) | Pa-s | (g/(cm·s)) |
|--------------------------------|--------------------------------|--------------------------------|
| 1 Pa-s | 10 Pa | 10^4 |

| 動粘度 | (m^2/s) | St | (cm²/s) |
|--------------------------------|--------------------------------|--------------------------------|
| 1 m²/s | 10 St | 10^4 |

| エネルギー | * | * | * |
|--------------------------------|--------------------------------|--------------------------------|
| 1 | 0.1019272 | 0.226249 | 1.000000 |
| 9.80665 | 1 | 2.0460 | 4.44822 |

| 1 cal | 4.18605 J (計量法) |
|--------------------------------|--------------------------------|--------------------------------|

| 放射線 | Bq | Ci | rad |
|--------------------------------|--------------------------------|--------------------------------|
| 1 | 2.70270 x 10^-11 | 1 | 0.100 |
| 3.7 x 10^10 | 1 | 0.010 |

(86年12月26日現在)