JAERI-Tech
2000-042

DEVELOPMENT OF ITER SHIELDING BLANKET PROTOTYPE MOCKUP BY HIP BONDING

July 2000

Satoshi SATO, Kazuyuki FURUYA, Toshihisa HATANO,
Toshimasa KURODA, Mikio ENOEDA,
Hideyuki TAKATSU and Yoshihiro OHARA

日本原子力研究所
Japan Atomic Energy Research Institute

本レポートは、日本原子力研究所が不定期に公刊している研究報告書です。
入手の問合わせは、日本原子力研究所研究情報部研究情報課（〒319-1195　茨城県那珂郡東海村）あて、お申し越しください。なお、このほかに財団法人原子力弘済会資料センター（〒319-1195　茨城県那珂郡東海村日本原子力研究所内）で複写による実費頒布をおこなっております。

This report is issued irregularly.
Inquiries about availability of the reports should be addressed to Research Information Division, Department of Intellectual Resources, Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki-ken 319-1195, Japan.

編集兼発行　日本原子力研究所

Development of ITER Shielding Blanket Prototype Mockup by HIP Bonding

Satoshi SATO, Kazuyuki FURUYA, Toshihisa HATANO, Toshimasa KURODA, Mikio ENOEDA, Hideyuki TAKATSU+ and Yoshihiro OHARA

Department of Fusion Engineering Research
Naka Fusion Research Establishment
Japan Atomic Energy Research Institute
Naka-machi, Naka-gun, Ibaraki-ken

(Received April 25, 2000)

A prototype (~900^H x 1700^W x 350^T mm) of the ITER shielding blanket module has been fabricated following the previous successful fabrication of a small-scale (~500^H x 400^W x 150^T mm) and mid-scale (~800^H x 500^W x 350^T mm) mock-ups. This prototype incorporates most of key design features essential to the fabrication of the ITER shielding blanket module such as 1) the first wall heat sink made of Al_2O_3 dispersion strengthened Cu (DSCu) with built-in SS316L coolant tubes bonded to a massive SS316LN shield block, 2) toroidally curved first wall with a radius of 5106 mm while straight in poloidal direction, 3) coolant channels oriented in poloidal direction in the first wall and in toroidal direction in the shield block, 4) the first wall coolant channel routing to avoid the interference with the front access holes, 5) coolant channels drilled through the forged SS316LN-IG shield block, and 6) four front access holes of 30 mm in diameter penetrated through the first wall and the shield block.

For the joining method, especially for the first wall/side wall parts and the shield block, the solid HIP (Hot Isostatic Pressing) process was applied. It is difficult to apply conventional joining methods such as field welding, brazing, explosion bonding and mechanical one-axial diffusion bonding to a wide area bonding because sufficient mechanical strengths can not be

---

This work is conducted as an ITER Technology R&D and this report corresponds to the 1996 ITER R&D Task (Task No. G16TT77 96-05-15 FJ, ID No. T216, Title : Blanket System Fabrication and Testing under Normal and Abnormal Conditions, Subtask 4J1, Fabrication of Primary Wall Prototype Modules).

+ Office of ITER Project Promotion

obtained and excessive deformations occurs. In order to solve these fabrication issues, HIP bonding was applied. The first wall stainless steel (SS) coolant tubes of 10 mm in inner diameter and 1 mm in thickness were sandwiched by semi-circular grooved DSCu plates at the first wall and the front region of the side wall, and by semi-circular grooved SS plates at the back region of the side wall. After assembling of these first wall/side wall parts with the shield block, they were simultaneously bonded by single step HIP in order to minimize thermal effects on the mechanical properties and to reduce the number of fabrication steps. Based on the results of study for optimization of the simultaneous HIP bonding conditions, the HIP conditions were 1050 ℃, 150 MPa and holding time of 2 hours. Before this assembly for the HIP process, a deep drilling was performed for the coolant channels of the shield block from both sides of the block, then the shield block was bent by 10000-ton press machine to provide the specified curvature. During the bending, iced water was inserted into the drilled holes to prevent excessive deformation of the holes. Iced water was applied as the inserted material in this study because it was easy to remove the inserted material from the drilled holes and chemical reaction could be prevented during removal of the inserted materials. After the HIP process, the first wall surface was finally machined. The back part of the module was also machined to provide coolant manifolds, then cover plates of the manifolds were welded by TIG welding.

A series of measurements and inspections was performed in the course of fabrication to make sure the dimensional accuracy and integrity of pressure boundaries. A destructive inspection was also performed with a cut specimen from the edge of the fabricated module to examine the bondability of HIPed interfaces. As a result of this fabrication experience, sufficient bonding by the single step solid HIP process has been demonstrated, and sufficient technical data base on the fabrication of the ITER shielding blanket module has been obtained.

Keywords : ITER, Shielding Blanket, Prototype Mockup, Solid HIP, First Wall, DSCu.

HIP接合によるITER遮蔽ﾌﾞﾗﾝｹｯﾄﾌﾟﾛﾄﾀｲﾌﾟの開発

日本原子力研究所那珂研究所核融合工学部
佐藤 聡・古谷 一幸・秦野 歳久・黒田 敏公
榎枝 幹男・高津 英幸+・小原 祥裕

（2000年4月25日受理）

国際熱核融合実験炉（ITER）遮蔽ﾌﾞﾗﾝｹｯﾄのﾌﾟﾛﾄﾀｲﾌﾟﾓｼﾞｭｰﾙ（高さ約900mm、幅約1700mm、奥行き約350mm）を製作した。製作したﾌﾟﾛﾄﾀｲﾌﾟﾓｼﾞｭｰﾙは、ITER遮蔽ﾌﾞﾗﾝｹｯﾄ設計に基づいた以下に示す主要な特徴を有している。

１）第一壁はｵｰｽﾃﾅｲﾄｽﾃﾝﾚｽ鋼(SS316L)の円形冷却配管が内蔵されたｱﾙﾐﾅ分散強化銅(DSCu)の熱ｼﾝｸ材から構成されている。またその第一壁は、SS316LN製の遮蔽体ﾌﾞﾛｯｸに接合されている。

２）第一壁は、ﾎﾟﾛｲﾀﾞﾙ方向にはｽﾄﾚｰﾄであるが、ﾄﾛｲﾀﾞﾙ方向には5106mmの曲率を有している。

３）第一壁の冷却流路はﾎﾟﾛｲﾀﾞﾙ方向に、遮蔽体ﾌﾞﾛｯｸの冷却流路はﾄﾛｲﾀﾞﾙ方向に流れている。

４）第一壁の冷却流路はﾌﾛﾝﾄｱｸｾｽﾎｰﾙとの干渉を避けるように、迂回している。

５）遮蔽体ﾌﾞﾛｯｸの冷却流路は、SS316LN-IG（ITERｸﾞﾚｰﾄﾞ）の鍛造ﾌﾞﾛｯｸをﾄﾞﾘﾙ孔加工することによって製作されている。

６）直径30mmの４本のﾌﾛﾝﾄｱｸｾｽﾎｰﾙが第一壁と遮蔽体ﾌﾞﾛｯｸを貫通している。

第一壁はこれまでの接合技術開発の成果を反映し、DSCuとSS316LN、DSCuとDSCu、SS316LNとSS316LNとを、高温等方加圧(HIP)法により接合し製作した。第一壁の製作に対して、溶接やろう付け、爆着、機械的な一軸拡散接合などの従来からの接合方法は、広い面積での接合が不可能なことや十分な強度が確保できないこと、また変形が大きいことなどから、適用は難しい。そこでそれらの課題を解決するため、高温等方加圧法（以下HIP法という。Hot Isostatic Pressingの略）を適用した。半円溝加工を施した１組のDSCuのﾌﾟﾚｰﾄの間にSS316Lの円形冷却配管を挿入しHIP接合した。また第一壁と遮蔽体ﾌﾞﾛｯｸもHIP接合し製作した。HIP処理による熱履歴を最小限にし、また製作工程の簡素化を図るため、本製作における全てのHIP接合を一回のHIP処理で全ての接合箇所を同時に接合し製作した。それら同時HIP接合

本作業は、国際熱核融合実験炉 (International Thermonuclear Experimental Reactor) の工学設計活動として、1996年作業計画 (Task No. G16TT77 96-05-15 FJ, ID No. T216, Subtask 4J1) に基づいて実施した。
那珂研究所：〒310-0193 茨城県那珂郡那珂町向山801-1
+ ITER業務推進室

の最適化に関する研究結果に基づき、温度1050℃、圧力150MPa、保持時間2時間の条件でHIP接合を行った。HIP接合の前に、両端部からの長尺ﾄﾞﾘﾙ孔加工及び10,000ﾄﾝﾌﾟﾚｽによる曲げ加工により、遮蔽体ﾌﾞﾛｯｸを製作した。曲げ加工の際には、冷却流路の変形を防ぐために、氷を冷却流路内に挿入した。挿入材のﾄﾞﾘﾙ孔からの除去を容易にし、除去の際のｽﾃﾝﾚｽ鋼と挿入材との間の化学反応を防ぐため、本研究では氷を挿入材として適用した。

製作後の試験・検査の結果、所定の寸法精度、耐圧性能を確認できた。また、接合部の金相観察の結果、有為な欠陥は見受けられなかった。

ﾌﾟﾛﾄﾀｲﾌﾟﾓｼﾞｭｰﾙの製作により、一回のHIP処理での同時接合及びITER遮蔽ﾌﾞﾗﾝｹｯﾄの製作性を実証した。

Contents

目　　　次

Figure Captions

1. Introduction

The shielding blanket installed in the International Thermonuclear Experimental Reactor (ITER) during the Basic Performance Phase (BPP) has a modular structure with typical dimensions of ~ 0.9 m height, ~ 1.6 m width and ~ 0.4 m depth [1]. The shielding blanket module is composed of integrated first wall and shielding block. The first wall has poloidally oriented built-in coolant tubes to maintain heat removal capability and structural integrity against surface heat flux (~ 0.5 MW/m^2), neutron wall load (~ 1.2 MW/m^2) and huge electromagnetic force (~ 1 MN). It is composed of austenitic stainless steel (SS316LN) circular tubes and Al_2O_3 dispersion strengthened copper alloy (DSCu) heat sink layer surrounding the circular tubes. Also, DSCu surrounds the SS tube at the front region of the top/bottom walls, and SS surrounds the SS tube at the back region. The shielding block is made of SS316LN with drilled coolant channels.

For the fabrication of multi-layered structure composed of first wall/top wall/bottom wall, Hot Isostatic Pressing (HIP) bonding is utilized for the joining of three combinations of SS316L/SS316L, DSCu/DSCu and SS316L/DSCu. Also, the first wall/top wall/bottom wall and the shielding block are bonded by HIP including the bonding of the lid of the coolant header [2, 3]. HIP, being a promising technology to fabricate blanket structure integrated with first wall, coolant channels of which are embedded within the wall so as to keep both mechanical stiffness and coolant capability [4 - 10], has been selected as a reference fabrication method for the ITER shielding blanket/first wall [1]. Simultaneous HIP bonding of these joints in a single solid HIP process has been pursued in this study in order to minimize thermal effects on the material properties and to reduce fabrication steps. To investigate and demonstrate the fabricability of the integrated first wall/shielding blanket based on proposed fabrication method, a prototype mockup has been fabricated following the previous successful fabrication of small-scale (~500^H x 400^W x 150^T mm) and mid-scale (~800^H x 500^W x 350^T mm) mockups [2, 3, 8, 10].

2. Design and Specifications

2.1 Key Design Features

The design of the #8 primary first wall module prototype mock-up has been developed [11, 12] based on the ITER Detailed Design Report (DDR) [1]. The design of the #8 primary first wall module prototype mock-up has the following key design features;

(a) Shielding blanket composed of a massive shield block, made of a forged block of SS316LN-IG, integrated with the first wall, made of sixty-seven SS316L cooling pipes sandwiched by two DSCu plates
(b) Curved module in the toroidal direction with a curvature of 5106 mm at the first wall surface (without beryllium armor) and straight in the poloidal direction
(c) Cooling channel arrangement in the poloidal direction for the first wall and in the toroidal direction for the shield block, as shown in the reference drawing, both of which are connected in series with a pair of coolant inlet and outlet headers at the back
(d) Constant pitch of the first wall cooling pipes along the poloidal direction except around the front access penetration hole area, see (f), and the space in-between the cooling pipes filled with the DSCu heat sink material
(e) Constant pitch of the cooling passages in the shield block, which are provided by deep drilling through the SS316L forged block
(f) Four front access penetration holes provided through the first wall and the shield block as representatives of the nine penetration holes shown in the reference drawing. First wall cooling channels are detoured around the penetration holes, while shield block cooling passages are kept straight without interference of the penetration holes.
(g) Two support legs, 90 mm wide and 50 mm high, provided on the rear surface edges of the mock-up, running in the poloidal direction almost from the top to the bottom, for possible attaching the mock-up to the prototype back plate in the assembly test

This prototype mock-up incorporates most of the key design features essential to the fabrication technology development of the ITER shield blanket. The missing issues in the present prototype mock-up fabrication, relative to the ITER Engineering Design Activity (EDA) Final Design Report (FDR) design, are the beryllium armor fabrication and internal shield block cooling passages arrangement (detour) to accommodate front access penetration holes.

2.2 Outline of the Prototype Mock-up

A cut-away-view of the prototype mock-up is shown in Fig. 2.1. It is composed of the first wall without beryllium plasma facing armor, the shield block, coolant headers for the first wall and the shield block, and a coolant feeder/return pipes with representative outer dimensions shown in Table 2.1. This mock-up is slightly reduced in size, 70 mm in height and 35 mm in thickness, from the reference drawing, due to the limitation of the HIP facility available in Japan.

Table 2.1 Typical dimensions of the #8 primary first wall module prototype mock-up.

Item	Dimensions
Height (poloidal)	930 mm
Width (toroidal)	1574 mm (at the first wall)
Thickness (radial)	345 mm
Radius of Curvature	5106 mm (at the first wall)

The first wall has sixty-seven SS316L cooling pipes, 10-mm-inner-diameter and 1-mm-thick each, sandwiched by two DSCu plates, 11-mm-thick (plasma side) and 9-mm-thick (shield block side) and 20-mm-thick in total. These DSCu plates have semi-circular grooves on one side to fit with the cooling pipes. Each first wall cooling pipe runs from the bottom header, located at the rear bottom of the mock-up, goes up along the first wall in the poloidal direction and then returns back to the top header located at the rear top. The space in-between the cooling pipes are filled with DSCu on the first wall, while the space in-between the first wall cooling pipes on the top and bottom surfaces of the mock-up is filled with SS316LN-IG plates instead of DSCu. The pitch of the first wall cooling pipes is constant along the poloidal direction except around the two front access holes among four, where two first wall cooling pipes on both sides of the penetration holes each are detoured to avoid interference.

The shield block is made of a massive forged block of SS316LN-IG with sixty-six internal cooling passages drilled into the block. The layout of the cooling passages is also decided based on the reference drawing with slight modifications around the front access penetration holes, where cooling passages are shifted aside so as not to interfere the penetration holes. Internal cooling passages are composed of five rows from the first wall to the back, and sixty-six passages in total. At the drilling and bending stages, this block has a slightly larger size for final machining. This block is finally machined to give the nominal outer dimensions and to provide cooling headers on the top and bottom surfaces, which are then sealed by the closure plates (lids) made of SS316LN plates. The mock-up is equipped on its back with a pair of coolant feeder and return pipes TIG welded to the rear surface of the mock-up.

The mock-up to be fabricated in this R&D has a dummy part at its edge for the destructive examination. This part simulates the key elements of the mock-up, and is composed of two first wall cooling pipes embedded within the DSCu plates and a SS316LN-IG block. The first wall cooling pipes are arranged in a similar fashion to the real part. This dummy part is to be cut off from the real part and to be destructively examined in terms of HIP bonded interface quality, deformation of the cooling channels and any change of the metallurgical quality.

2.3 Specifications

(1) **Mock-up size:** #8 module with slightly reduced dimensions by 70 mm in height and 35 mm in thickness (see Fig. 2.1)

(2) **Typical dimensions**

- Height: 930 mm
- Width
  - first wall surface: 1574.0 mm
  - back surface: 1467.6 mm
- Thickness: 395 mm (including 50-mm high leg)
- Curvature: see Fig. 2.2, Section A-A
  - Poloidal direction: straight
  - Toroidal direction
    - first wall surface: 5106 mm
    - back surface: 4761 mm
- Front access hole layout: see Fig. 2.2
  - number: 4 holes (symmetric position)
  - diameter : 30 mm
  - position: 473 mm left/right and 215 mm upper/lower from the center
  - first wall cooling path layout: see Figs. 2.5 and 2.6
- Attachment: see Fig. 2.1, Section A-A
  - method: welding to the back plate
  - support leg
    - length: 480 mm (poloidal direction)
    - width: 90 mm

height: 50 mm
location: 75 mm from the mock-up edges

- Header layout: see Figs. 2.3 - 2.5

(3) Cooling path layout

- First wall: circular tubes (see Fig. 2.2, Section A-A)
    - outer diameter: 12 mm
    - thickness : 1 mm
    - pitch: 22 mm (except around the front access hole)
    - number: 67
- Shield block: 5 rows (see Fig. 2.4)
    - 1st row
        - diameter: 24 mm
        - pitch
            - upper/lower section: 39 mm
            - center section: 40 mm
            - around the front access hole: 80 mm
        - number: 20
    - 2nd row
        - diameter: 24 mm
        - pitch
            - upper/lower section: 48 mm
            - center section: 49 mm (except for 2 holes at just center)
            - 2 holes at just center: 50 mm
            - around the front access hole: 98 mm
        - number: 16
    - 3rd row
        - diameter: 40 mm
        - pitch
            - upper/lower section: 60 mm
            - center section: 64 mm
            - around the front access hole: 128 mm
        - number: 12
    - 4th row
        - diameter: 40 mm
        - pitch

upper/lower section: 70 mm
center section: 80 mm (except for 2 holes at just center)
2 holes at just center: 160 mm
around the front access hole: 110 mm
number: 10
5th row
diameter: 40 mm
pitch
upper/lower section: 90 mm
center section: 90 mm
around the front access hole: 180 mm
number: 8
interval
1st wall end/1st row center: 27 mm
1st row center/2nd row center: 46 mm
2nd row center/3rd row center: 53 mm
3rd row center/4th row center: 76 mm
4th row center/5th row center: 55 mm
5th row center/back surface: 68 mm

(4) Materials

Materials used in the present fabrication are summarized in Table 2.2. Basically, the same materials specified in the FDR design are used, though SS316L pipes instead of SS316LN-IG ones are used because of the availability at this stage.

Table 2.2 Materials used in the present fabrication.

Part	Material
First wall DSCu	GlidCop Al-25 IG0 (cross-rolled plate)
First wall cooling pipe	SS316L (pipe)
Shield block	SS316LN-IG (forged)
Top/bottom plates	SS316LN-IG (rolled plate)
Other closure plates	SS316LN (rolled plate)
Support legs	SS316LN (rolled plate)

2.4 Fabrication procedures

(1) Fabrication route

Fabrication route of the #8 primary first wall module prototype mock-up has been decided based on the successful experiences of the trial fabrication of small and medium scale shield blanket mock-ups integrated with the first wall and on promising results obtained so far in thermo-mechanical performance tests [2, 3, 7-10, 13-24]. Fabrication processes are grouped into three steps, a) fabrication of the first wall elements, b) fabrication of the shield block, and c) assembly with HIP process and final machining. Flow charts of the fabrication steps of the first wall panel and the shield block are schematically shown in Figs. 2.7 - 2.8 and 2.9 - 2.10, respectively, and are described in Tables 2.3 and 2.4, respectively.

Table 2.3 Fabrication steps of the first wall panel.

Step	Fabrication Process	Remarks
1 (a)	Preparation of DSCu plates	
1 (b)	Preparation of SS316L pipes	
2 (a)	Machining of DSCu plates for cooling channel grooves	Semi-circular grooves on one side each
3 (a)	Bending of DSCu plates	Cold working
3 (b)	Bending of SS316L pipes	Cold working
4	Assembly of DSCu plates and SS316L pipes	

Table 2.4 Fabrication steps of the shield block.

Step	Fabrication Process	Remarks
1	Preparation of forged SS316L block	
2	Drilling of internal cooling passages	From both ends
3	Insertion of ice into cooling passages	For suppression of excessive deformation
4	Bending of shield block	Cold working
5	Solution annealing	1010-1054 ℃, 9.75 hr
6	Machining of cooling header on the top/bottom surfaces	
7	Welding of closure plates	TIG-welding

In the final step c), all of the first wall elements and the shield block are assembled into one assembly unit, and canned by thin SS plates for the HIP treatment. After evacuating the internal of the canned assembly, it is HIP treated in the HIP furnace, and then the can liners are removed by machining and coolant feed/return pipes are welded. Detailed conditions on the HIP process are described in (2). Flow charts of the assembly process and HIP canning process are schematically shown in Figs. 2.11 and 2.12, respectively.

(2) HIP conditions

For the fabrication of a shielding blanket integrated with the first wall, JAHT has pursued to apply one-step solid HIP joining from the following views, a) solid HIP bonding is a non-melting welding method with a potential capability of minimizing welding deformation and residual stress, realizing higher mechanical strength of the joints, almost close to the base metals in case of identical materials joints, and relaxing IASCC concern under the anticipated high neutron and stress fields, all of which are relative to fusion welding, b) solid HIP bonding can provide better dimensional accuracy during fabrication process and more stable metallurgical microstructures, relative to powder HIP joining, and (c) one-step HIP joining has advantages in terms of minimizing grain coarsening effects during fabrication heat cycles and reducing fabrication steps and cost, relative to multi-step HIP joining. The concept of one-step HIP joining is schematically shown in Fig. 2.13.

Based on the selection studies of the optimum HIP conditions applicable to the combinations of SS316/SS316, SS316/DSCu and DSCu/ DSCu, and a series of related studies, in particular, on the mechanical strength evaluations of the HIP joints[9, 10, 13, 20, 22, 23], the HIP conditions shown in Table 2.5 are to be applied on the present fabrication, namely, at the temperature of 1050 ℃ and the pressure of 150 MPa in 2 hr. These conditions have been applied to the small scale primary first wall panels and small and medium scale shield blanket mock-ups integrated with the first wall, and satisfactory quality of the HIP joints has been confirmed both by destructive examinations of the fabricated mock-ups [2-8, 24] and by both of thermo-mechanical performance tests and low cycle mechanical fatigue test [16-21, 24].

Fine surface finish of the HIP interface by precise machining and careful surface preparation prior to the HIP treatment are very important factors to realize high quality HIP joints. For this, all of the HIP interface surfaces are machined to realize fine surface finish of around 2 μm, and then wiped by acetone to remove oxide and hydrocarbons from the surfaces. Furthermore, special attention is paid on the DSCu plates, which are degassed, prior to the assembling, in a vacuum furnace to outgass any moisture or air trapped on the surfaces. Prior to the HIP treatment the internal of the canned HIP assembly is evacuated down to 10^{-5} Torr by baking the assembly at the temperature of 500 ℃ for 30.5 hr.

Time evaluations of the temperature and pressure to be applied during the HIP treatment are schematically shown in Fig. 2.14. At first, the temperature of the work, monitored by thermocouples attached, is raised up to 900 ℃ and are kept for around four hours to realize uniform temperature distribution within the work as much as possible. At the same time, the pressure applied is raised gradually, and finally reaches the nominal conditions of 1,050 ℃ and 150 MPa. After keeping these conditions for two hours, the temperature and the pressure are lowered down gradually, as shown in Fig. 2.14.

Table 2.5 HIP conditions applied to the prototype mock-up fabrication for joining SS316/SS316, SS316/DSCu and DSCu/DSCu in one-step HIP cycle.

Item	Unit	Specifications
Temperature	℃	1,050
Pressure	MPa	150
Holding Time	hr	2
Surface Finish	μm	~2 (mean)
Surface Treatment	-	Cleaning by acetone
Internal Vacuum	Torr	10^{-5} after 500 ℃, 30.5 hr baking*

* DSCu plates are pre-baked in a vacuum furnace at 800 ℃, 2 hr.

(3) Inspections

As a course of quality assurance, a series of inspections are applied in each fabrication step. They are categorized into a) visual inspection and dimensional check, including first wall thickness measurement by ultrasonic testing, b) pressure boundary integrity tests such as pressure test and He leak test, and c) tests on integrity of the welding lines such as penetrant test and radiographic test. Inspection items and specifications are summarized in Table 2.6.

Pressure test is to be performed by applying water pressure of 60 kg/cm^2 for 30 min to all of the cooling lines, and any leakage or excessive deformation is checked. Helium leak test is to be performed by evacuating the cooling channel of the first wall and the cooling passages of the shield with the allowable He leak rate of less than 1.0 x 10^{-7} Torr l/sec. Non-destructive inspections are to be applied for the detectable area of the HIP bonded joints by Ultra-sonic Test (UT) from the surface, and existence of defects are checked with the detectable limit of around 1 mm. The dummy part of the prototype mock-up is to be cut off after the HIP process and be destructively examined in terms of HIP bonded interface quality, deformation of the cooling channels and any change of the metallurgical quality.

Table 2.6 Inspection items and specifications.

No.	Inspection Item	Specifications
1	Visual inspection	No harmful flaws and defects
2	Dimensional test	Specified in each step
3	Pressure test	No leakage and deformation at 60 kg/cm^2 for 30 min
4	He leak test	Less than 1.0 x 10^{-7} Toll.l/s by hood method
5	Penetrant test	No indication
6	Radiographic test	No indication
7	Ultrasonic test	No detectable flaw at HIP interface DSCu layer thickness from cooling pipe to FW surface within 5 +/- 0.5 mm

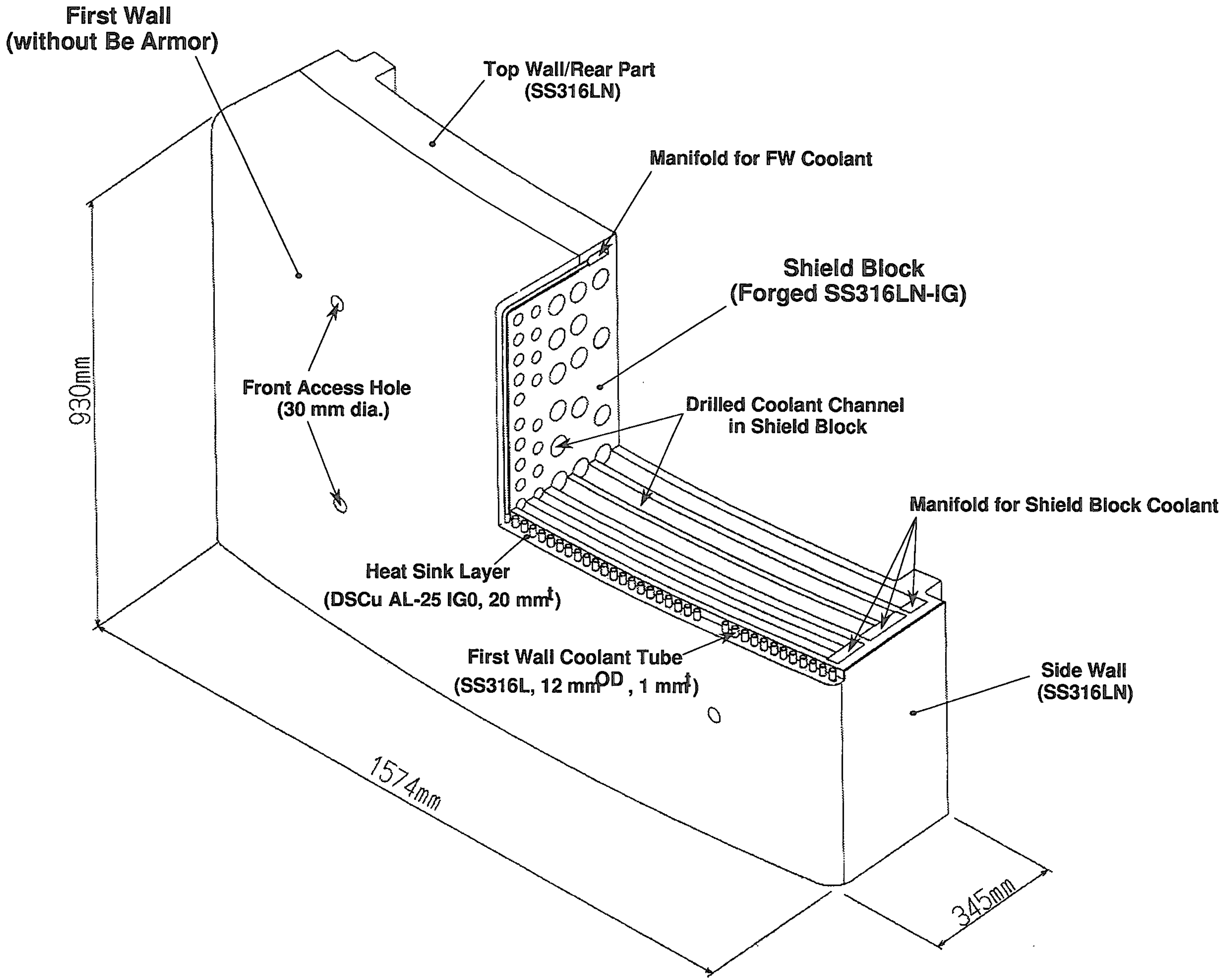


Fig. 2.1 A cut-away-view of a primary first wall prototype mockup

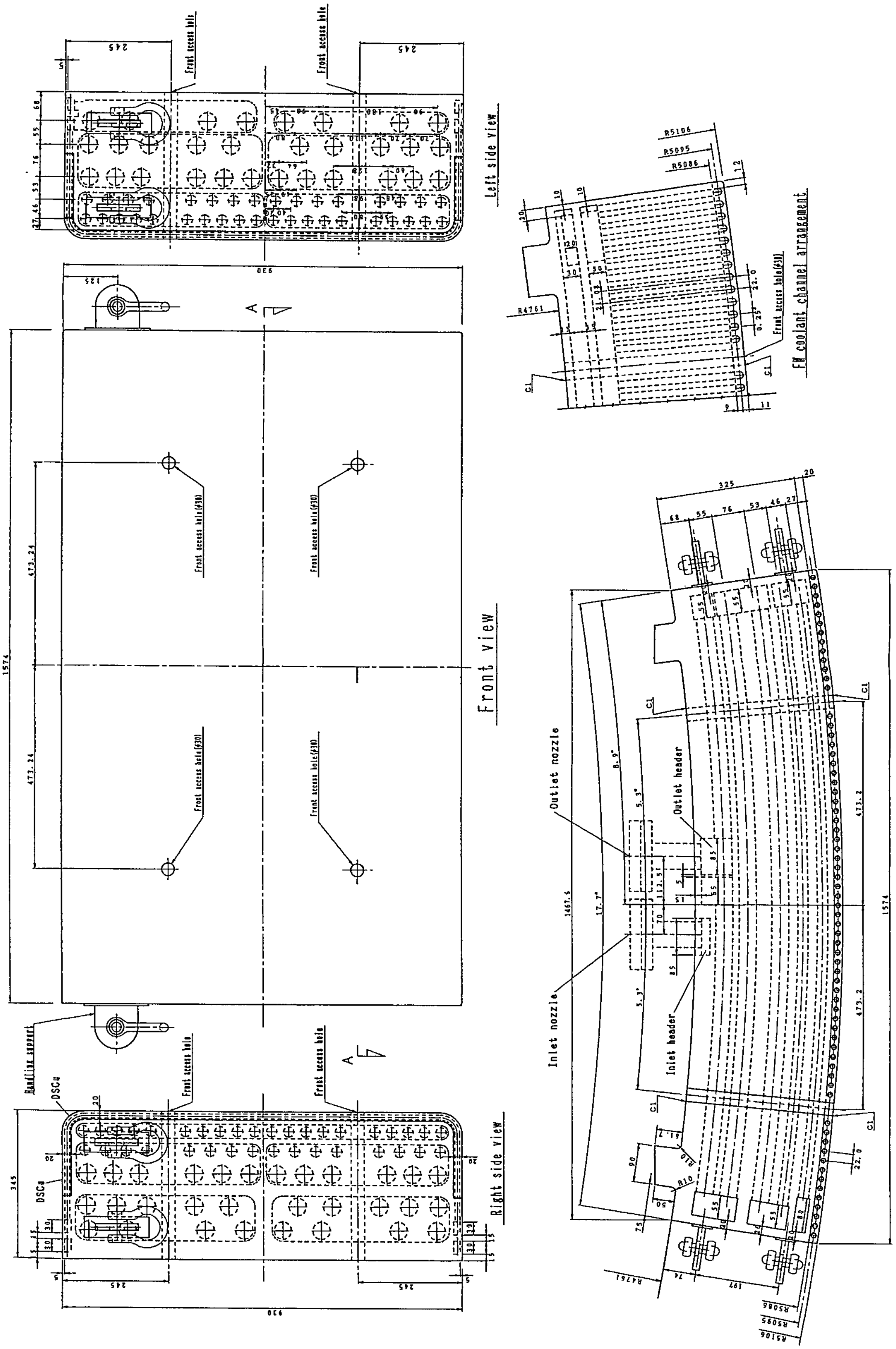


Fig. 2.2 Fabrication drawing for an ITER shielding blanket prototype mockup.

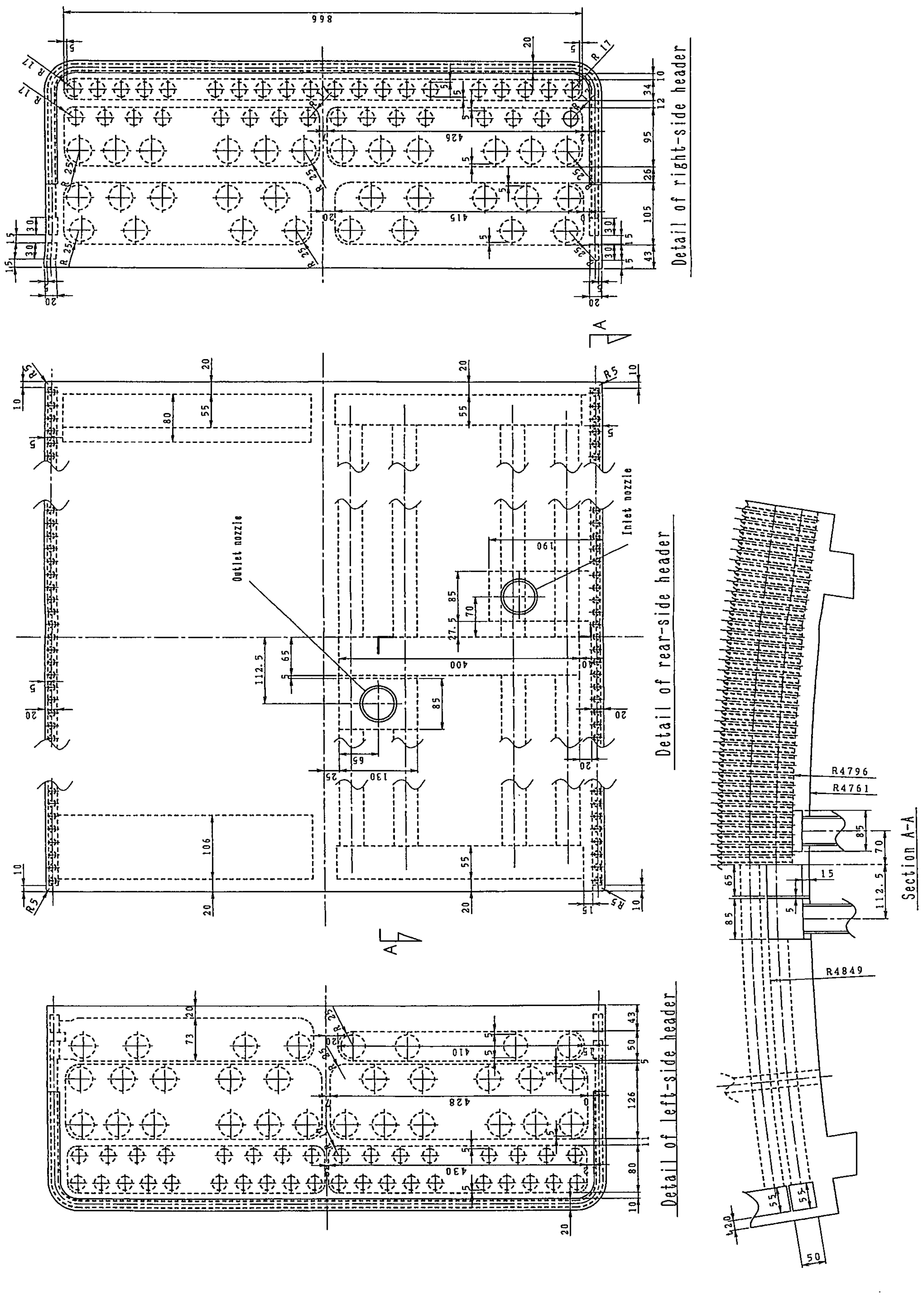


Fig. 2.3 Fabrication drawing for an ITER shielding blanket prototype mockup.

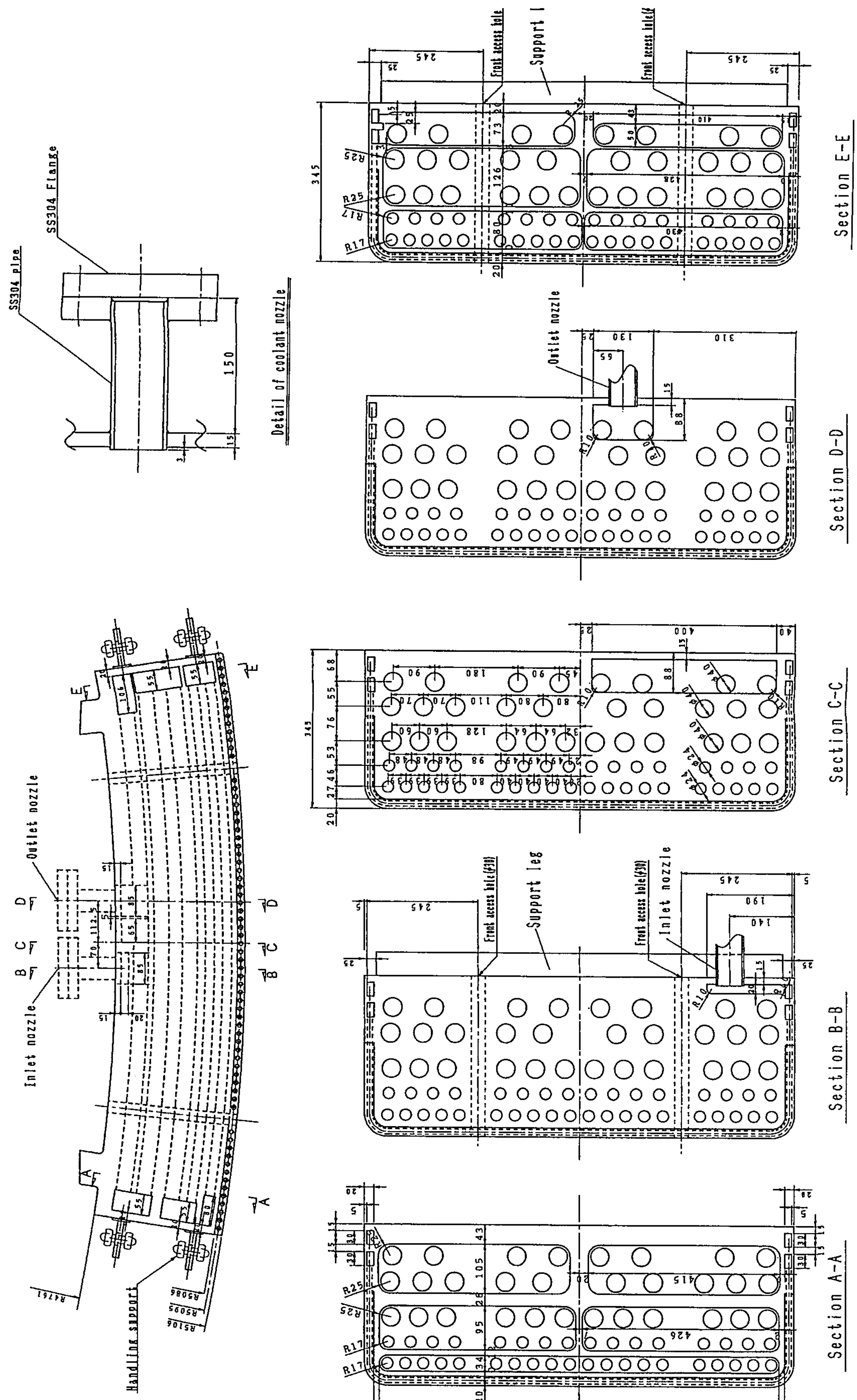


Fig. 2.4 Fabrication drawing for an ITER shielding blanket prototype mockup.

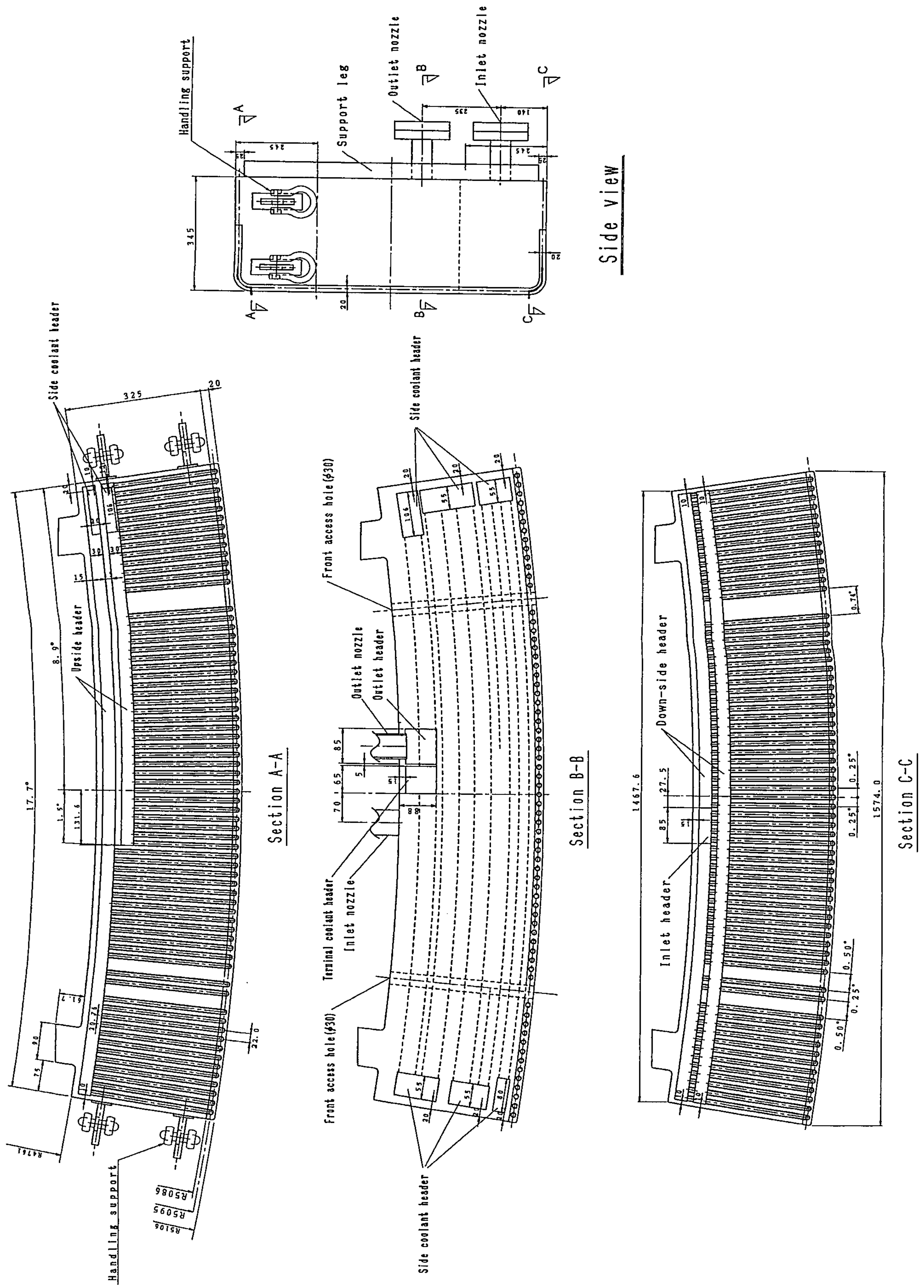


Fig. 2.5 Fabrication drawing for an ITER shielding blanket prototype mockup.

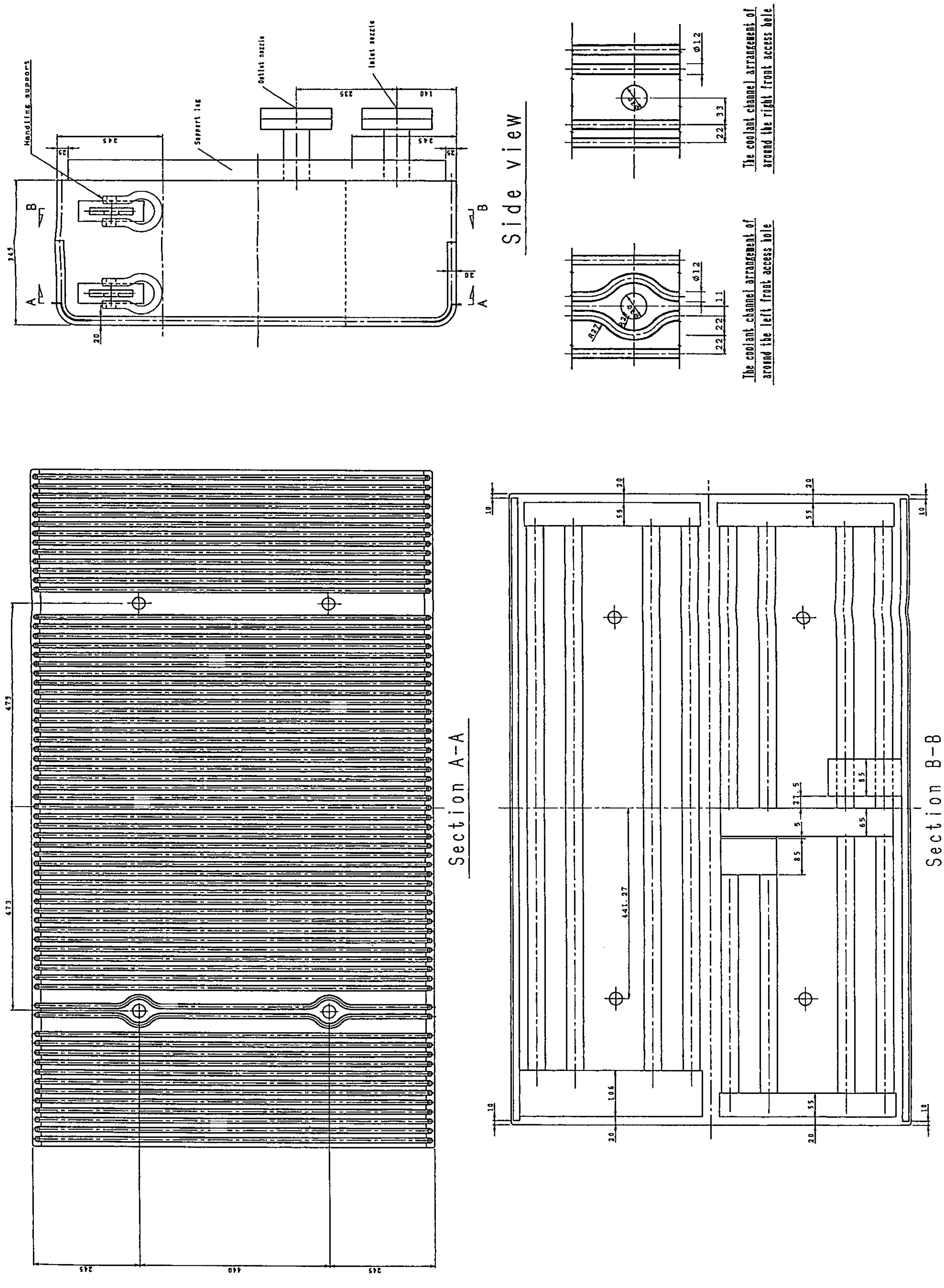


Fig. 2.6 Fabrication drawing for an ITER shielding blanket prototype mockup.

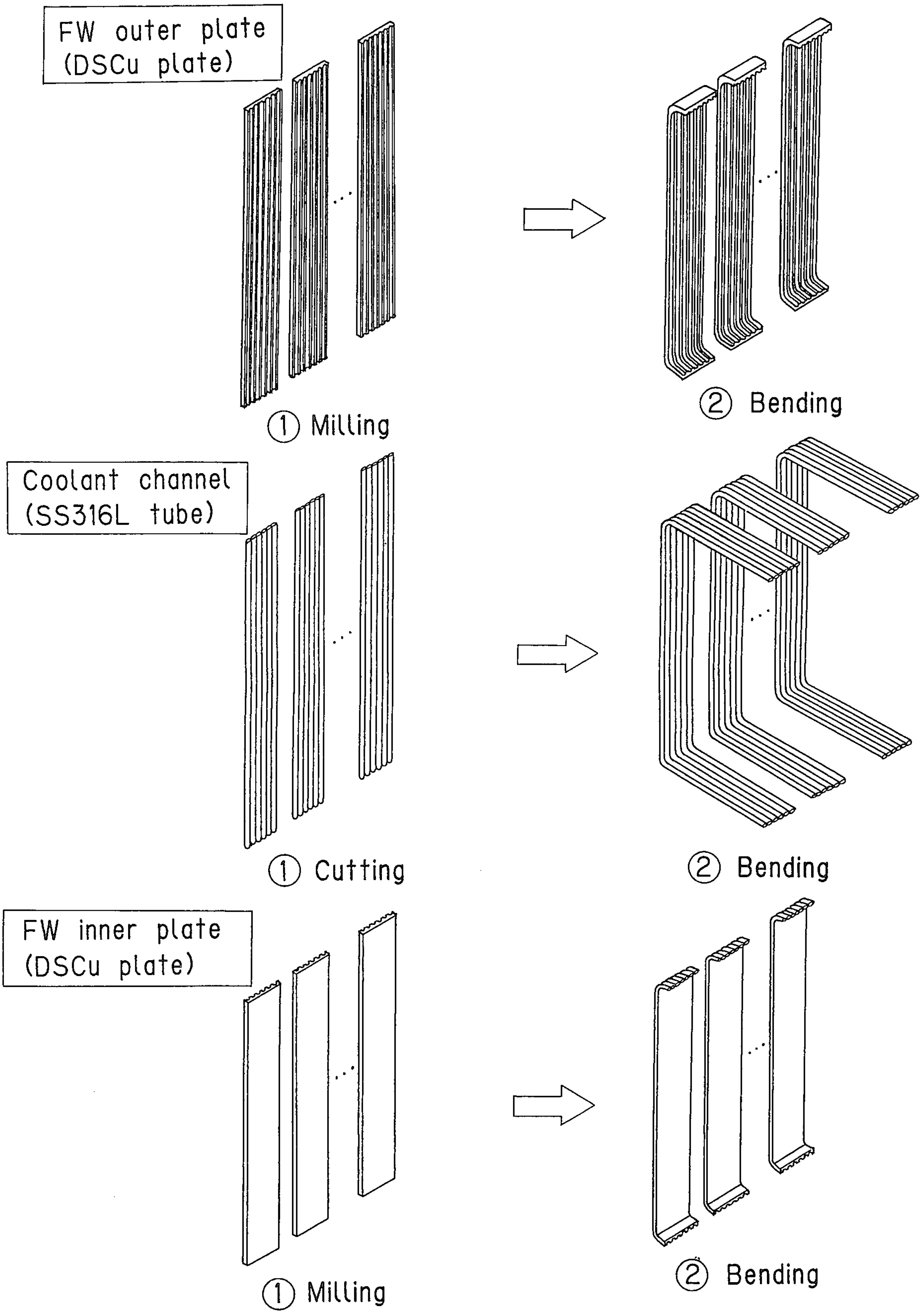


Fig. 2.7 Flow diagram of the first wall fabrication route.

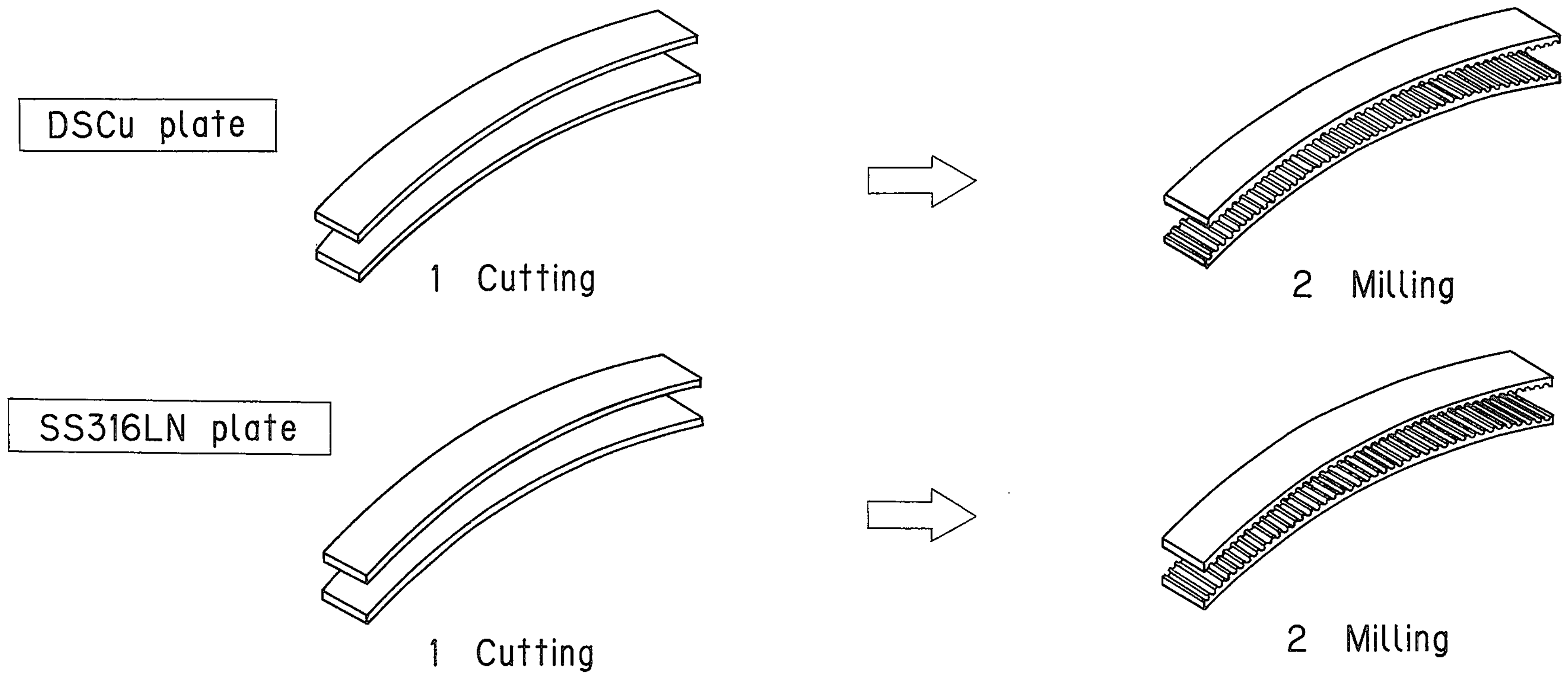


Fig. 2.8 Fiow diagram of the top and bottom wall fabrication route.

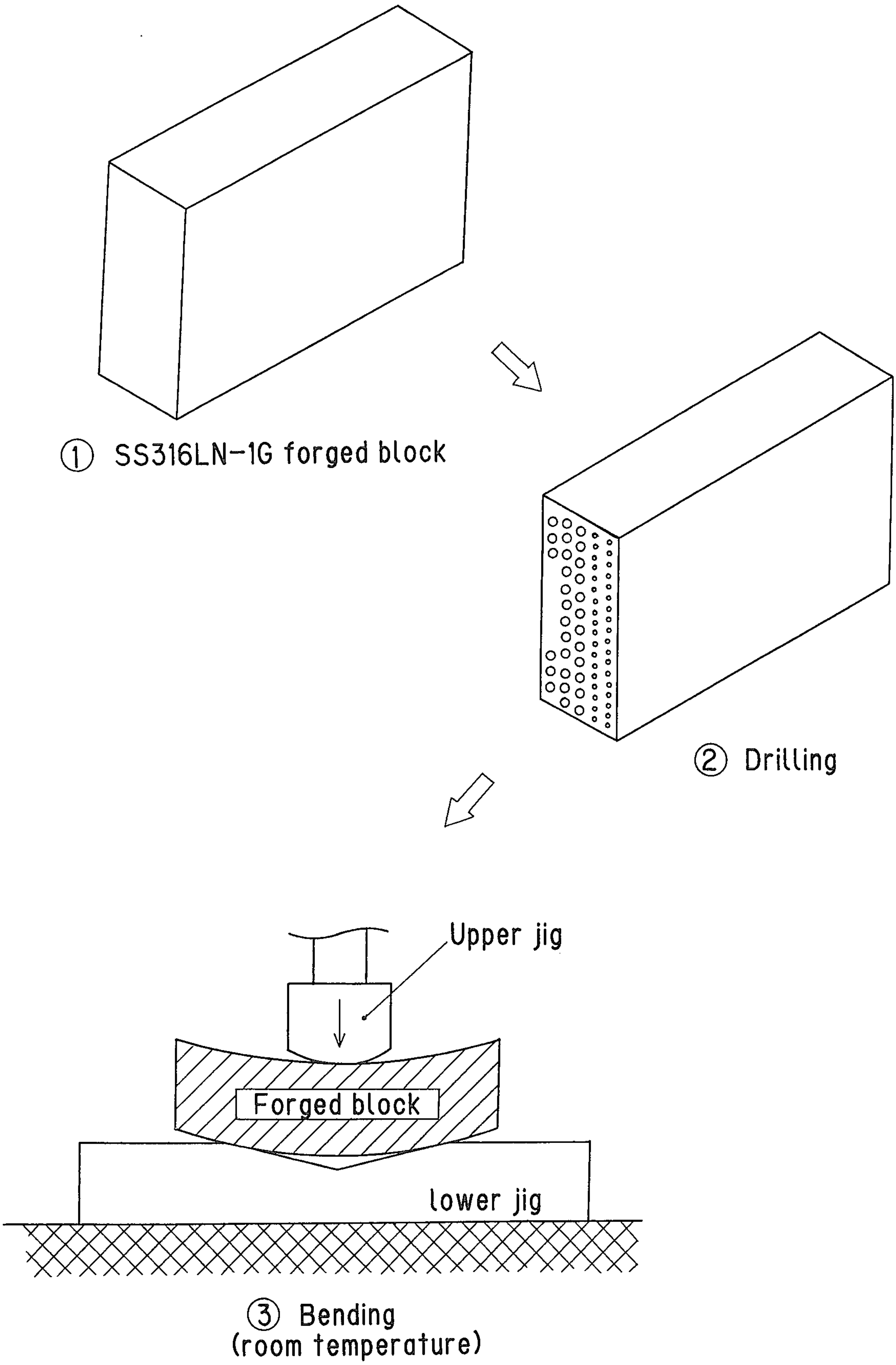


Fig. 2.9 Flow diagram of the shield block fabrication route.

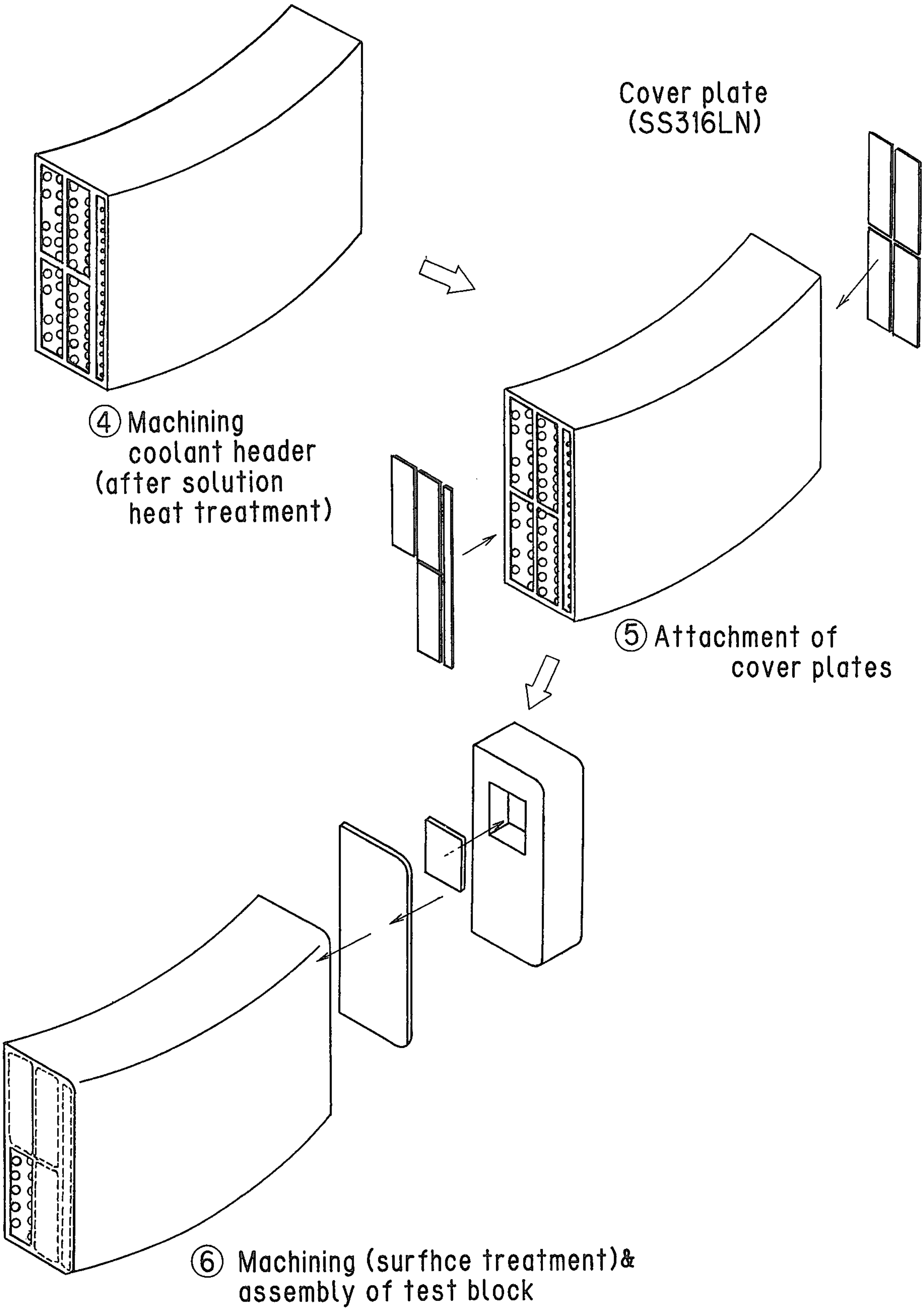


Fig. 2.10 Flow diagram of the shield block fabrication route.

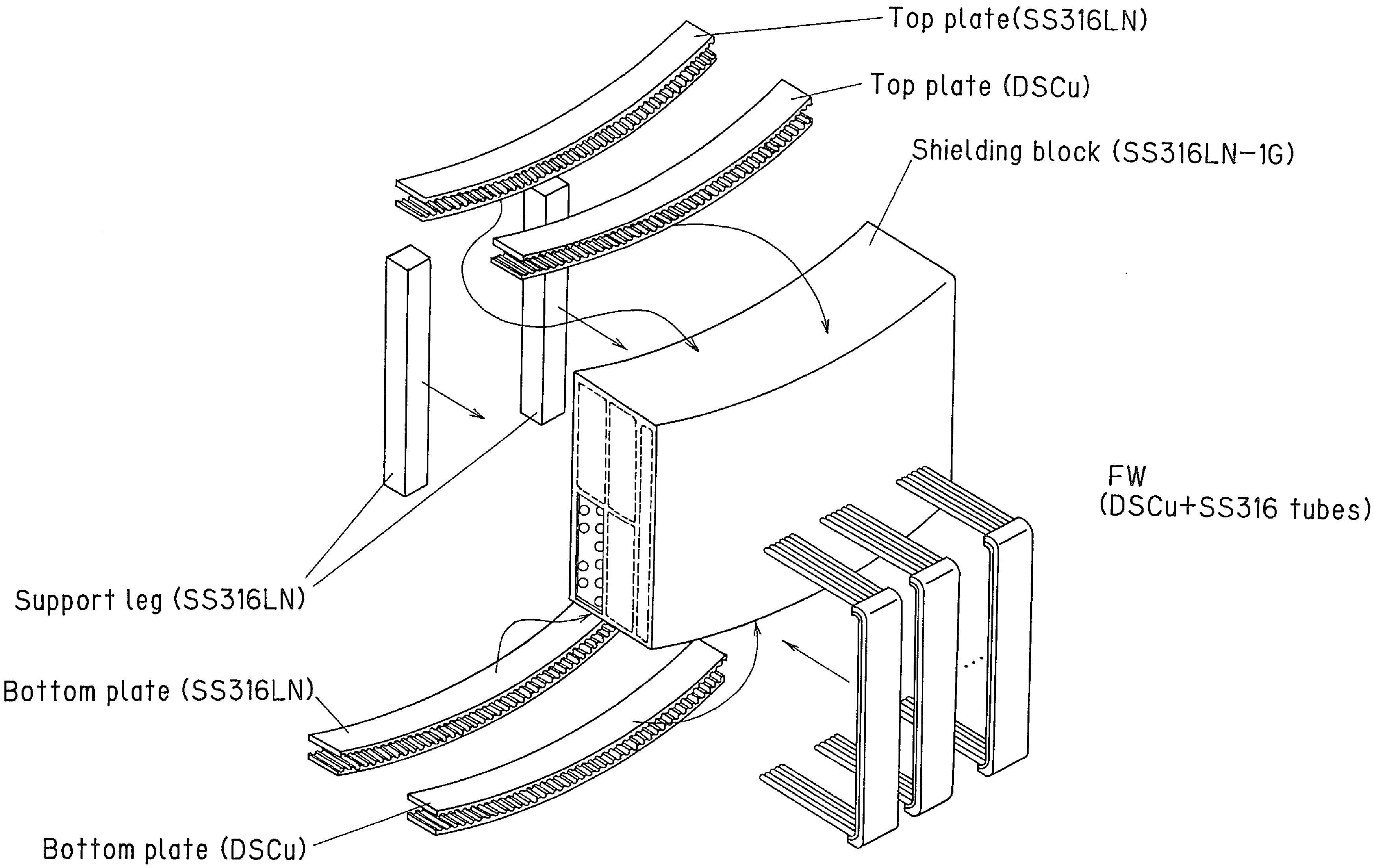


Fig. 2.11 Assembly of the shield block and the first wall parts before HIPping.

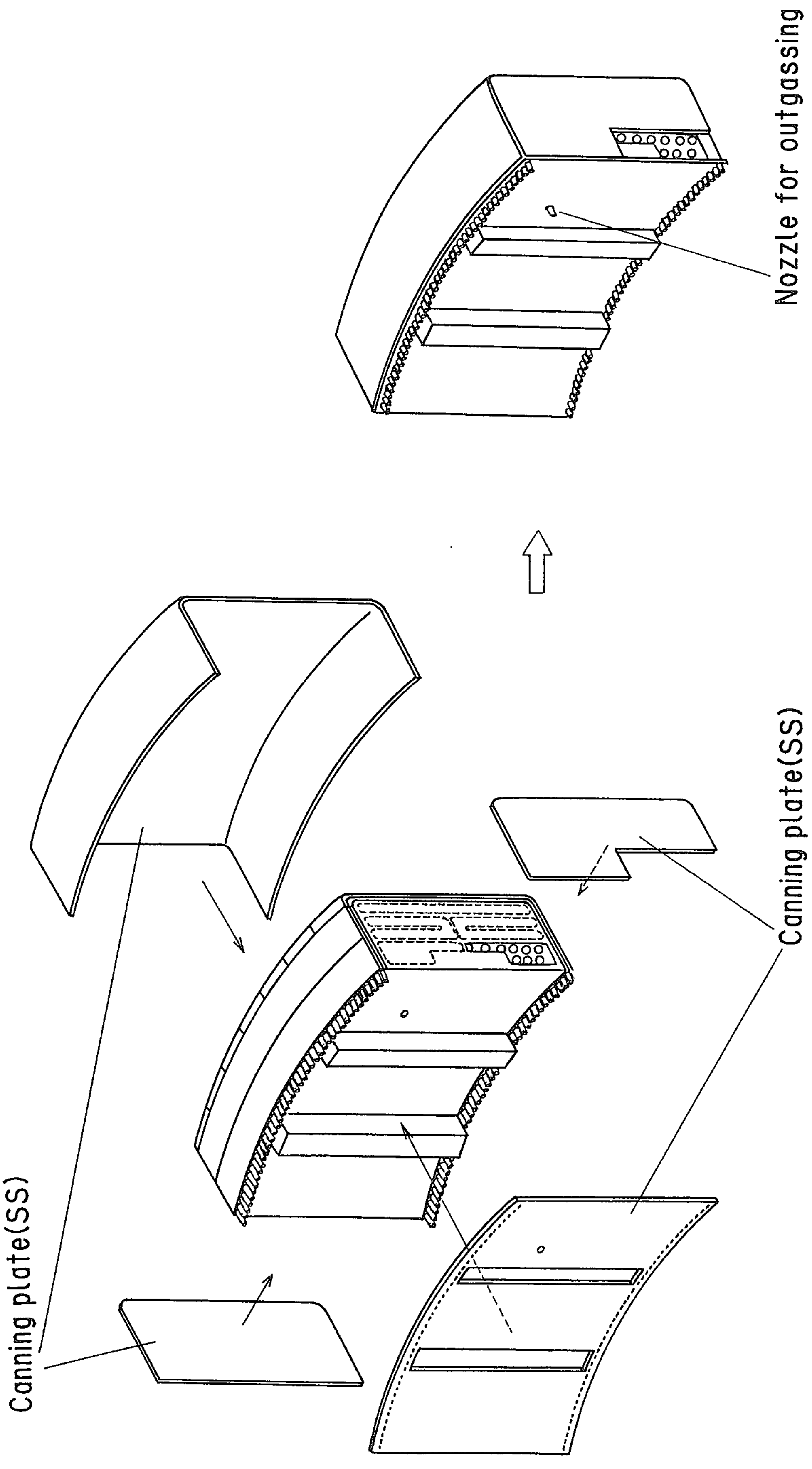


Fig. 2.12 Canning procedure for HIPping.

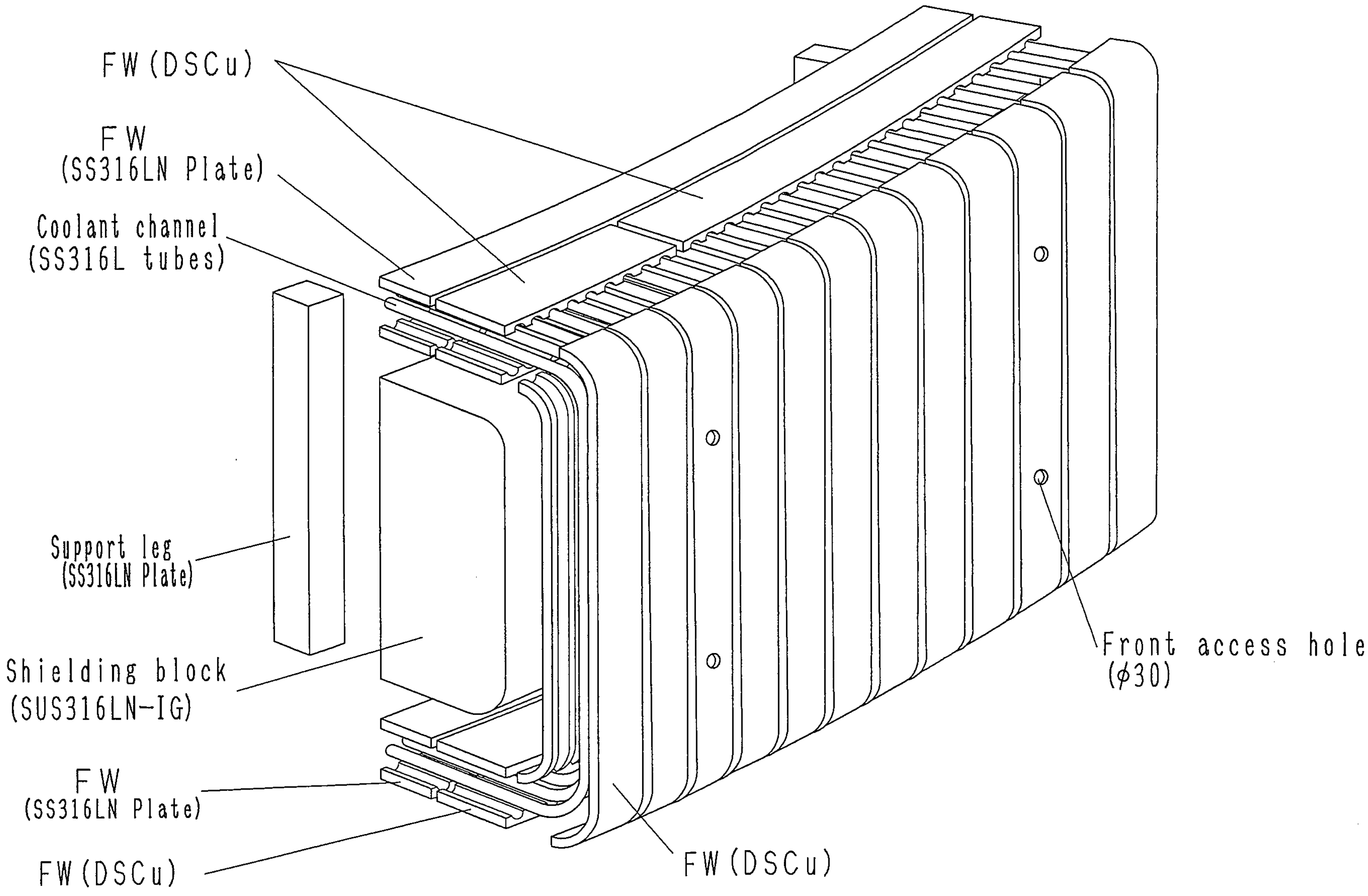


Fig. 2.13 A concept of a single-step HIP joining of the shield block with the first wall.

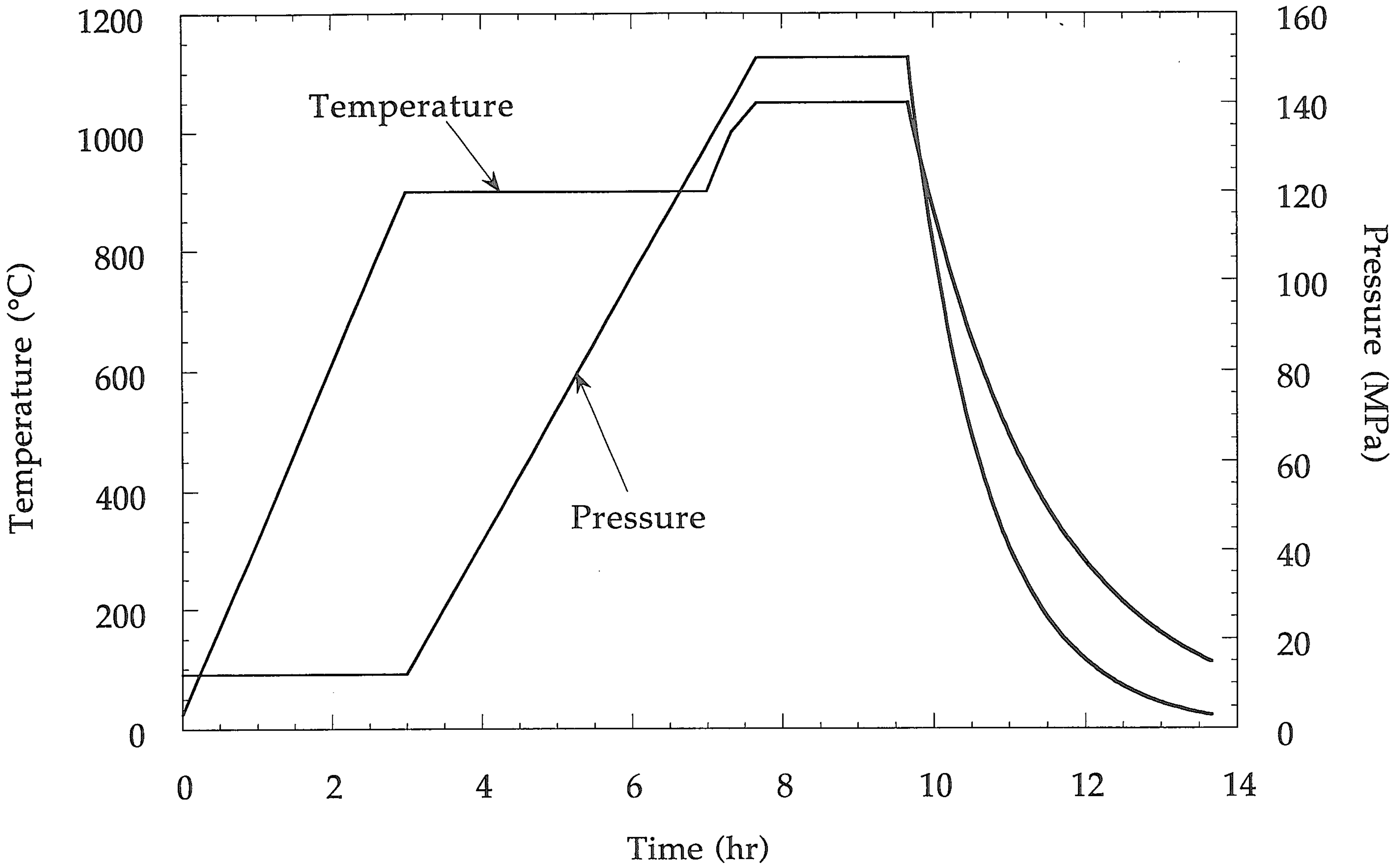


Fig. 2.14 Typical time histories of the work temperature and applied pressure during the HIP process

3. Preparatory tests

Prior to the fabrication of the prototype primary first wall module mock-up, preparatory tests were performed on the bending technology to examine the applicability of the candidate fabrication methods. In the following the results of the preparatory tests with their implication to the selection of the fabrication methods is described.

In order to examine the deformation of the internal cooling passages of a massive block during the cold press bending process, preparatory tests were performed by using a one-tenth model with internal holes.

The block made of SS316L with a dimension of 180 mm x 40 mm x 100 mm and three longitudinal holes of 3.2-mm-diameter, was prepared and bent by a cold press machine with a pair of pressing jigs, as shown in Fig. 3.1. Three points bendings were performed by the combination of upper and lower jigs. Two kinds of upper jigs with a dimension of 45 and 200 mm radius, were used. Also, the bendings of a block with insertion materials were performed to prevent excessive deformation of the holes. In this trial, iced water was inserted into the holes. The bendings were performed at -60 ℃. The load/deformation curve obtained by the test using the upper jig with 200 mm radius, is shown in Fig. 3.2. From the curves, it was found that it needed 52 and 57.4 ton for the 45 and 200 mm radius upper jigs to get the specified deformation, respectively, and the cold bending by about 6,000-ton pressing machine was required for the prototype. After the bendings, this block was cut into two pieces and deformation of the holes was measured. Appearance of one of the cut pieces are shown in Fig. 3.3. It is shown that the deformation was suppressed well by the iced water. AsMeasured deformation rates R_b of each of the hole caused by cold press bending, defined by $R_b = (D_i-D_0)x100/D_0$ where D_0 and D_i are the hole diameters in the load direction before and after the cold pressing, respectively, are plotted along the longitudinal direction. As shown in Fig. 3.4, measured deformation rates were below 3 and 6 % for the 45 and 200 mm radius upper jigs, respectively. From these trials, it was decided to apply the iced water for the insertion material into the internal cooling passages of the shield block in the cold press bending process and the upper jig with 200 mm radius.

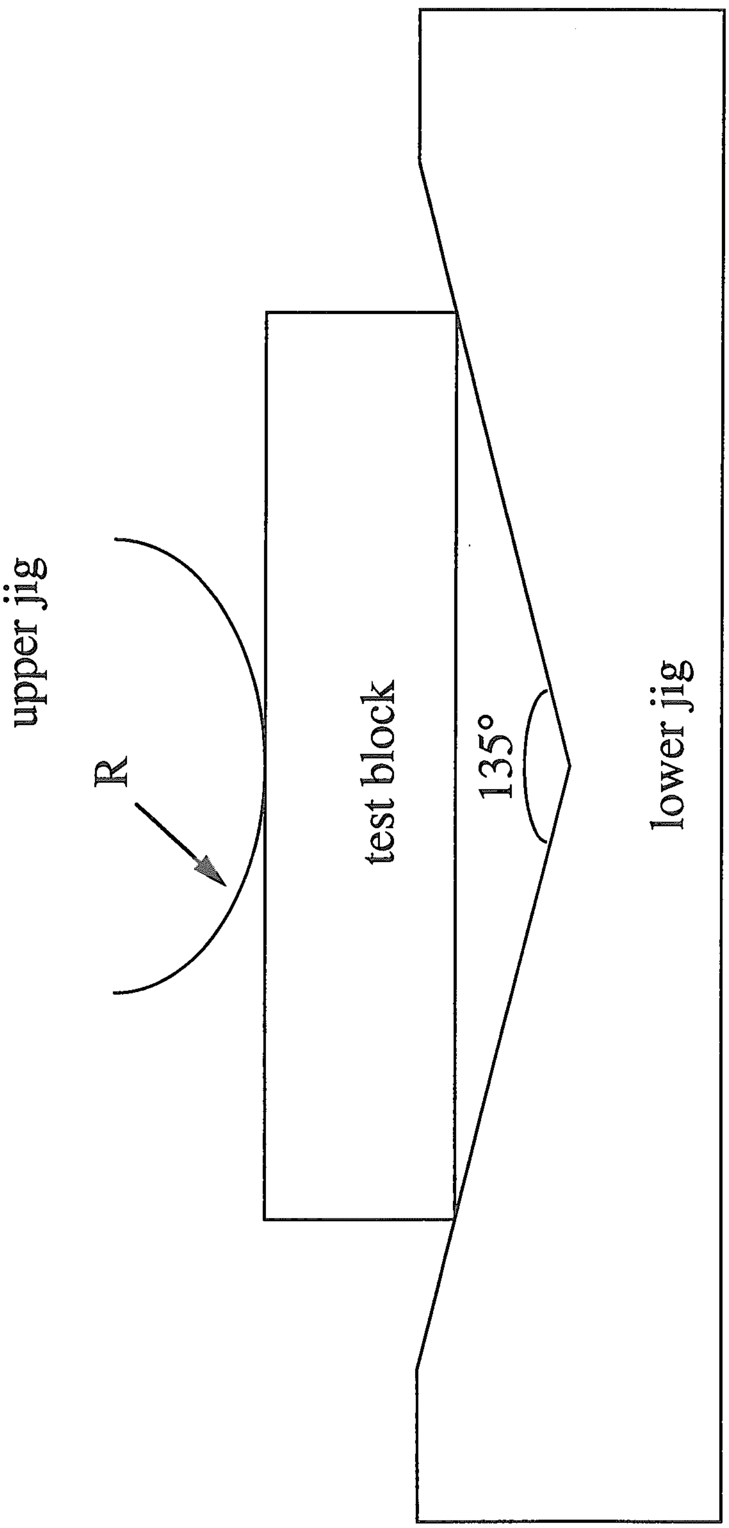


Fig. 3.1 A image of the preparatory three point bending tests

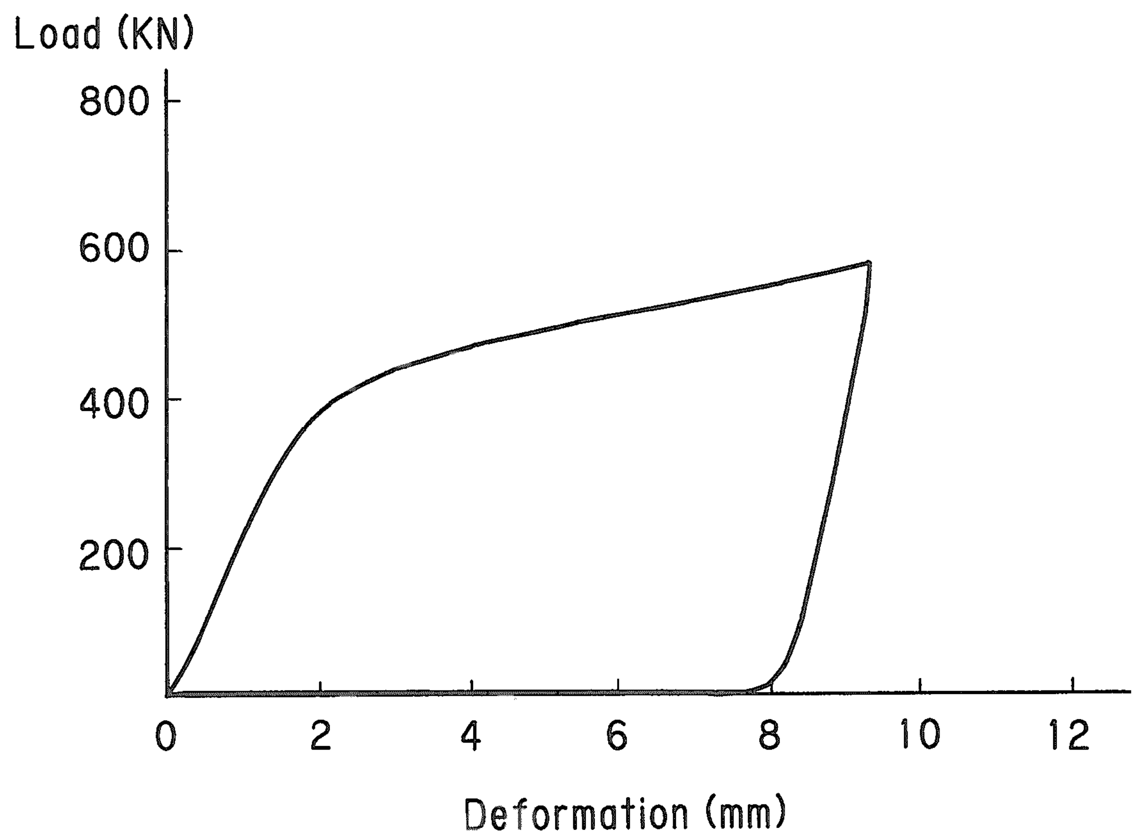
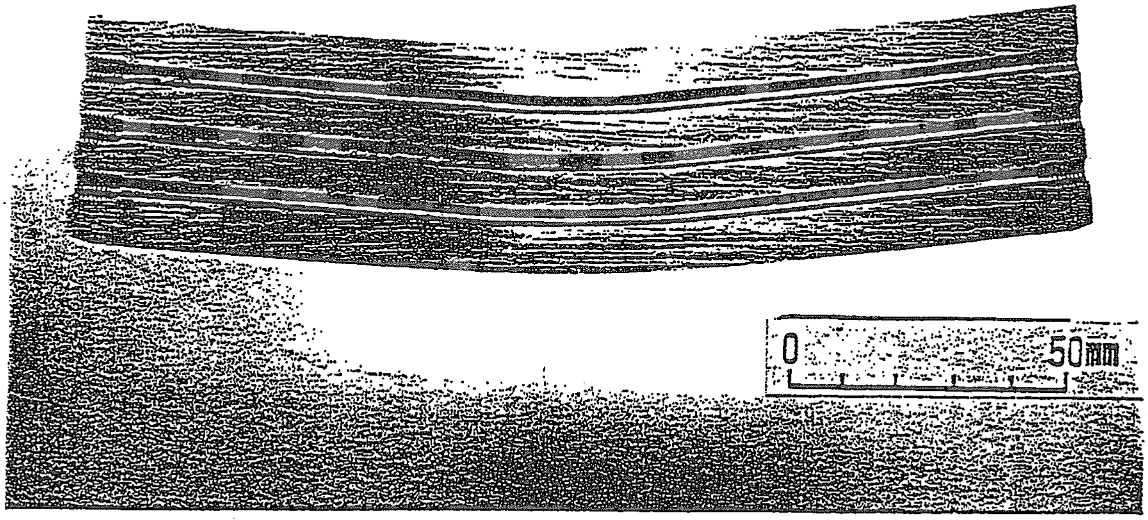
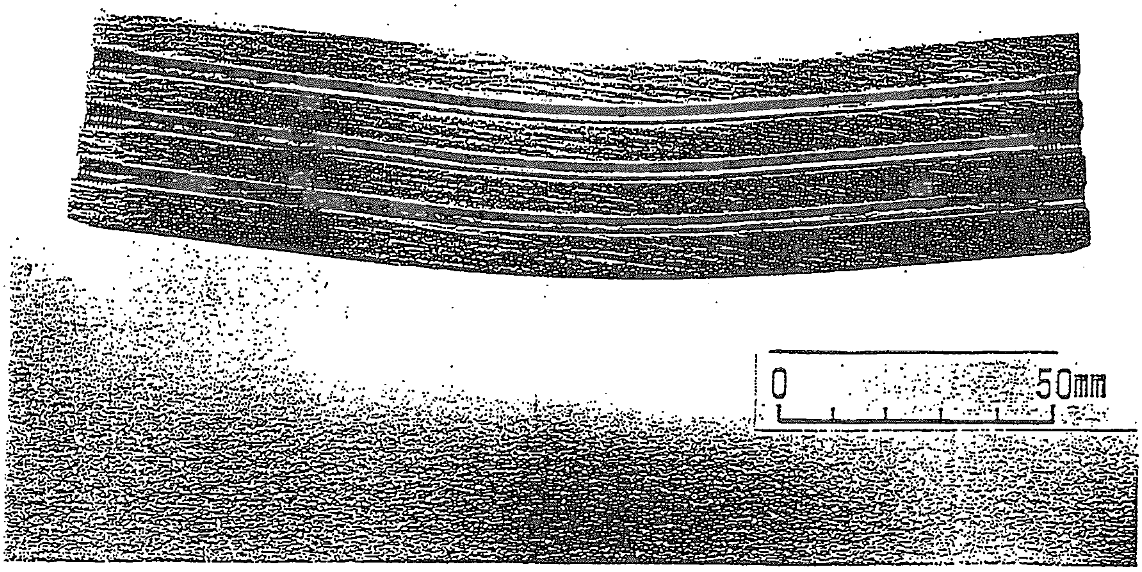


Fig. 3.2 A load/deformation curve for the preparatory three point bending test used by the upper jig with 200 mm radius.



Upper jig : 45 mm radius



Upper jig : 200 mm radius

Fig. 3.3 A cut-away cross sectional view of the test block after cold pressing.

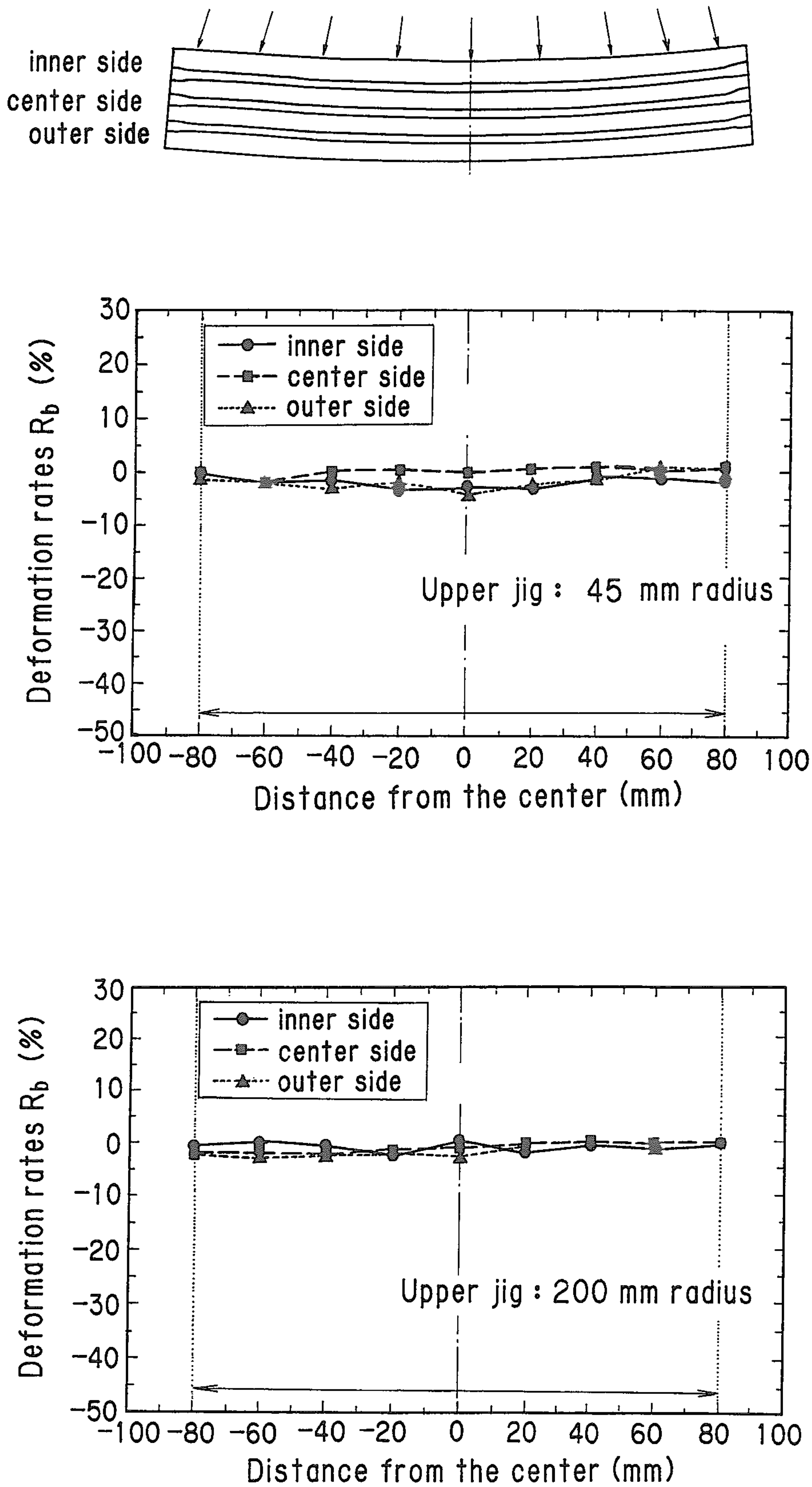


Fig.3.4 Deformations along the cooling lines of the test block after cold pressing.

4. Fabrication of Prototype Mock-up

4.1 Fabrication Results

(1) Shield Block

SS316LN forged block delivered was pre-machined, and then sent to the drilling process. Internal cooling passages were drilled by a drilling mill under the conditions listed in Table 4.1. Drilling was started with an end mill machining for precise positioning of the hole locations, followed by four steps deep drillings. Final appearance just after the end mill machining process is shown in Fig. 4.1. Each of the deep drilling processes can be seen in Figs. 4.2 and 4.3, and a final appearance just after the drilling process is presented in Fig. 4.4. After four steps of deep drillings, diameter and arrangement of the cooling passages at the edge of the block were measured by calipers. Cooling passages with 40 and 24 mm diameter were within 40.0 - 40.3 and 24.1 - 24.2 mm, respectively, and they could satisfy the specified tolerances (±0.3 and ±0.2 mm for cooling passages with 40 and 24 mm diameter, respectively). Difference from the specified pitches of the cooling passages were within ±0.3 mm for the intervals less than 128 mm, and ±0.5 mm for the intervals more than 128 mm, and they also could satisfy the specified tolerances.

Table 4.1 Conditions for deep drilling

Item	24-mm-diameter hole			
	0-300 mm	300-550 mm	550-870 mm	870 mm-
Length of drill	450 mm	700 mm	1050 mm	1200 mm
Rotation speed of drill	110 rpm	110 rpm	110 rpm	35 rpm
Traveling speed (machining speed)	10 mm / min	10 mm / min	10 mm / min	3 mm / min
Cutting length by 1 step	3.5 mm	3.5 mm	3.5 mm	0.5 mm

Item	40-mm-diameter hole			
	0-300 mm	300-550 mm	550-870 mm	870 mm-
Length of drill	450 mm	700 mm	1050 mm	1200 mm
Rotation speed of drill	90 rpm	90 rpm	90 rpm	35 rpm
Traveling speed (machining speed)	9 mm / min	9 mm / min	9 mm / min	3 mm / min
Cutting length by 1 step	3.5 mm	3.5 mm	3.5 mm	0.5 mm

After deep drilling process, the forged block was bent by 10,000 ton press machine to provide the specified curvature. During the bending, iced water was inserted into the drilled holes to prevent excessive deformation of the holes. After water was inserted into the drilled holes in the room temperature, the forged block with the water was frozen to -90 ℃ by the liquid nitrogen. During the freezing process, temperatures of the block were measured by the thermo-couples (Fig. 4.5) and the block was controlled to be kept -90 ℃. After the freezing process, the forged block was cold pressed by 10,000-ton-capacity pressing machine, as shown in Fig. 4.6. After checking rough dimensions of the bent block, as shown in Fig. 4.7, it was then solution annealed at the temperature range of 1,010 to 1,054 ℃ for less than 9.75 hr, as shown in Fig. 4.8. After the bending process, diameter of the 1st raw cooling passages at the edge of the block were measured by cylinder gauge in order to evaluate the deformation due to the bending process. Measured deformations R_b of each of the hole caused by cold press bending, defined by $R_b = D_i - D_0$ where D_0 and D_i are the hole diameters in the load direction before and after the cold pressing, respectively, are plotted along the longitudinal direction. Plugs were installed at the inlet of the cooling passages in some passages, and deformation were compared for the cases with/without the plugs. Maximum deformations are 0.29 and 0.61 mm in the cases with and without plugs, respectively, as shown in Fig. 4.9. So it was found that deformation could be reduced by a factor of more than two by the plugs.

After the bending process, the edge of the block were cut away, and the length of the block was reduced from 1800 mm to 1574 mm. After the cutting away process, diameter of the cooling passages at the edge of the block were measured by cylinder gauge. Cooling passages with 40 and 24 mm diameter were within 40.0 - 40.8 and 24.1 - 24.8 mm, respectively, and they could satisfy the specified tolerances (±1.0 and ±1.5 mm for cooling passages with 40 and 24 mm diameter, respectively).

(2) Assembly and HIP Treatment

Parts of the first wall element (first wall, top wall and bottom wall) were machined and bent, and all of the first wall elements were assembled with the shield block into one assembly, as shown in Figs. 4.10 and 4.11. This assembly was canned by TIG seam-welding of 3-mm-thick SS304 plates as shown in Fig. 4.12, and HIPped together (single step HIP) under the HIP conditions shown in Fig. 2.14. The prototype installed in the HIP facility is shown in Fig. 4.13. A lot of thermo-couples were attached to the mock-up, and the temperatures at the mockup surface and inside the first wall cooling channels were monitored during the HIP process. The measured temperatures were within 1050 ± 7 ℃, so the HIP process was successfully performed. After the HIPing, the mock-up was finally machined, and coolant manifold cover plates and supply/return pipes were welded. The final appearance of the fabricated proto-type mock-up is shown in Fig. 4.14.

4.2 Inspections

Through the fabrication, a series of inspections, summarized in Table 2.6, were performed by a non-destructive manner. The results were shown in Table 4.2.

After completing all of the non-destructive inspections, the dummy part fabricated together with the main part was cut away, and the quality of the HIP bonded interface and deformation of the internal cooling passages due to HIP process were examined by a destructive manner.

Typical micro-scopic images at the HIP bonded interfaces are shown in Fig. 4.15 for the DSCu semi-circular grooved plate /SS tube /DSCu semi-circular grooved plate, and SS semi-circular grooved plate /SS tube /SS semi-circular grooved plate bondings. No harmful defeats were observed, and sound bondings were confirmed. Detailed results are listed in Appendix.

Results of the dimensional measurement for this piece are summarized in Table 4.3. Measured locations are shown in Fig. 4.16. Deformations of the outer diameter of the coolant tube were less than 0.5 and 0.8 mm for the straight and corner parts, respectively, except for the tube-1 at the location-D near the evacuating nozzle, and it was found that the dimensional accuracy was well maintained at almost all locations in proto-type mock-up during HIP process. Deformations more than 1 mm were observed for the outer diameter of the cooling tube near the nozzle used for vacuum exhausting before HIPping. At this location, the DSCu intruded into the void of the nozzle. From this results, it can be concluded that the dummy part including one coolant tube will be required to be attached on the main module with the final configuration in order to remove the edge part including the deformed coolant tube.

Table 4.2 Results of non-destructive inspections.

Inspection item	Specifications	Results
Visual inspection	No harmful flaws and defects	No harmful flaws and defects on the surfaces confirmed
Dimensional test	Within specified range	All of the dimensions measured within the specified ranges
Pressure test	No leakage/deform. at 60 kg/cm^2 for 30 min	No leakage and any excessive deformation observed
He leak test	Less than 1.0 x 10^{-7} Toll.l/s	Not detectable (below 6.2 x 10^{-10} Toll.l/s
Penetrant test	No indication	No indication observed
Radiographic test	No indication	No indication observed
Ultrasonic test	DSCu layer thickness over cooling pipe within 5 +/- 0.5 mm	Within the specified range confirmed

Table 4.3 Results of the dimensional measurement

	outer diametr of the cooling pipe				inner diametr of the cooling pipe								
	a	c	e	g	b	d	f	h	i	j	l	k	m
A	12.41	12.35	12.36	12.34	10.60	10.50	10.48	10.54	9.71	2.57	2.52	8.68	8.62
B	12.38	12.21	12.12	12.36	10.61	10.43	10.30	10.54	9.80	2.56	2.54	8.66	8.59
C	12.33	12.44	12.09	12.49	10.55	10.62	10.34	10.67	9.94	2.66	2.61	8.56	8.46
D	13.44	12.81	12.15	12.71	10.79	10.98	10.35	10.90	9.61	2.83	2.84	8.57	8.39
E	12.26	12.30	12.10	12.40	10.38	10.41	10.27	10.55	9.70	2.71	2.72	8.50	8.68
Design Value	12.00	12.00	12.00	12.00	10.00	10.00	10.00	10.00	A, B, C : 10 D : 9.87, E : 9.74	3.00	3.00	9.00	9.00

unit : mm

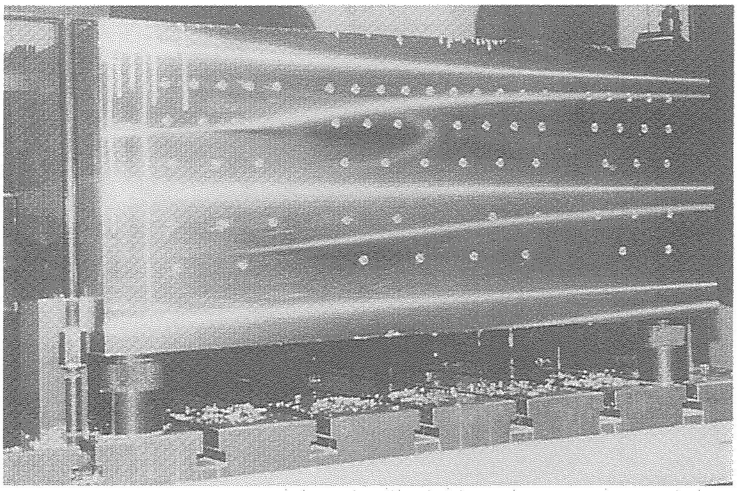


Fig. 4.1 Drilling the shield block - positioning

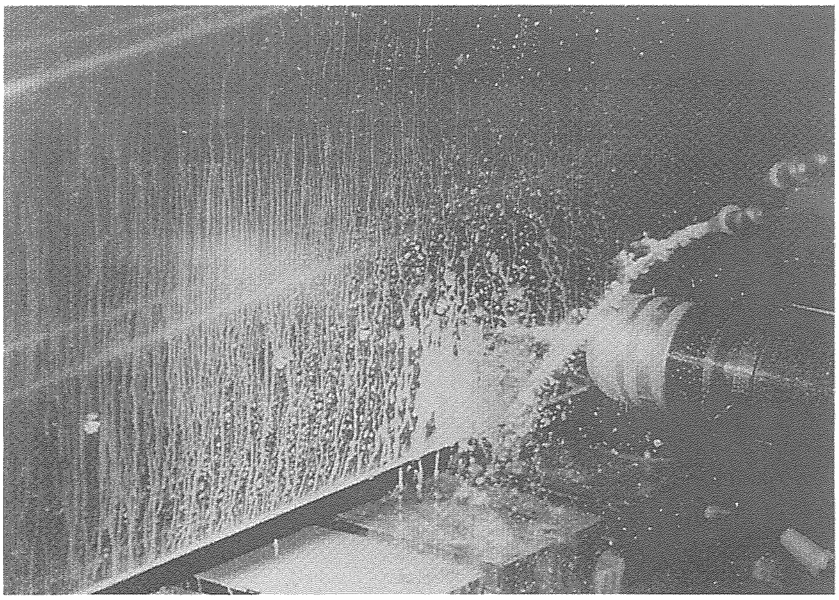


Fig. 4.2 Drilling the shield block - deep drilling

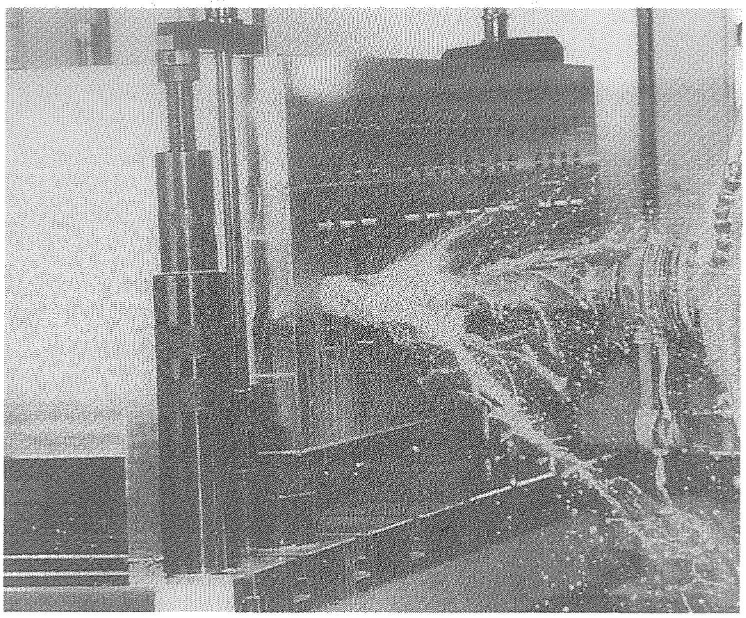


Fig. 4.3 Drilling the shield block - deep drilling

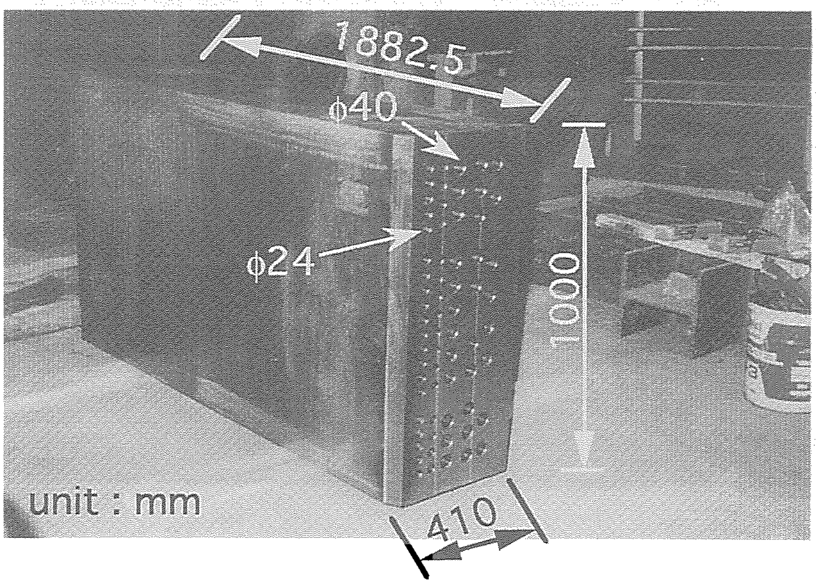


Fig. 4.4 Drilling the shield block - final appearance

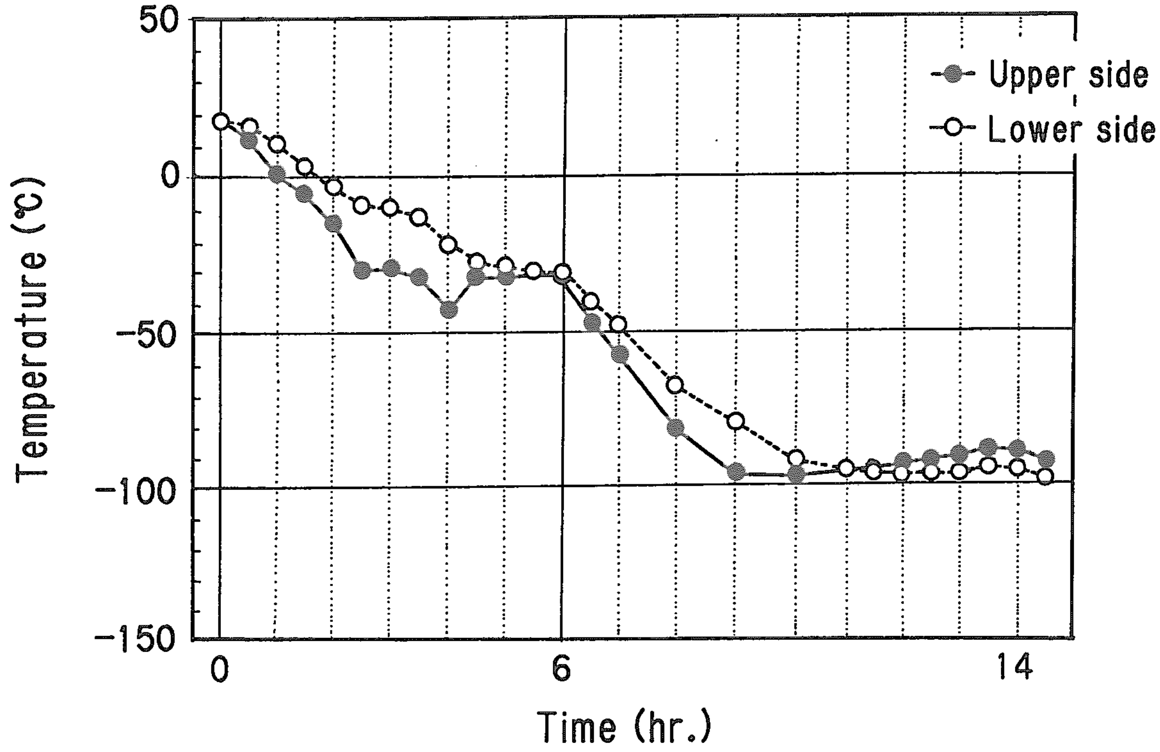
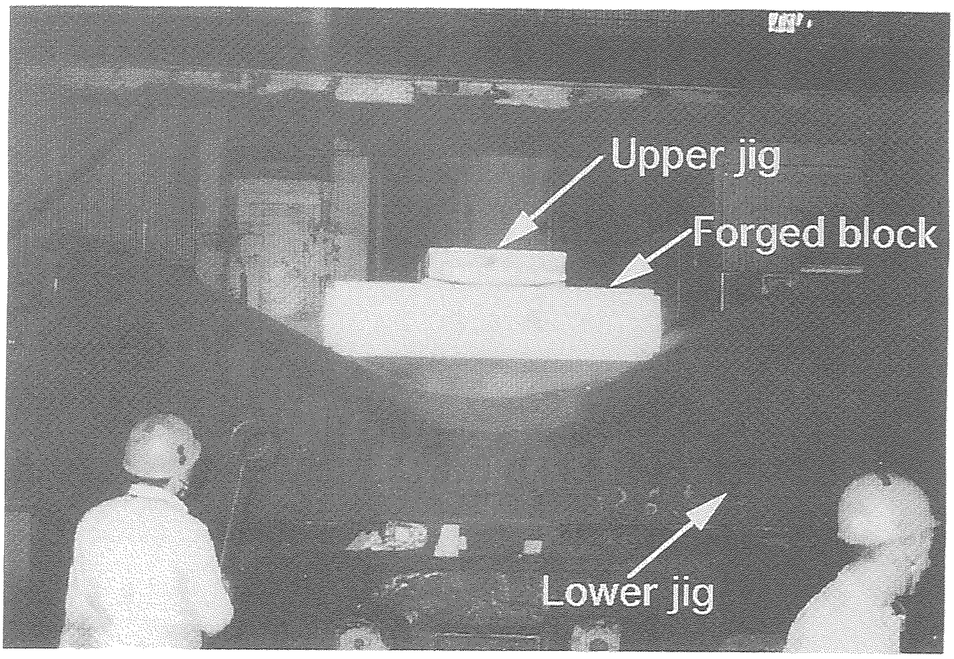


Fig.4.5 Time histories of the temperature during the freezing process.

This is a blank page.



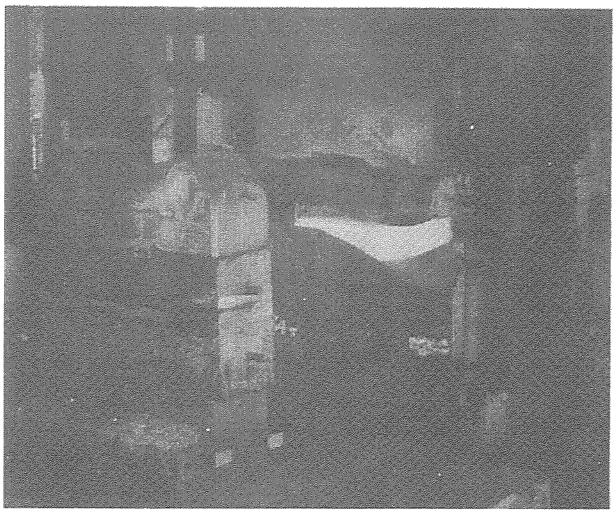


Fig. 4.6 Shield block before and during cold pressing

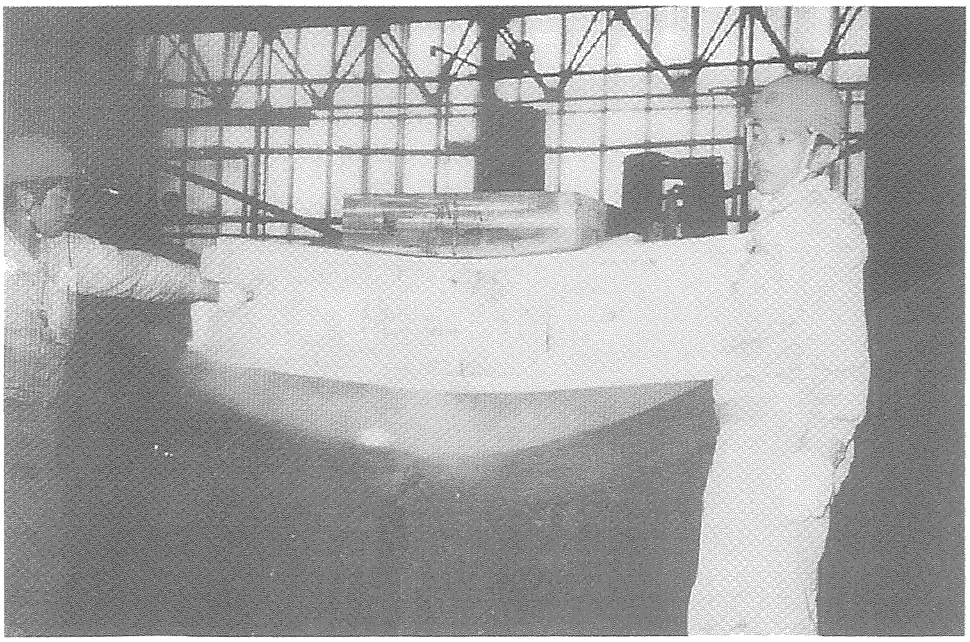


Fig. 4.7 Shield block after cold pressing

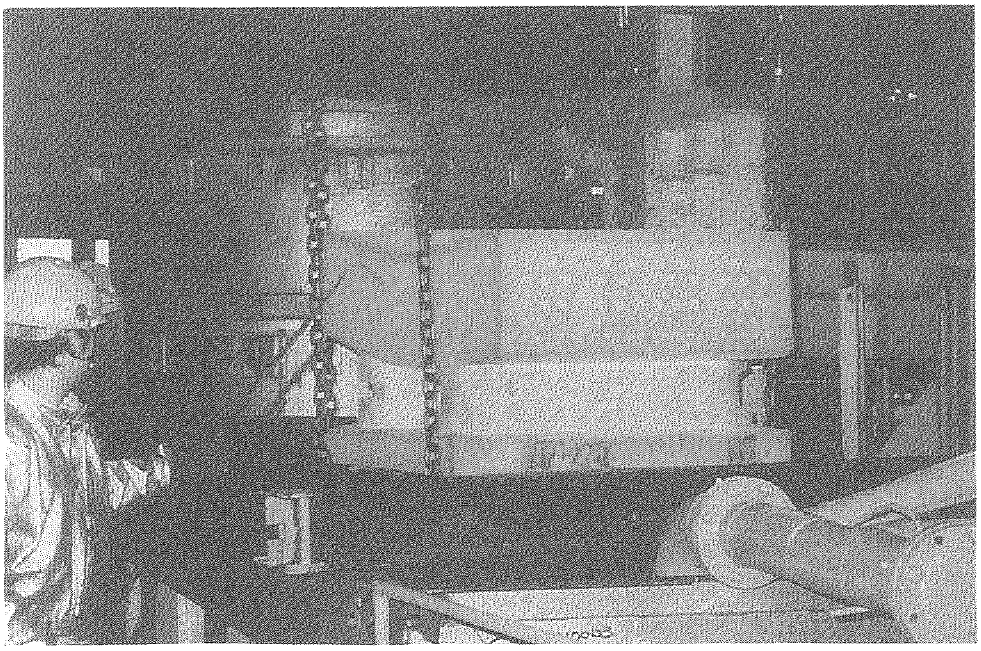


Fig. 4.8 Shield block after heat treatment

This is a blank page.

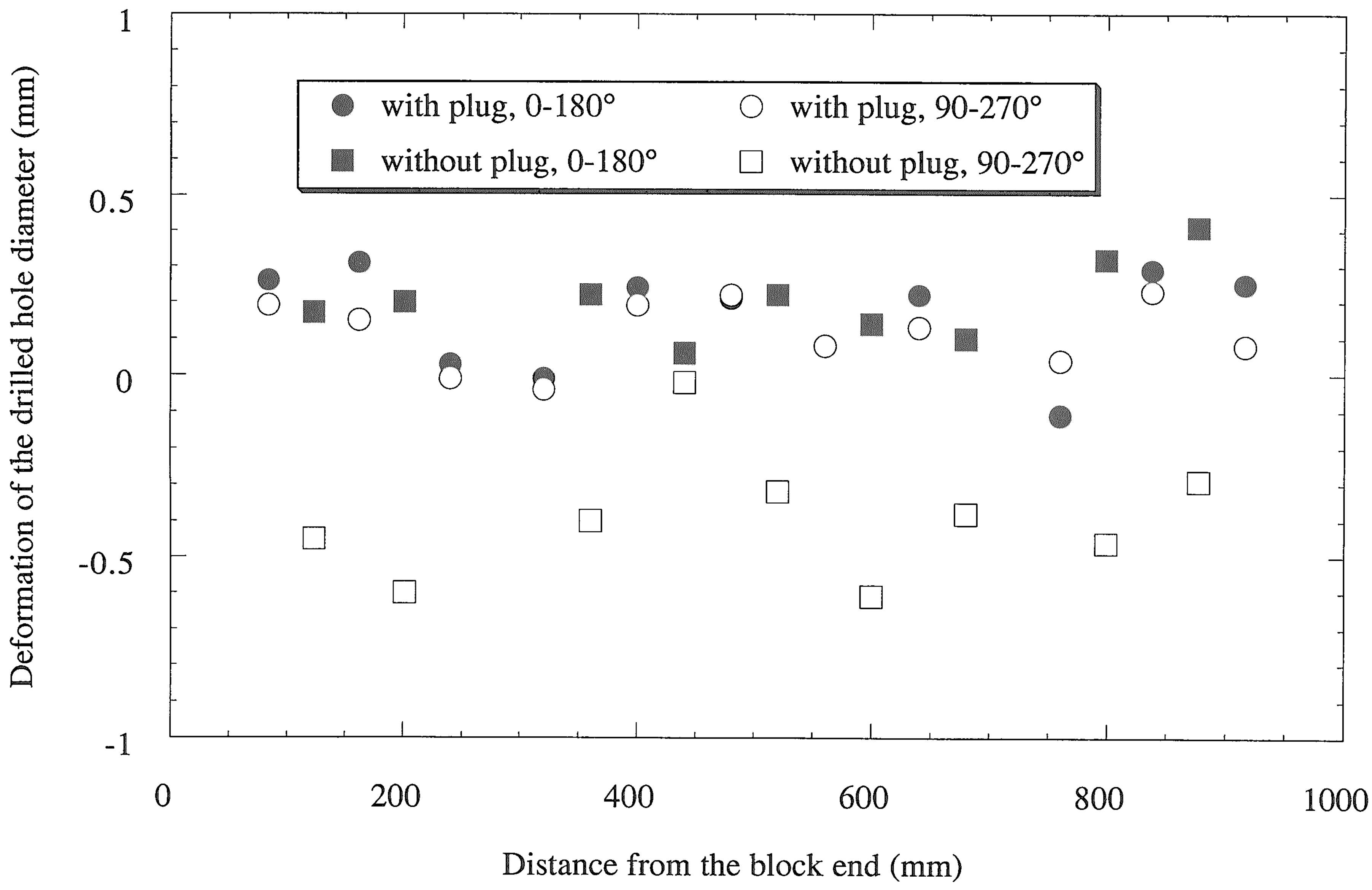
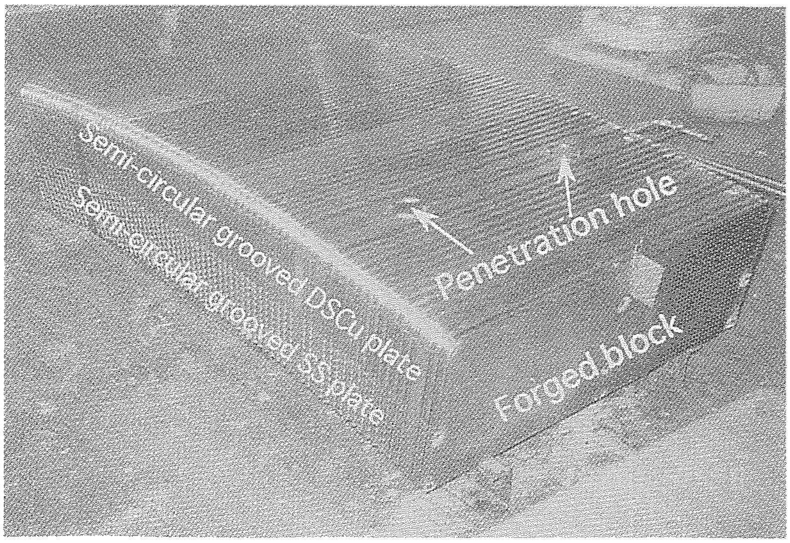
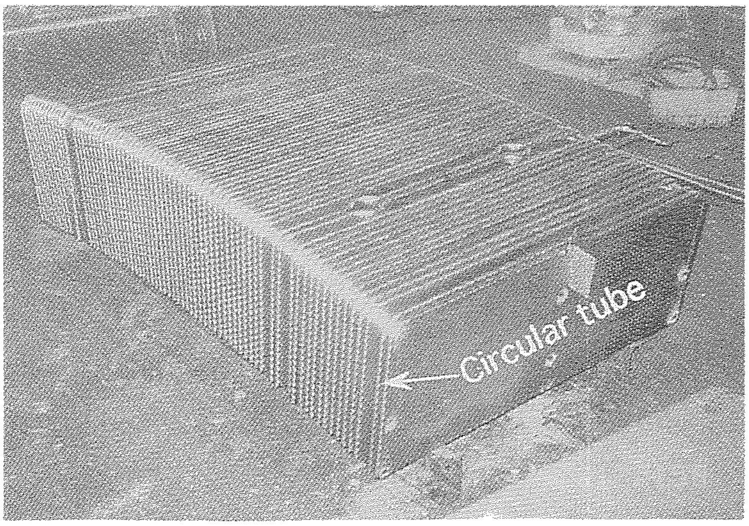


Fig. 4.9 Deformations along the cooling lines of the forged block after cold pressing

This is a blank page.



Assembly of the semi-circular grooved plate (shield-side) with the forged block



Assembly of the circular tube

Fig. 4.10 Assembly of the first wall elements with the shield block into one assembly

Fig. 4.11 Assembly of the first wall elements with the shield block into one assembly. Assembly of the semi-circular grooved DSCu plate (plasma-side)

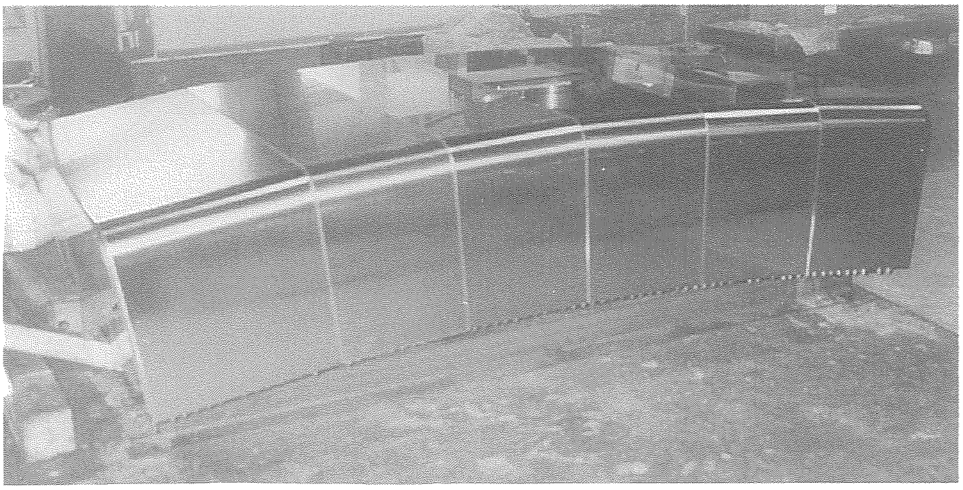
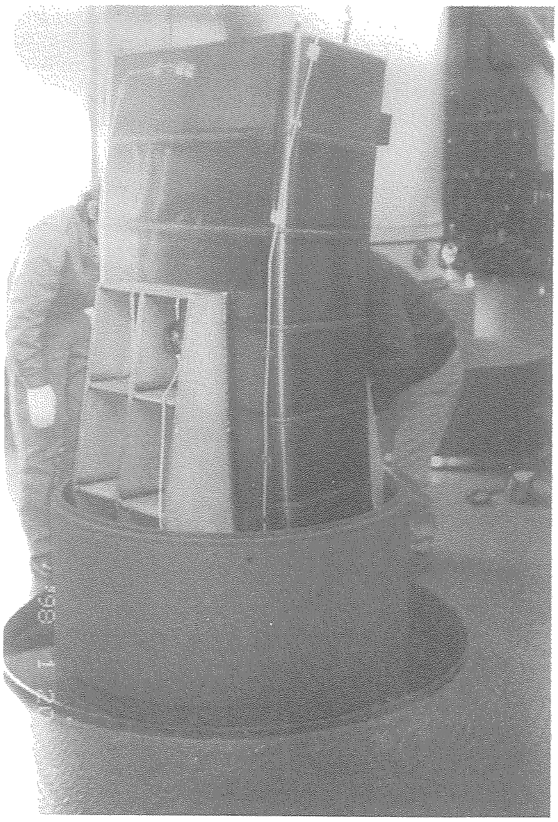
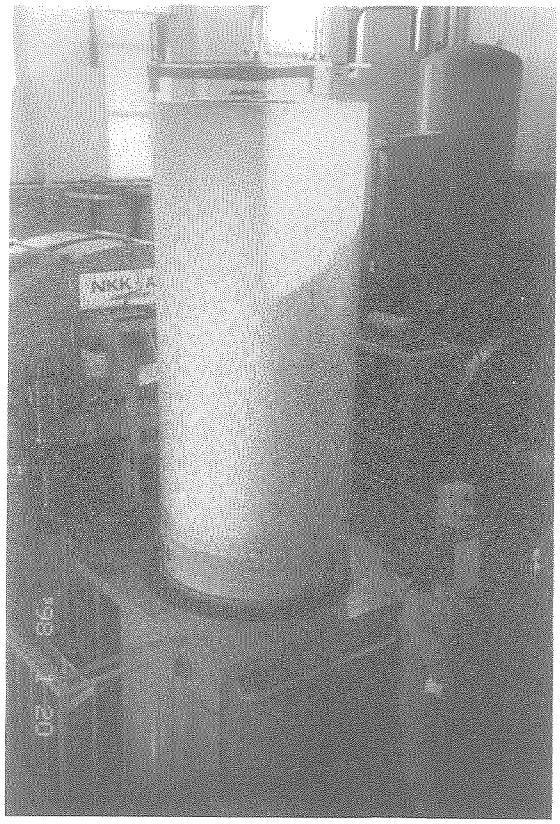


Fig. 4.12 Assembly of the SS canning for HIP process



Mockup Assembly



Installation in HIP Facility

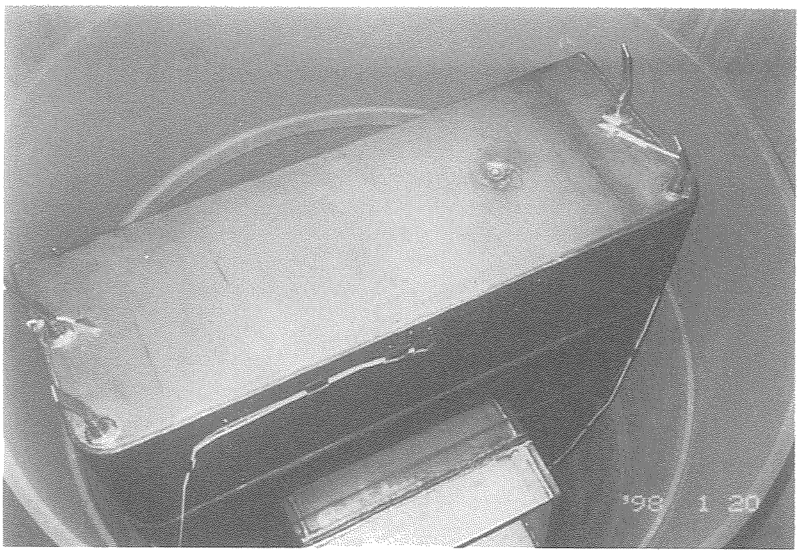


Fig. 4.13 Installation of the prototype in HIP facility

This is a blank page.

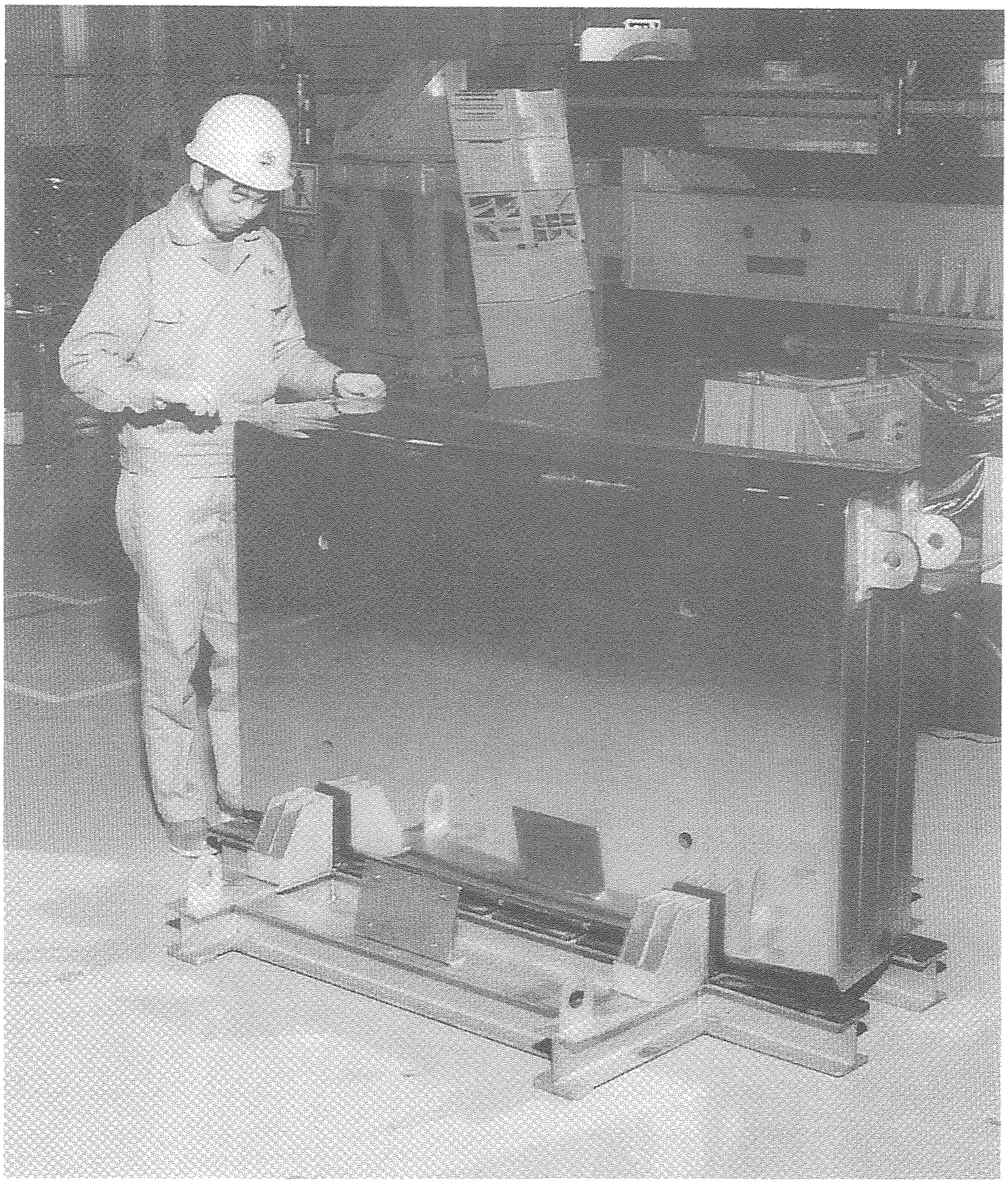


Fig. 4.14 Appearance of the fabricated prototype mockup

This is a blank page.

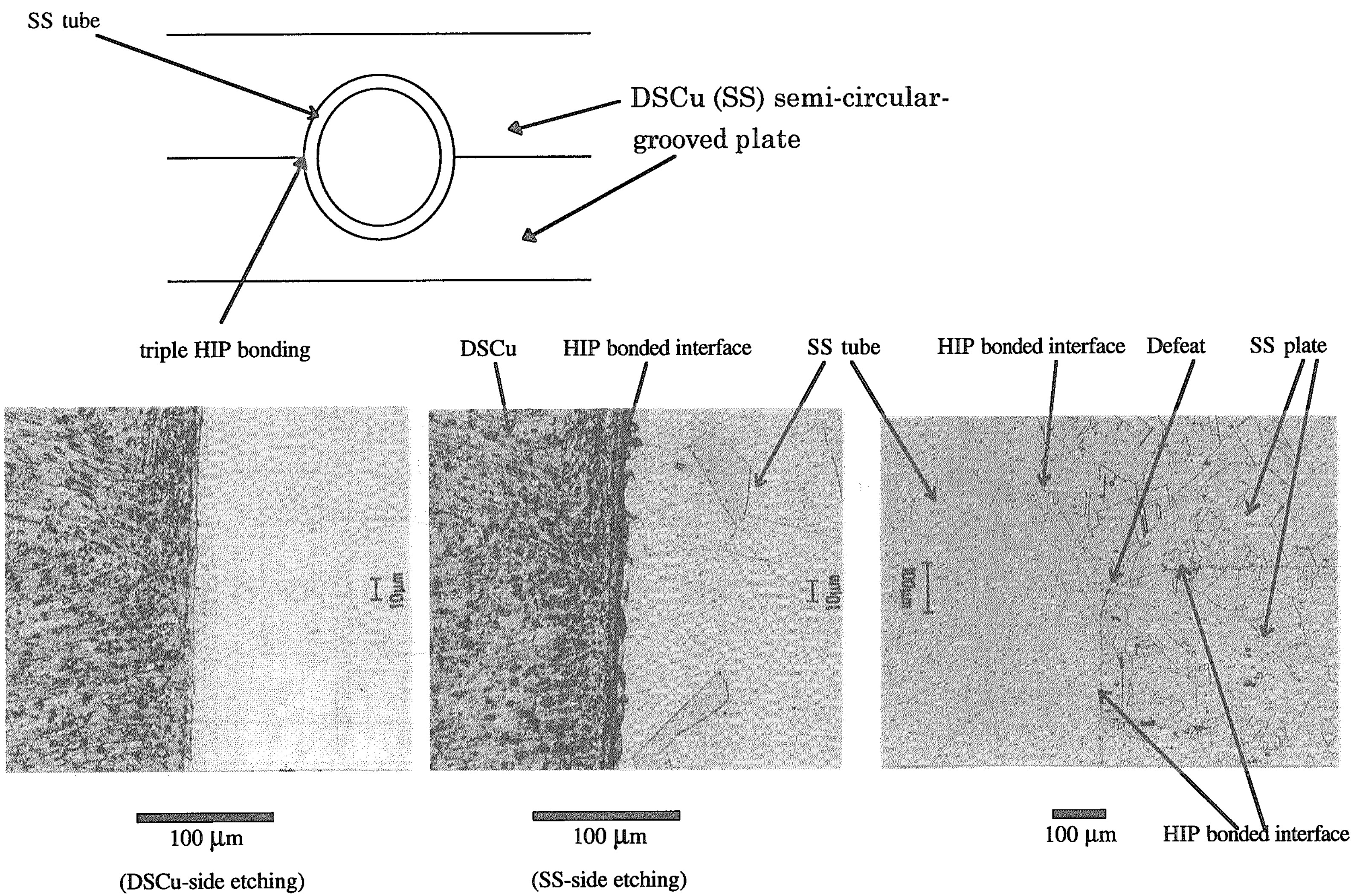


Fig. 4.15 Typical micro-scopic images at the HIP bonded interfaces

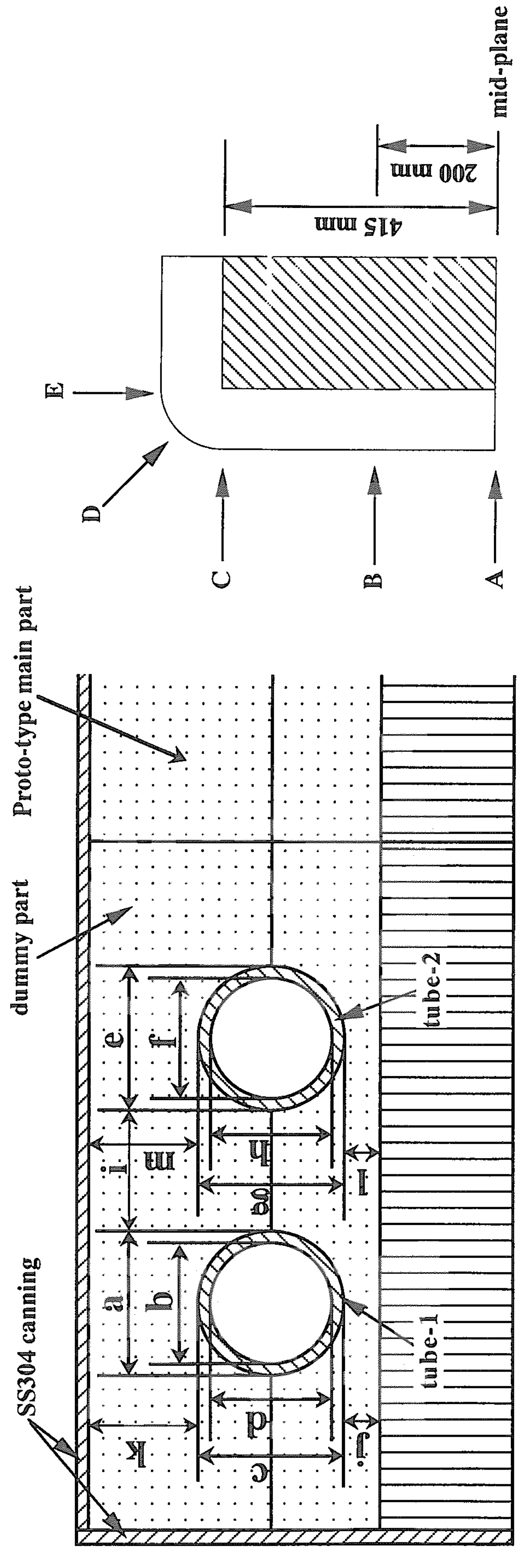


Fig. 4.16 Measured locations of the dummy piece

5. Summary

A detailed design of a prototype for the ITER shielding blanket module was developed based on the ITER Detailed Design Report (DDR) [1]. This prototype incorporates most of key design features essential to the fabrication of the ITER shielding blanket module such as: 1) the first wall heat sink made of Al_2O_3 dispersion strengthened Cu (DSCu) with built-in SS316L coolant tubes bonded to a massive SS316LN shield block, 2) toroidally curved first wall with a radius of 5106 mm while straight in poloidal direction, 3) coolant channels oriented in poloidal direction in the first wall and in toroidal direction in the shield block, 4) the first wall coolant channel routing to avoid the interference with the front access holes, 5) coolant channels drilled through the forged SS316LN-IG shield block, and 6) four front access holes of 30 mm in diameter penetrating through the first wall and the shield block. The issues which have not been covered in the present prototype fabrication are the bonding of Be armor tiles onto the first wall surface and the coolant channel routing inside the shield block to accommodate the front access holes. The size of the prototype was approximately 930 mm x 1700 mm x 350 mm.

A prototype mockup was successfully fabricated. A fabrication route was decided based on the single step solid HIP of DSCu/DSCu, DSCu/SS316L and SS316L/SS316L reflecting the results of joining techniques development and testing. The HIP conditions applied were the temperature of 1050 ℃, the pressure of 150 MPa and the holding time of 2 hours. Through this study, the following results were obtained.

(1) A full-scale prototype mockup of the ITER shielding blanket composed of the first wall with built-in circular tubes and the shield block was successfully fabricated by single step solid HIP bonding method.

(2) No harmful defeats were observed at the HIP bonded interfaces from the results of metallurgical examination for the dummy piece. Also, dimensional accuracy was almost well maintained during the HIP process.

(3) No decrease of pressure was observed at the pressure-resistant test. So it can be concluded that the soundness of HIP bonded parts and pressure boundary was confirmed in the fabricated prototype mockup.

(4) It could be demonstrated that an ITER shielding blanket could be fabricated by simultaneous HIP bonding of DSCu/DSCu, DSCu/SS and SS/SS in a single step solid HIP process under the temperature condition of 1050 ℃.

(5) It could be also demonstrated that joints of the first wall/the shield block as well as those of the DSCu/DSCu, DSCu/SS and SS/SS in the first wall, could be simultaneously HIP bonded.

(6) The fabrication of the shielding block by drilling and bending was also demonstrated. Also, it was found that the bending process of the shielding block was successfully performed by the

insertion and freezing of water into the drilled holes.

(7) Engineering data on fabrication including the procedure and conditions were obtained. As a whole, the feasibility of the fabrication technologies of an ITER shielding blanket was demonstrated.

(8) Though some discrepancy was observed in the depth of first wall coolant channels, more precise depth can be obtained by the optimization of the bending jigs.

Acknowledgment

The authors would like to express their sincere appreciation to Drs. S. Matsuda, Y. Seki, T. Nagashima, M. Seki and T. Tsunematsu for their continuous support and guidance. They also would like to acknowledge Dr. A. Cardella of the ITER Joint Central Team for fruitful discussion, and the members of Kawasaki Heavy Industries, Ltd. for fabrication of the mockup.

References

[1] ITER EDA DOCUMENTATION SERIES No. 13, Technical Basis for the ITER Detailed Design Report, Cost Review and Safety Analysis, INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1997.

[2] Sato S. et al., : "Fabrication of an ITER Middle-Scaled Shielding Blanket Module Mock-up", Fusion Engineering and Design 39-40 (1998) 765-773.

[3] Yamada H. et al., : "Manufacturing of a Medium Scale Shielding Blanket Module for ITER", Proc. 17th IEEE/NPSS Symp. Fusion Eng., San Diego (1997) 937-940.

[4] Sato S. et al., : "Fabrication of a blanket box structure integrated with the first wall for a fusion experimental reactor", Proc. 15th IEEE/NPSS Symp. Fusion Eng., Cape Cod (1995) 259-262.

[5] Hashimoto T. et al., : "Development and Trial Manufacturing of 1/2-scale Partial Mock-up of Blanket Box Structure for Fusion Experimental Reactor", JAERI-Tech 94-009, Japan Atomic Energy Research Institute (1994) (in Japanese).

[6] Mohri K. et al., : "Development of blanket box structure fabrication technology", Fusion Engineering and Design 27 (1995) 438-443.

[7] Sato S. et al., : "Fabrication of HIPped First Wall Panel for Fusion Experimental Reactor and Preliminary Analyses for Its Thermo-mechanical Test", Proc. 16th IEEE/NPSS Symp. Fusion Eng., Champaign (1995) 202-205.

[8] Furuya K. et al., Fabrication of Small-scaled Shielding Blanket Module and First Wall Panel for International Thermonuclear Fusion Reactor, Proc. 19th Symp. on Fusion Technology, FUSION TECHNOLOGY 1996, Elsevier, B, Lisbon 1343-1346 (1997).

[9] Sato S. et al., : "Mechanical Properties of HIP Bonded Joints of Austenitic Stainless Steel and Cu-alloy for Fusion Experimental Reactor Blanket", J. Nucl. Mater. 233-237 (1996) 940-944.

[10] Sato S. et al et al., : "Development of First Wall/Blanket Structure by HIP in JAERI", Fusion Engineering and Design 39-40 (1998) 609-614.

[11] Sato S. et al., : "Fabrication of an ITER Shielding Blanket Prototype", J. Fusion Tech., 30 (1998) 892-897.

[12] Osaki T. et al., Fabrication of The Curved Shielding Blanket Module with Inner Coolant Channels for ITER, Proc. 20th Symp. on Fusion Technology, FUSION TECHNOLOGY 1998, Marseille 1259-1262 (1998).

[13] Sato S. et al., : "Optimization of HIP Conditions for ITER Shielding Blanket/First Wall Made from Austenitic Stainless Steel and Dispersion Strengthened Copper Alloy", J. Nucl. Mater. 258-263 (1996) 265-270.

[14] Kuroda T. et al., : "Development of HIPed Cu-alloy/SS First Wall for Fusion Experimental Reactor", Proc. 4th Japan/China Symposium MAESFFE, Sapporo, Aug. (1996).

[15] Furuya K. et al., : "ITER Blanket R&D", J. Plasma and Fusion research, 73 Supplement (1997) 206-219 (in Japanese).

[16] Hatano T. et al., : "High Heat Flux Testing of HIP Bonded DS-Cu/316SS First Wall Panel for Fusion Experimental Reactors", J. Fusion Tech., 30 (1996) 752-756.

[17] Hatano T. et al., Post-mortem Analysis of HIP Bonded First Wall Panel Made of SS316 and DS-Cu after High Heat Flux Testing, Proc. 19th Symp. on Fusion Technology, FUSION TECHNOLOGY 1996, Elsevier, Lisbon (1996) 511-514.

[18] Hatano T. et al., : "High Heat Flux Testing of a HIP Bonded First Wall Panel with Built-in Circular Cooling Tubes", Fusion Engineering and Design 39-40 (1998) 363-370.

[19] Hatano T. et al., : "Low Cycle Fatigue Lifetime of HIP Bonded Bi-metallic First Wall Panels of Fusion Reactors under Cyclic Mechanical Loads", J. Nucl. Sci. Technol., 35 (1998) 705-711.

[20] Hatano T. et al., : "Fracture Strengths of HIPed DS-Cu/SS Joints for ITER Shielding Blanket/First Wall", J. Nucl. Mater., 258-263 (1998) 950-954.

[21] Hatano T. et al., : "High Heat Flux Testing of a HIP Bonded DS-Cu/316SS First Wall Panel for Fusion Experimental Reactors", JAERI-Research 97-017, Japan Atomic Energy Research Institute (1998) (in Japanese).

[22] Sato S. et al., : "DSCu/SS Joining Techniques Development and Testing", JAERI-Research 97-092, Japan Atomic Energy Research Institute (1997).

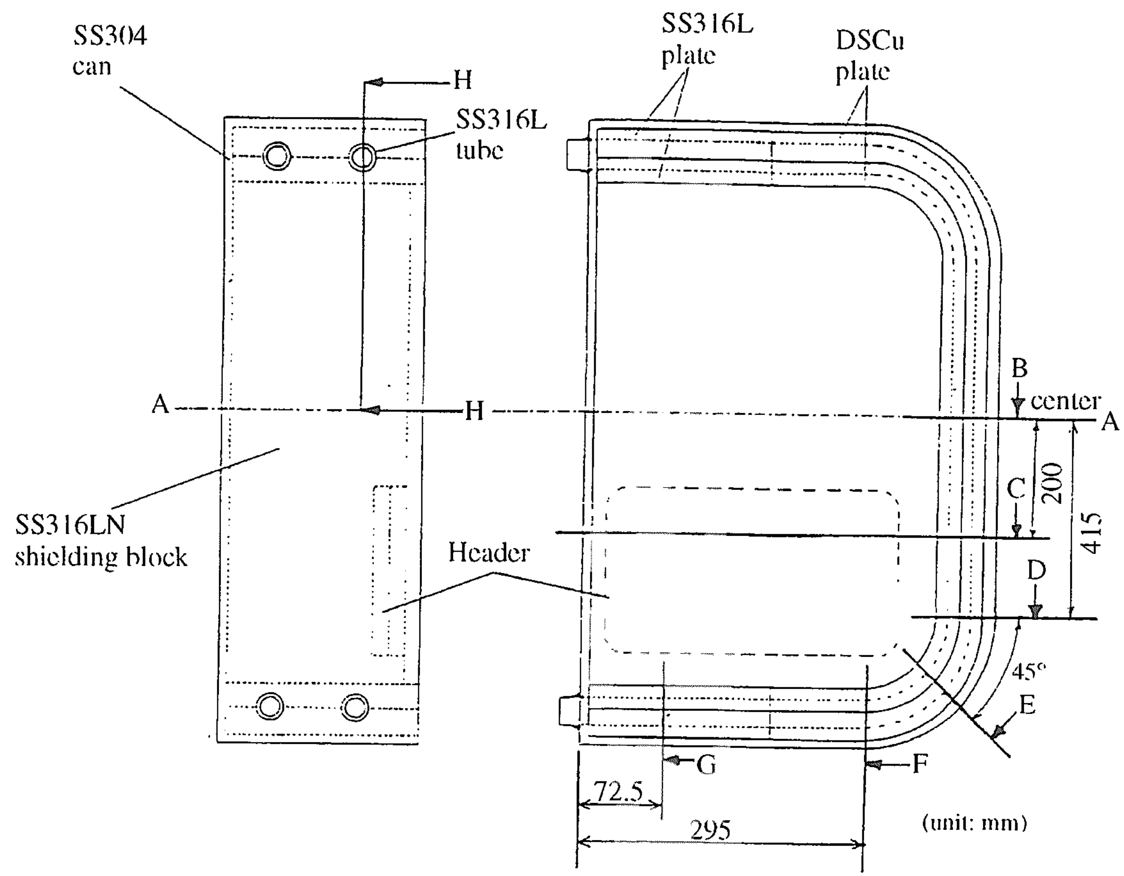
[23] Kanari M. et al., : "Characterization of HIP Bonded DSCu/SS316L Joints for Fusion Experimental Reactors", JAERI-Research 98-004, Japan Atomic Energy Research Institute (1998) (in Japanese).

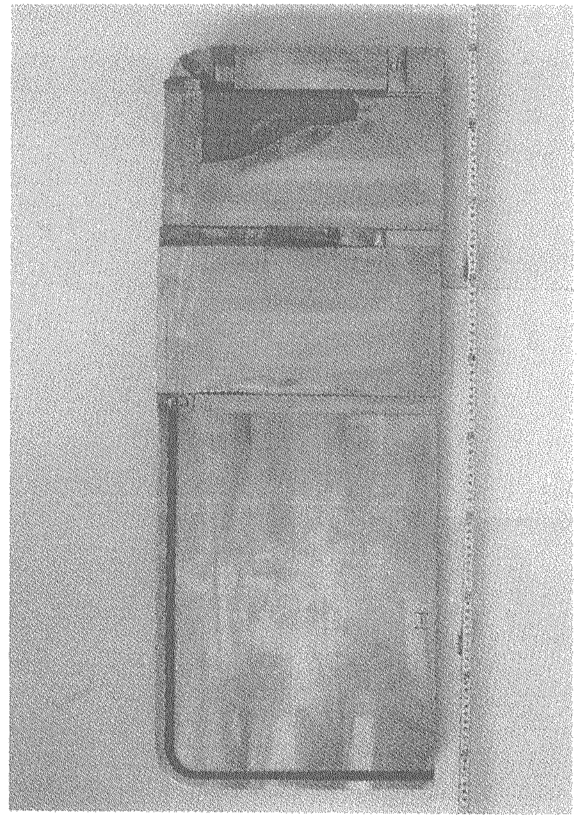
[24] Hatano T. et al., : "Fabrication and Testing of Small Scale Mock-ups of ITER Shielding Blanket", JAERI-Tech 98-058, Japan Atomic Energy Research Institute (1998).

Appendix

Detailed results of the micro-scopic images at the HIP bonded interfaces

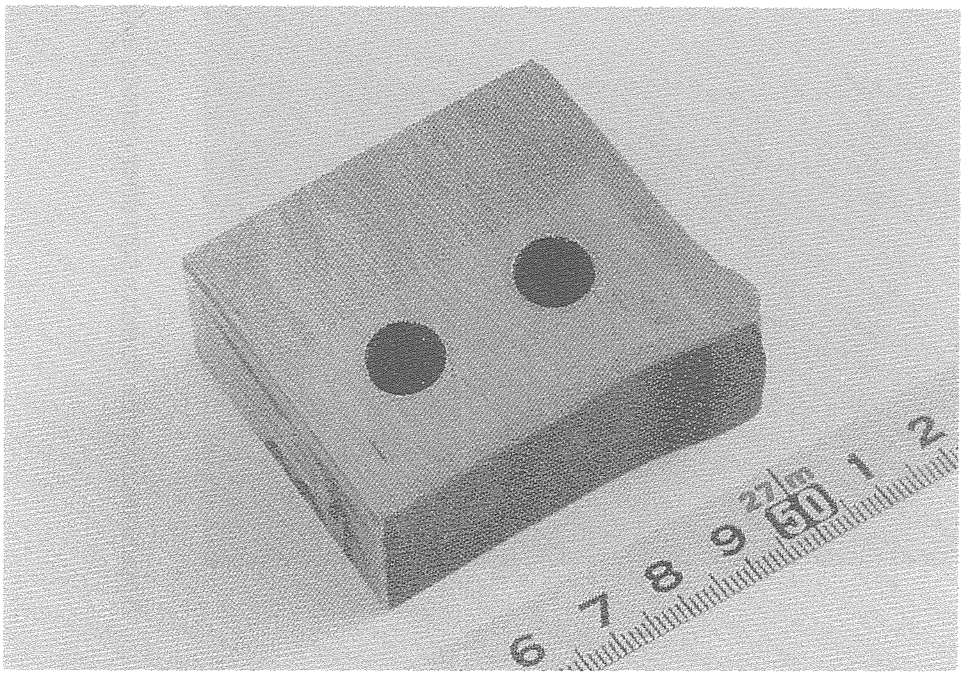
This is a blank page.



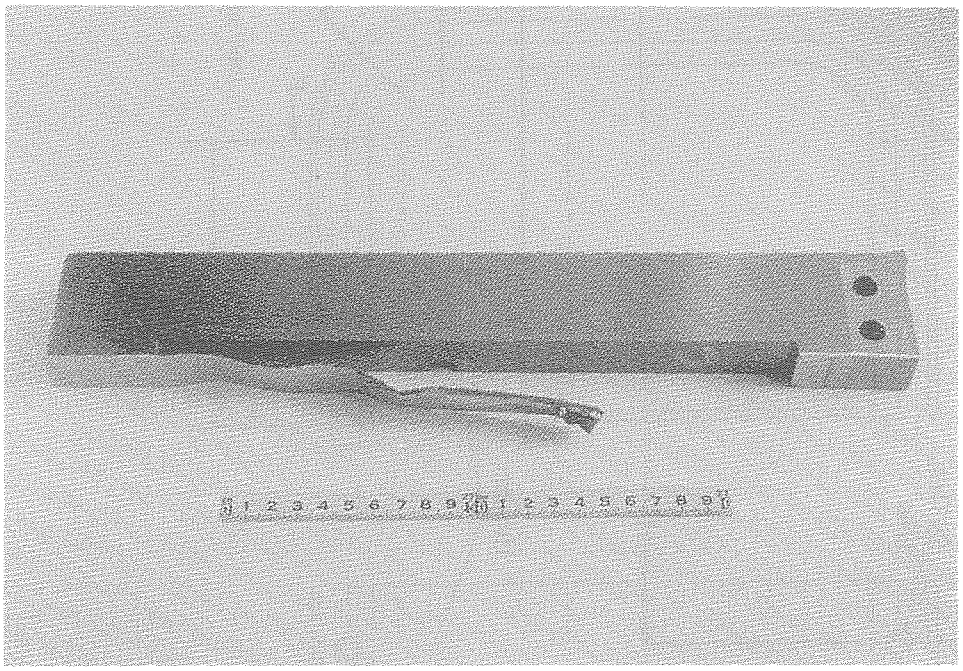


Appearance of the dummy part after cutting away

Fig. A-1 Locations of the observed test pieces in the dummy part of the fabricated ptoto-type mo
for the metallurgical observation of the HIP boded interfaces

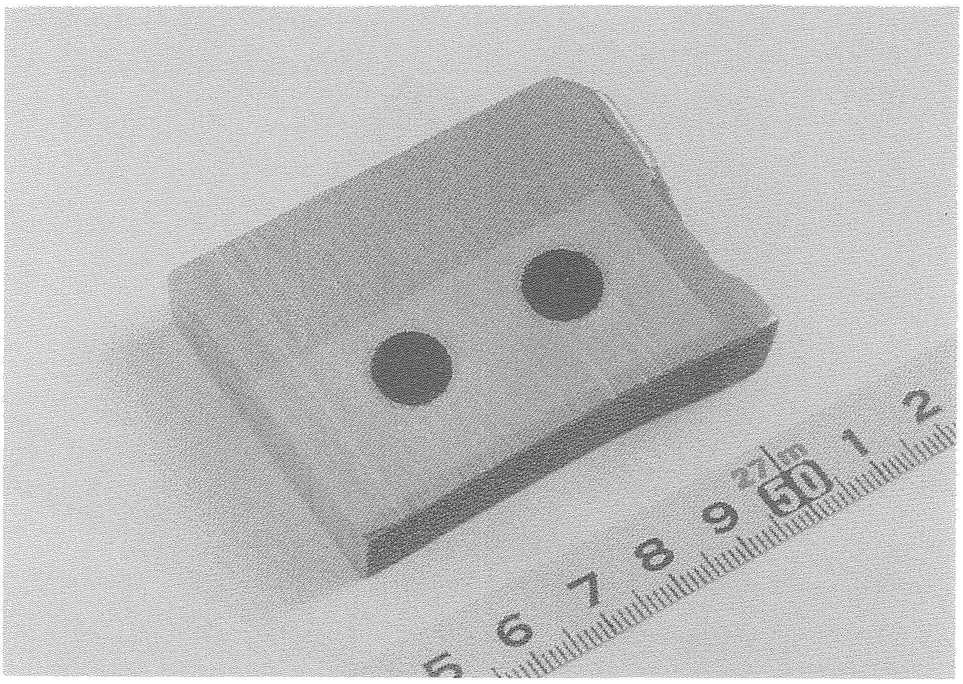


(1) Cross-section B

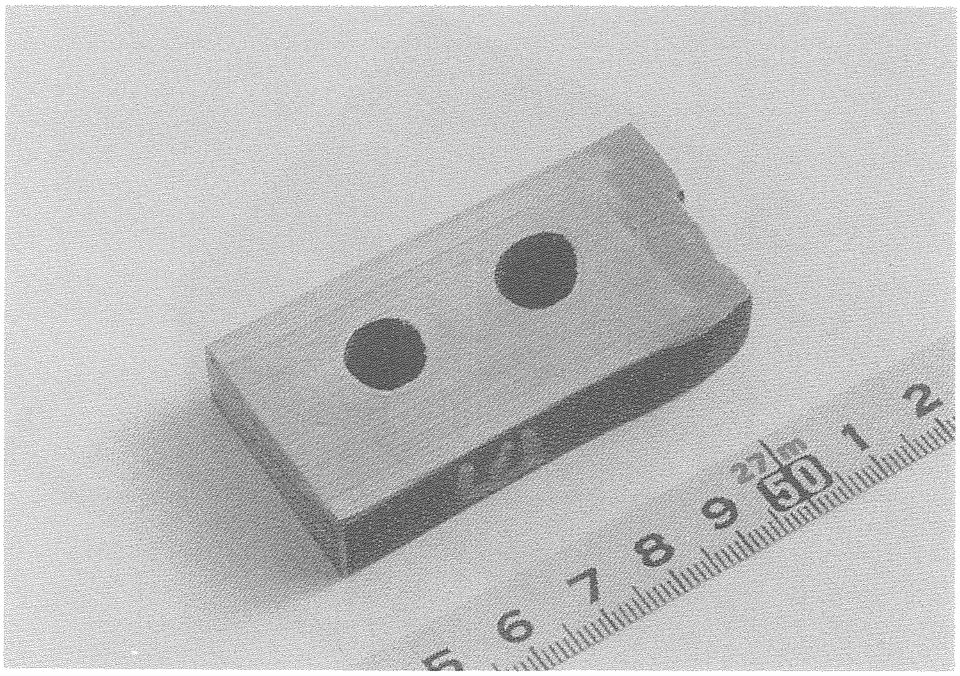


(2) Cross-section C

Fig. A-2.1 Appearance of the test pieces

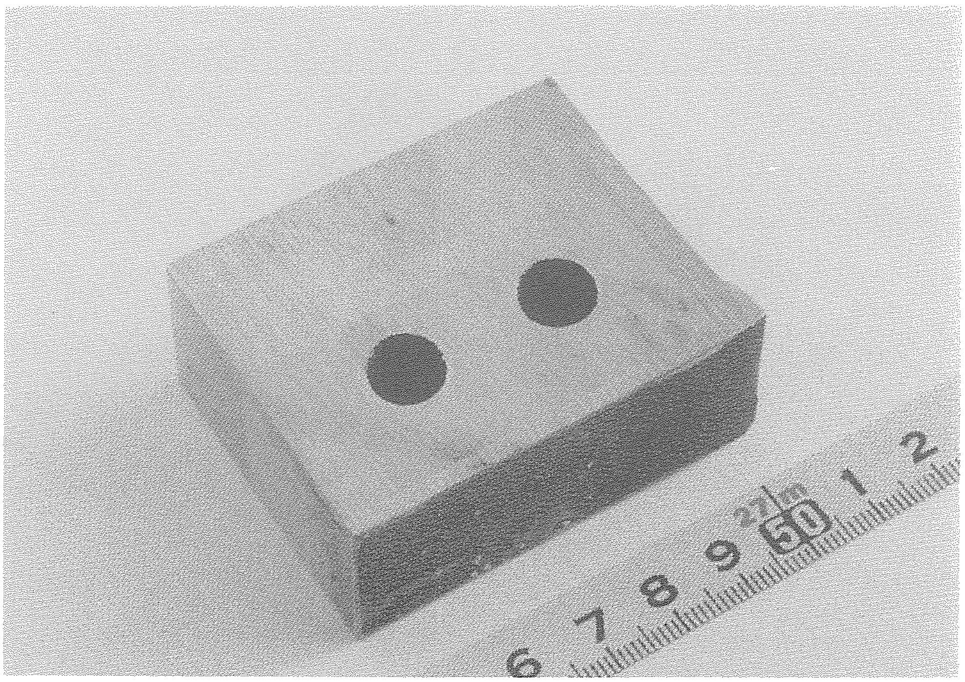


(1) Cross-section D

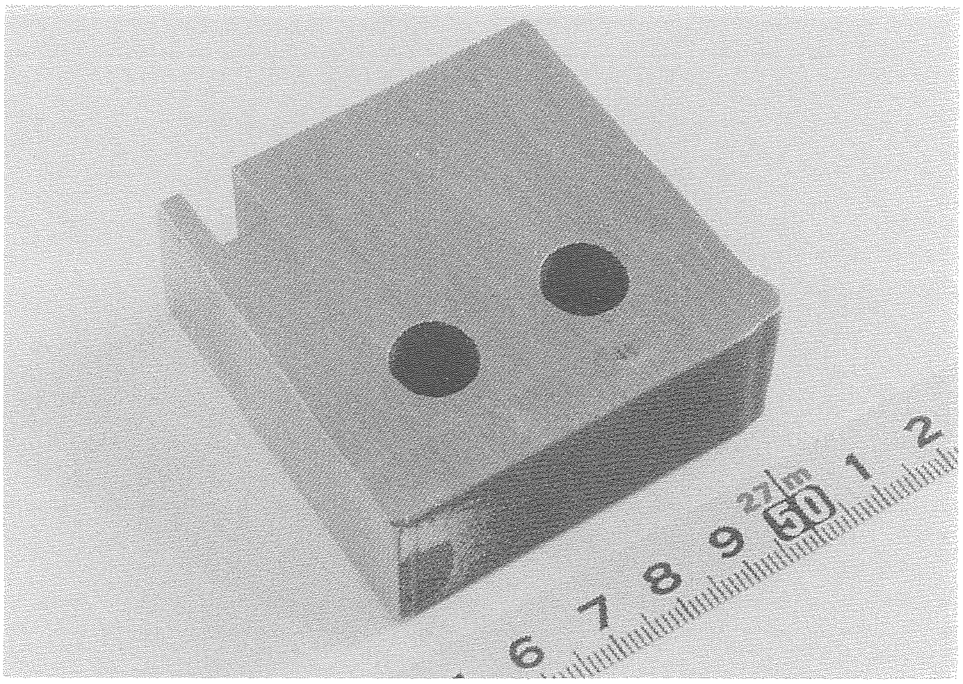


(2) Cross-section E

Fig. A-2.2 Appearance of the test pieces

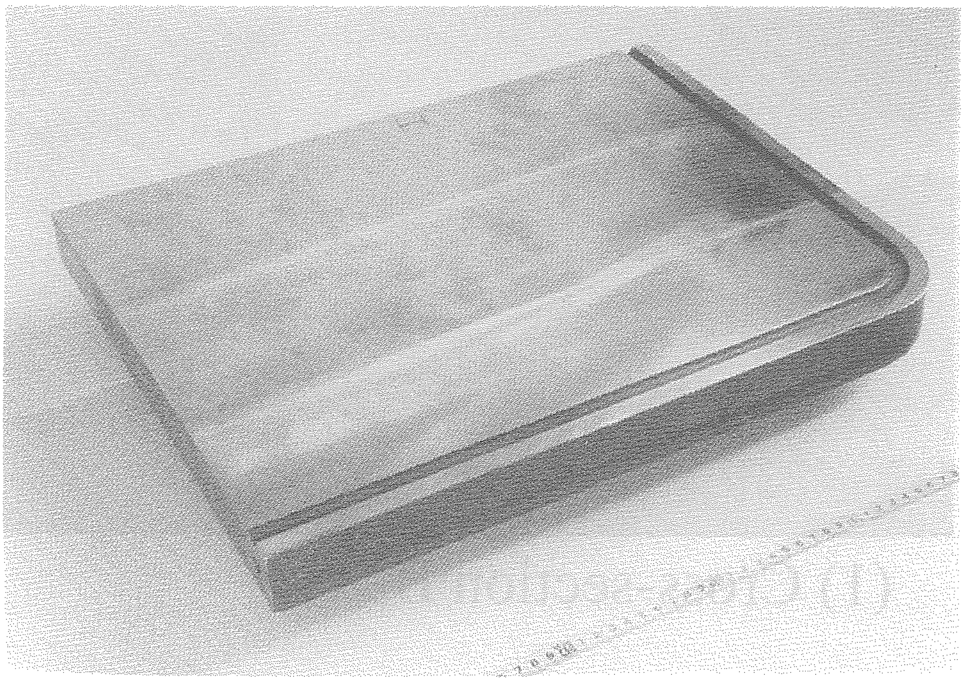


(1) Cross-section F



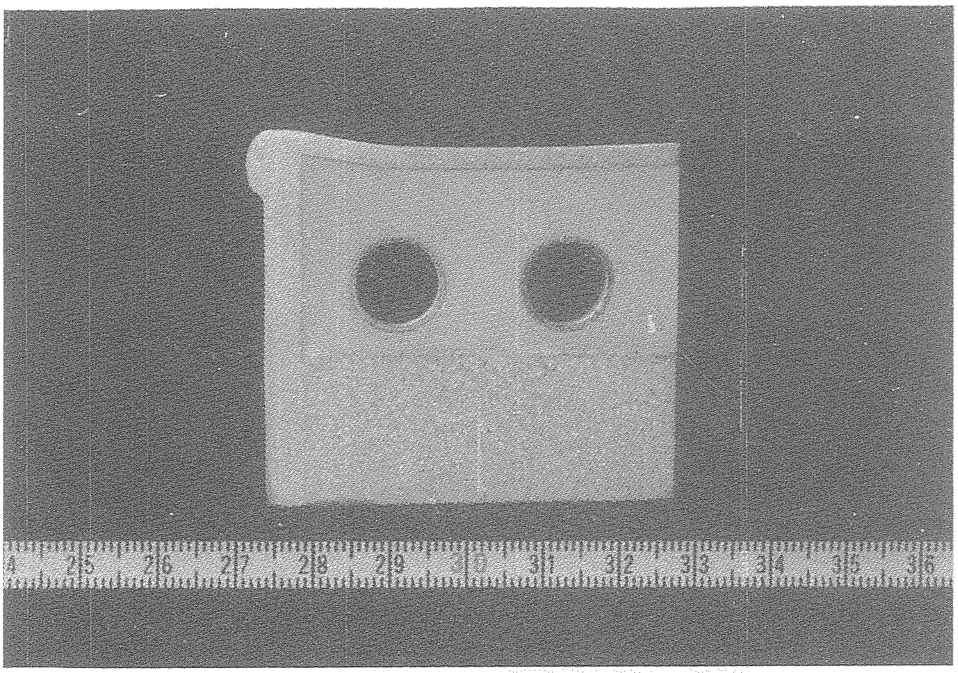
(2) Cross-section G

Fig. A-2.3 Appearance of the test pieces

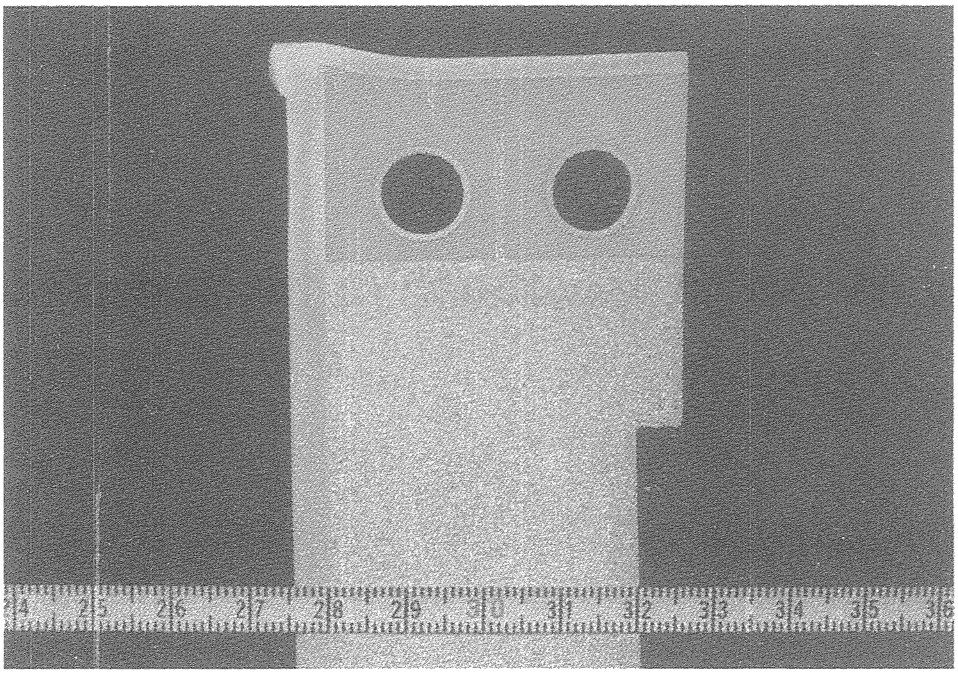


Cross-section H

Fig. A-2.4 Appearance of the test pieces

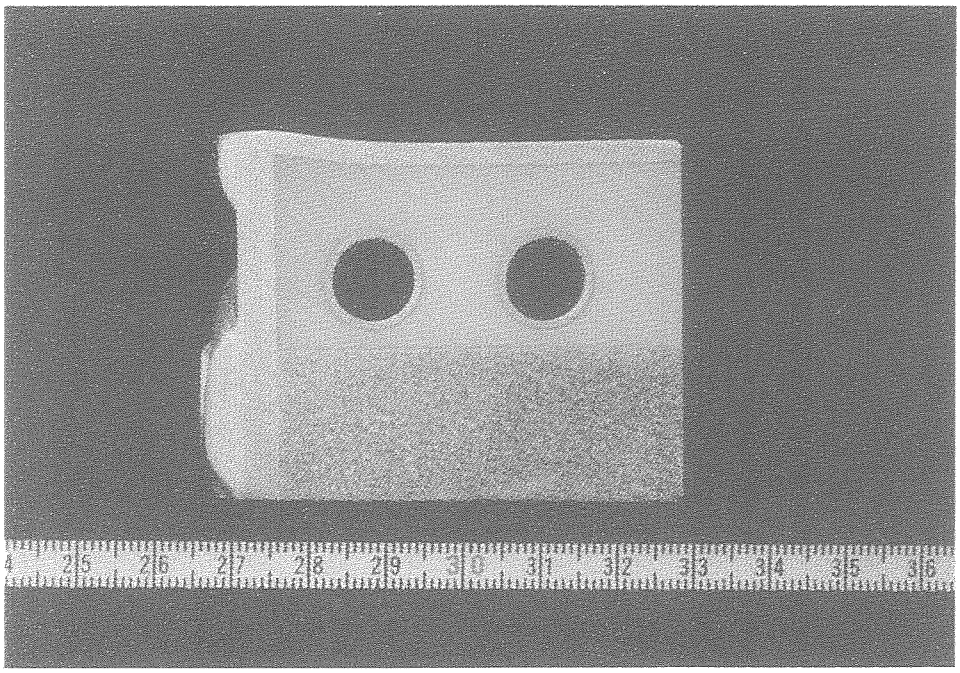


(1) Cross-section B

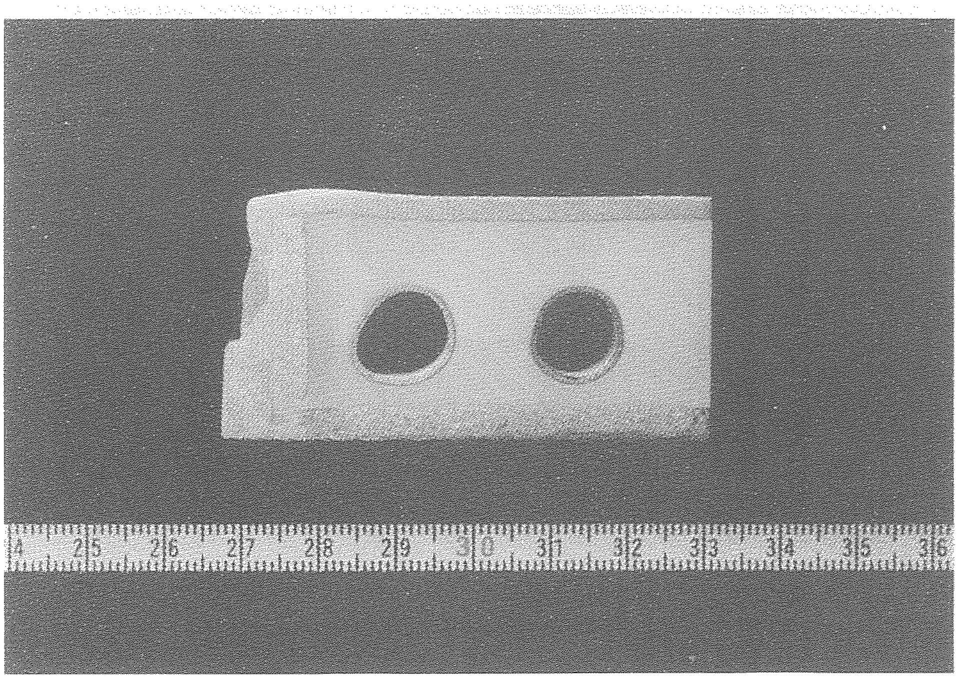


(2) Cross-section C

Fig. A-3.1 Cross-sectional view of the test pieces

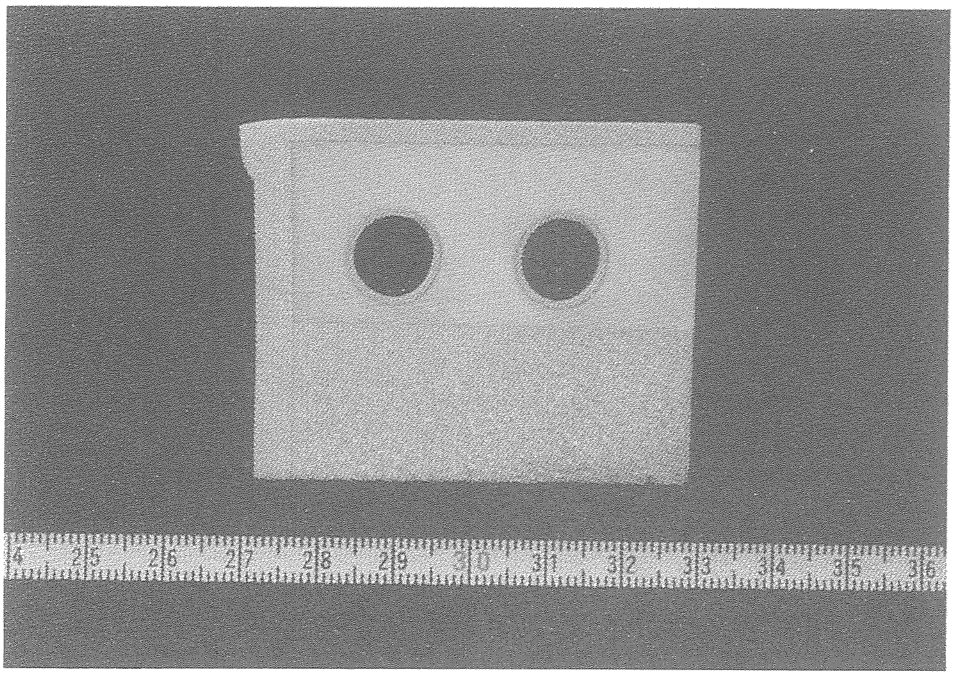


(1) Cross-section D

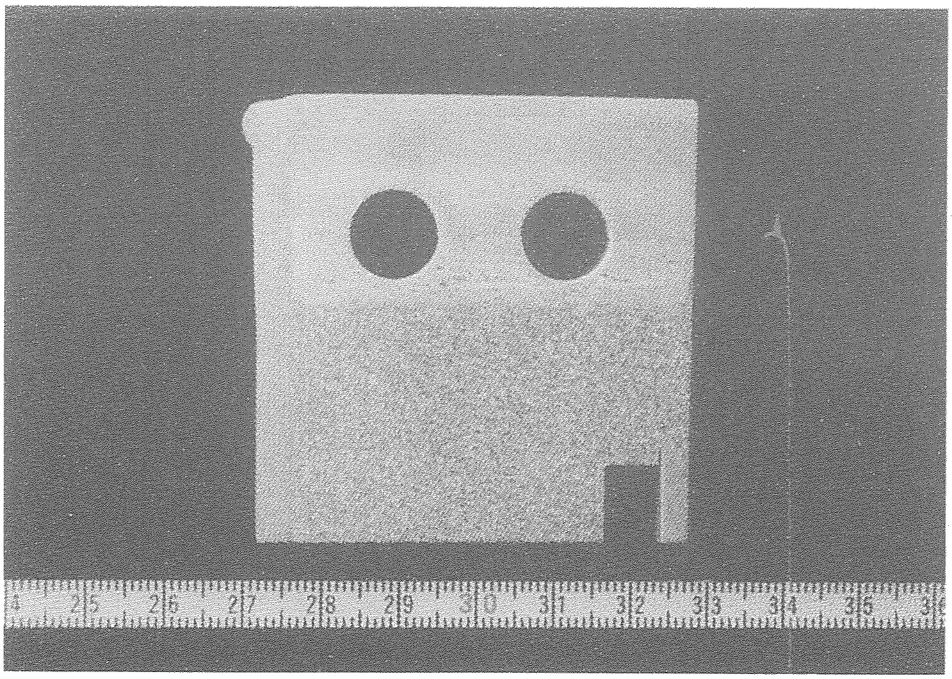


(2) Cross-section E

Fig. A-3.2 Cross-sectional view of the test pieces

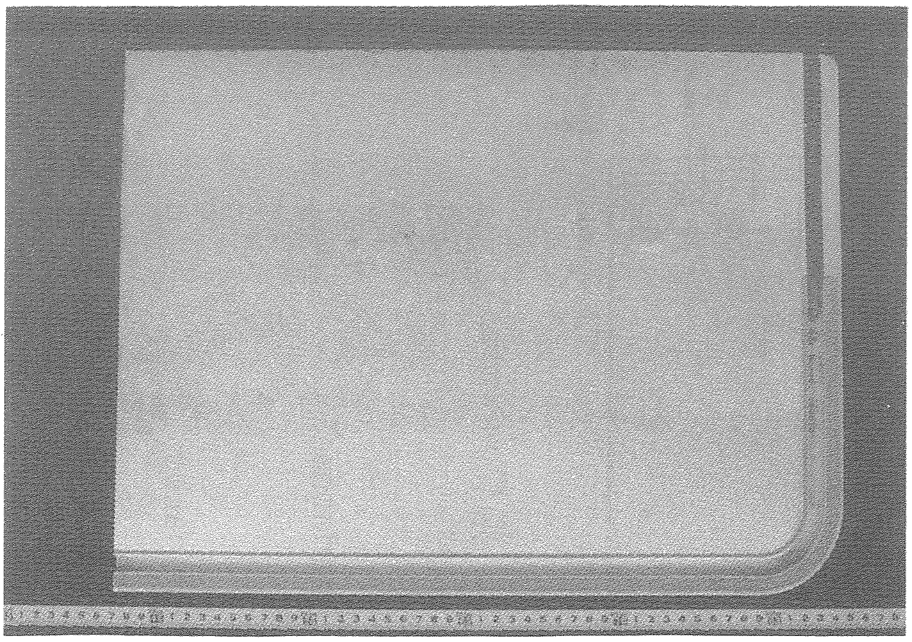


(1) Cross-section F

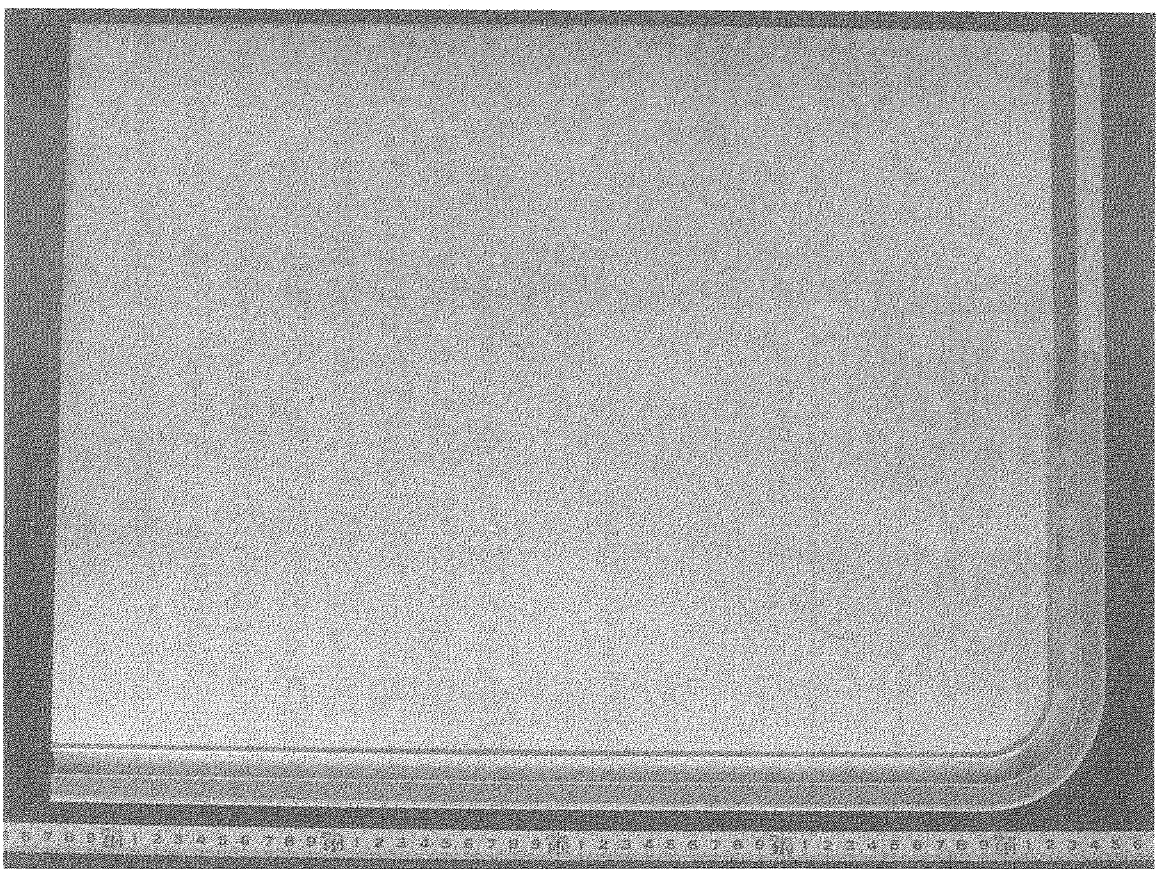


(2) Cross-section G

Fig. A-3.3 Cross-sectional view of the test pieces

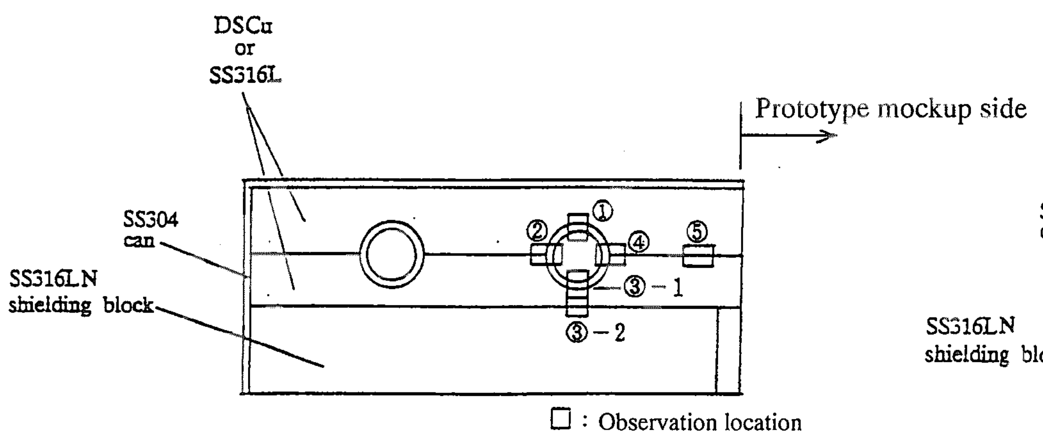


(1) Cross-section H

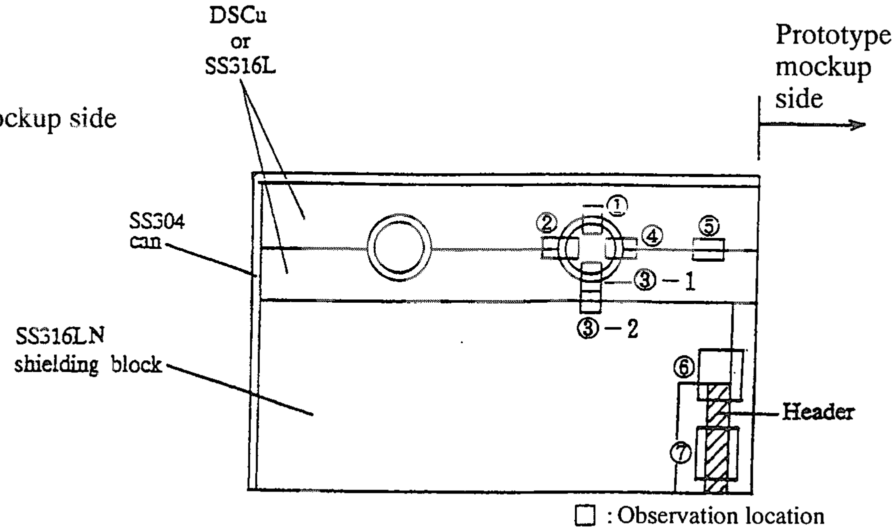


(2) Cross-section H (Zoom-up view)

Fig. A-3.4 Cross-sectional view of the test pieces



(1) Cross-section B, D, E, F, G



(2) Cross-section C

①: DSCu or SS316L/SS Cooling Pipe HIP Interfaces
②: DSCu or SS316L/DSCu or SS316L/SS Cooling Pipe HIP Interfaces
③-1: DSCu or SS316L/SS Cooling Pipe HIP Interfaces
③-2: DSCu or SS316L/SS Shield Block HIP Interfaces
④: DSCu or SS316L/DSCu or SS316L/SS Cooling Pipe HIP Interfaces
⑤: DSCu or SS316L/DSCu or SS316L HIP Interfaces
⑥: SS Shield Block/TIG Weld SS HIP Interfaces
⑦: SS Shield Block/SS Header Led HIP Interfaces

Fig. A-4 Obervation location of micro-scopic images at cross-section C, D, E, F and G of dummy block shown in Fig. A-1

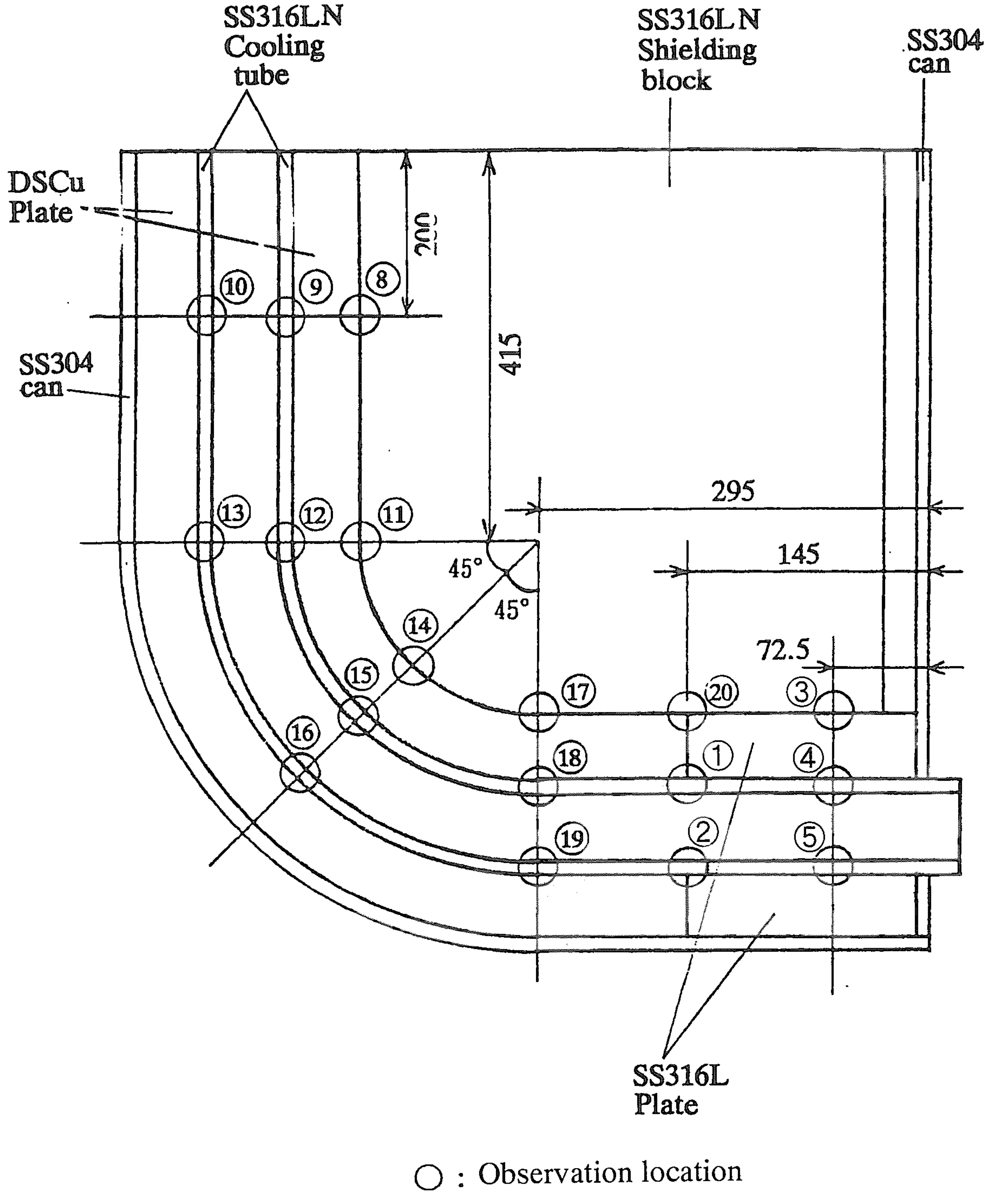
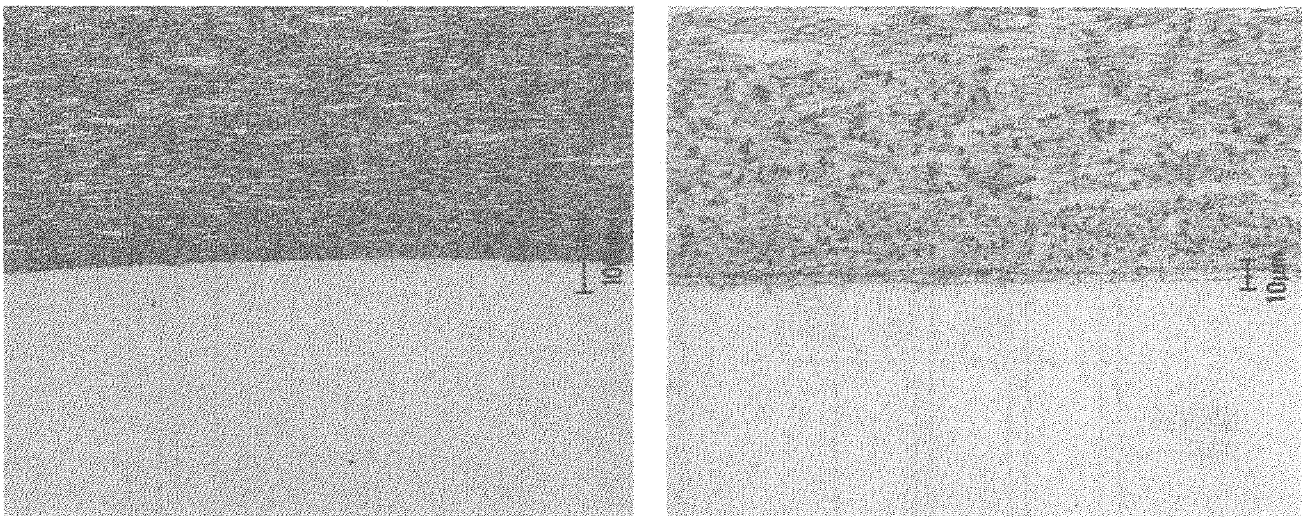
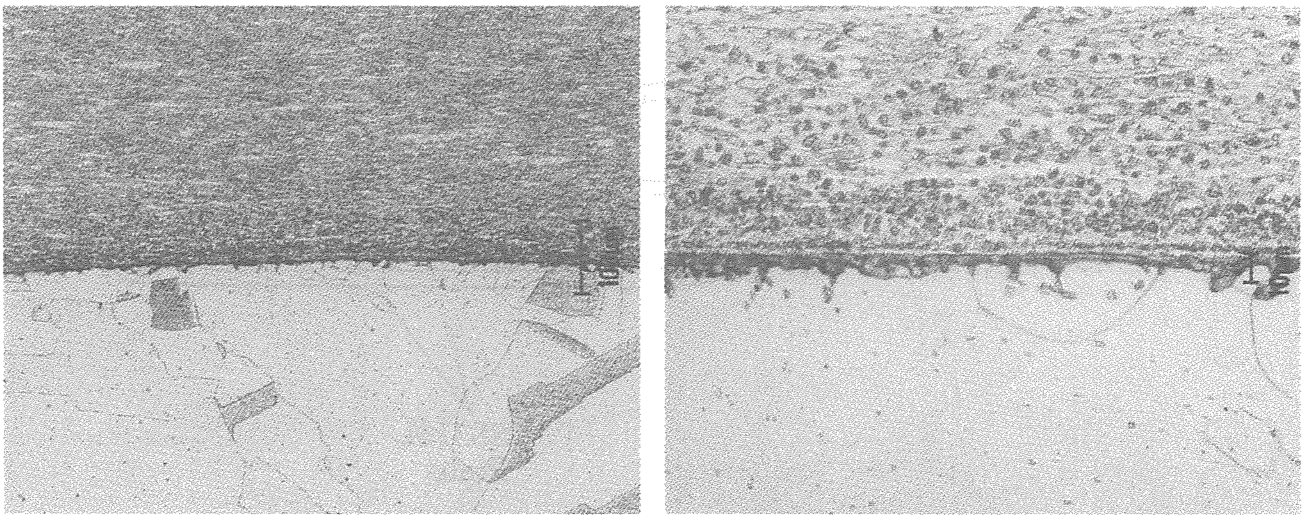


Fig. A-5 Obervation location of micro-scopic images at cross-section H-H of dummy block shown in Fig. A-1

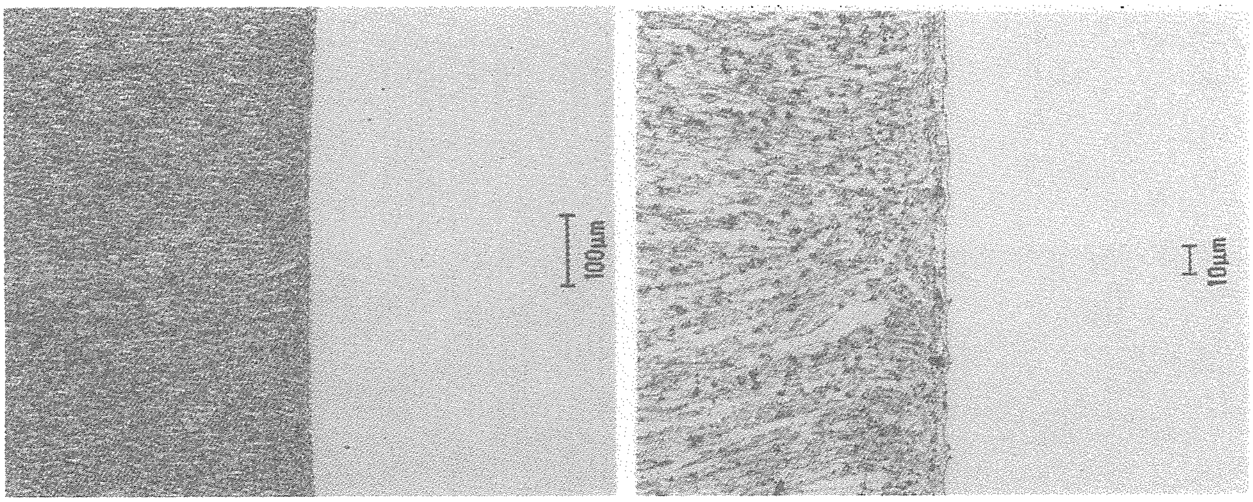


Etching for DSCu side

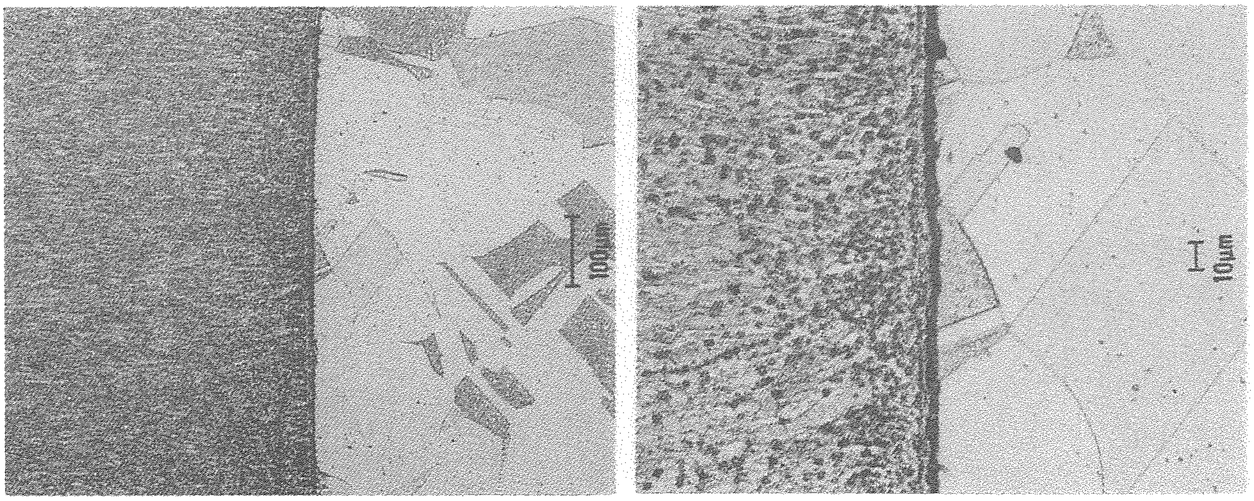


Etching for SS side

Fig. A-6.1 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ① of the cross-section B shown in Figs. A-1 and A-4



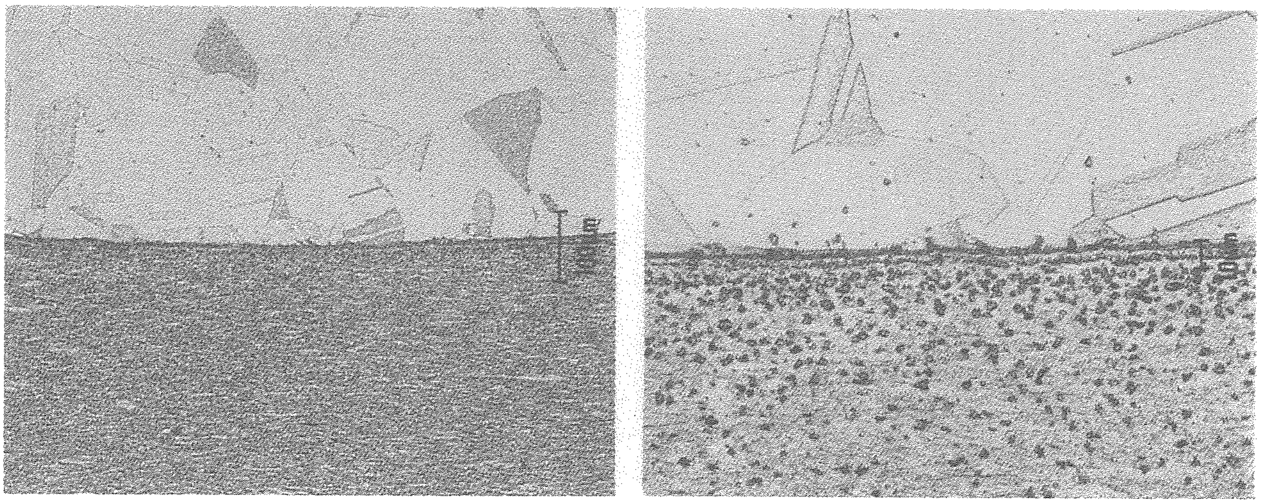
Etching for DSCu side



Etching for SS side

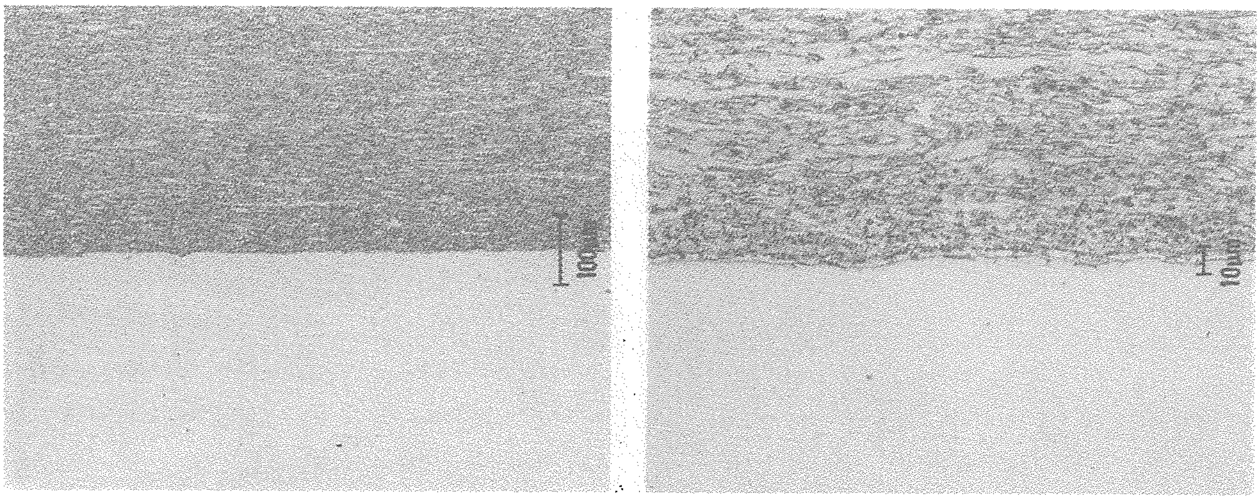
Fig. A-6.2 Micro-scopic images at the DSCu/DSCu/SS HIP bonded interface in the location ② of the cross-section B shown in Figs. A-1 and A-4

Etching for DSCu side

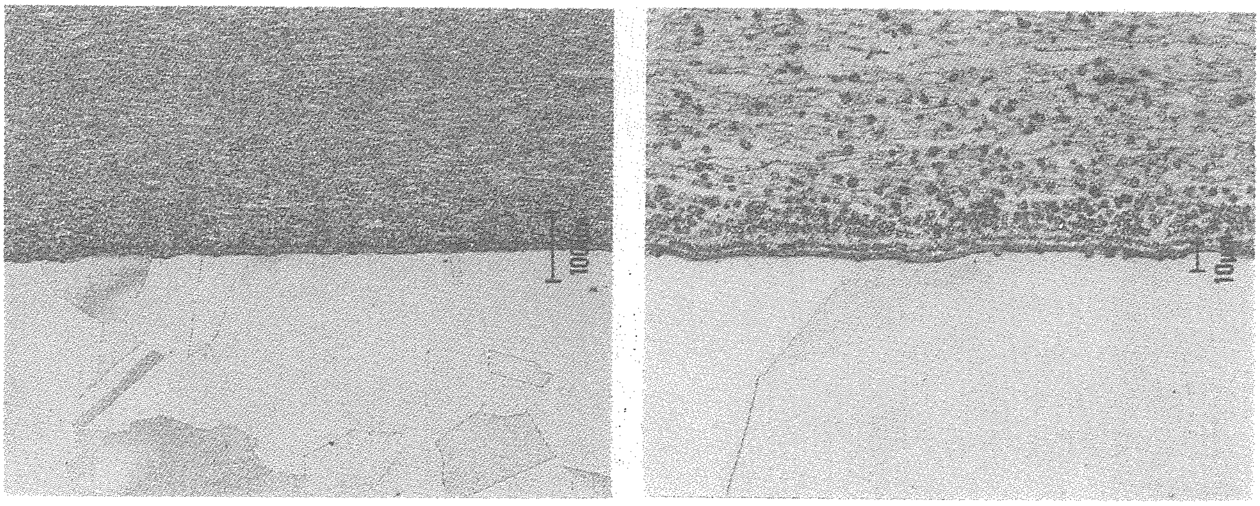


Etching for SS side

Fig. A-6.3.1 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ③-1 of the cross-section B shown in Figs. A-1 and A-4



Etching for DSCu side



Etching for SS side

Fig. A-6.3.2 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ③-2 of the cross-section B shown in Figs. A-1 and A-4

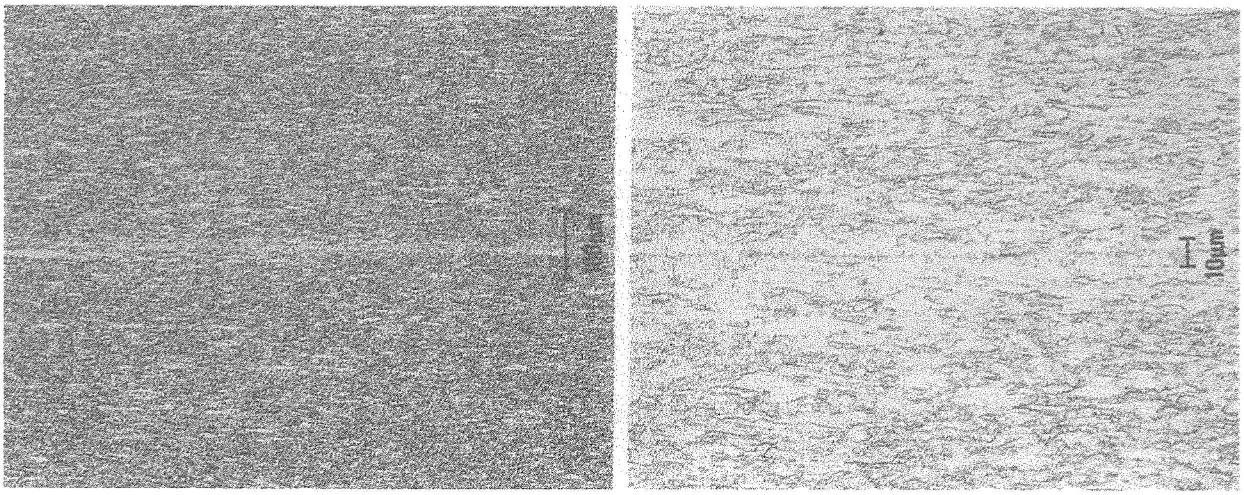
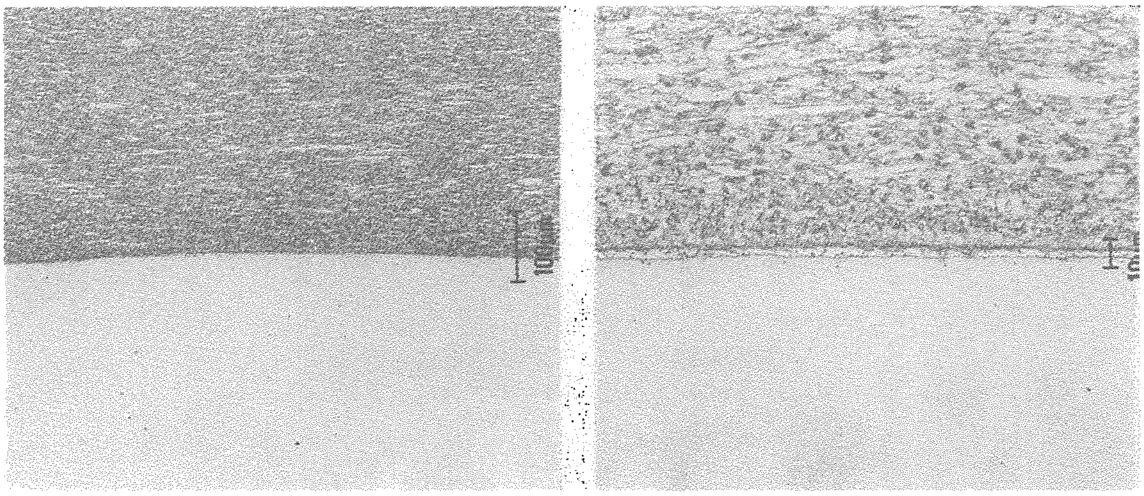
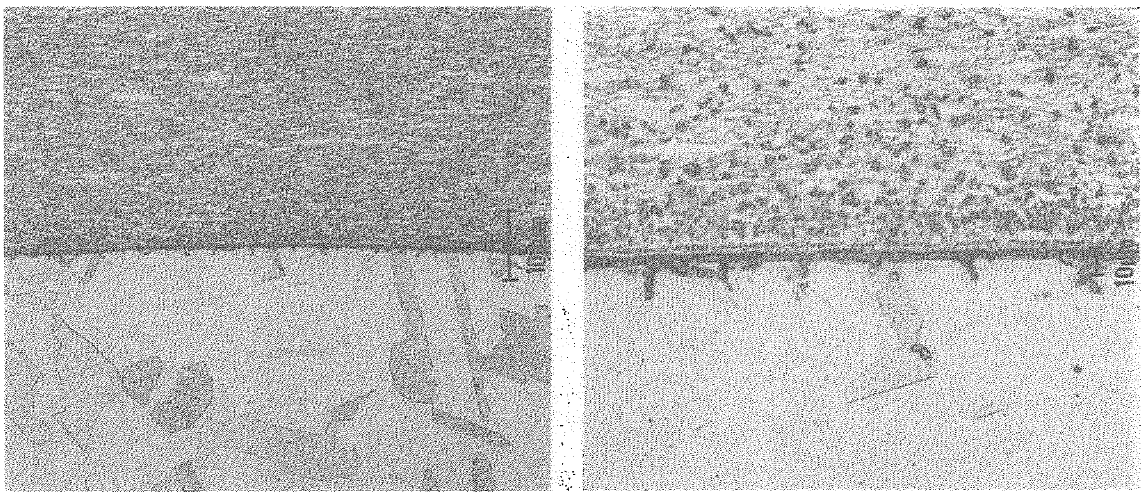


Fig. A-6.5 Micro-scopic images at the DSCu/DSCu HIP bonded interface in the location ⑤ of the cross-section B shown in Figs. A-1 and A-4

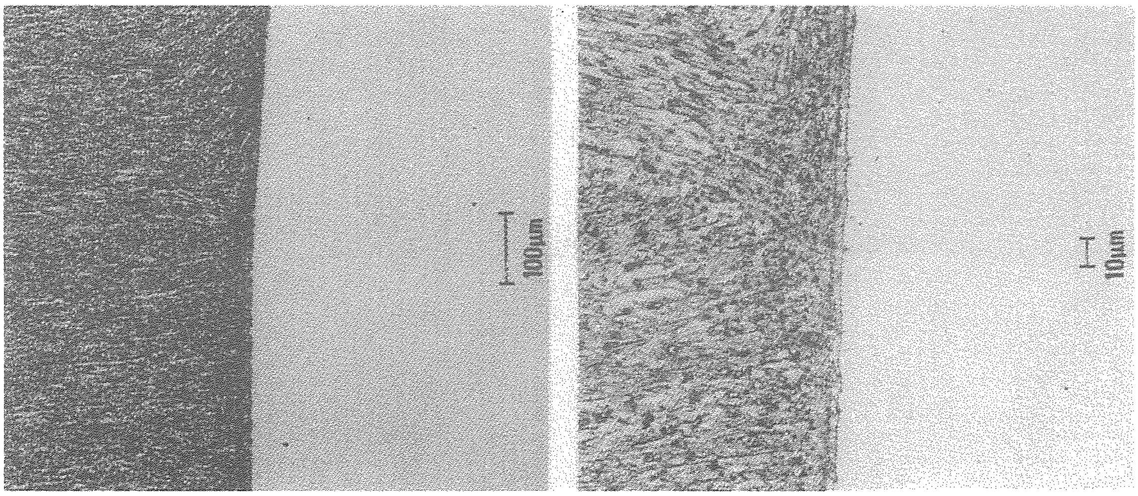


Etching for DSCu side

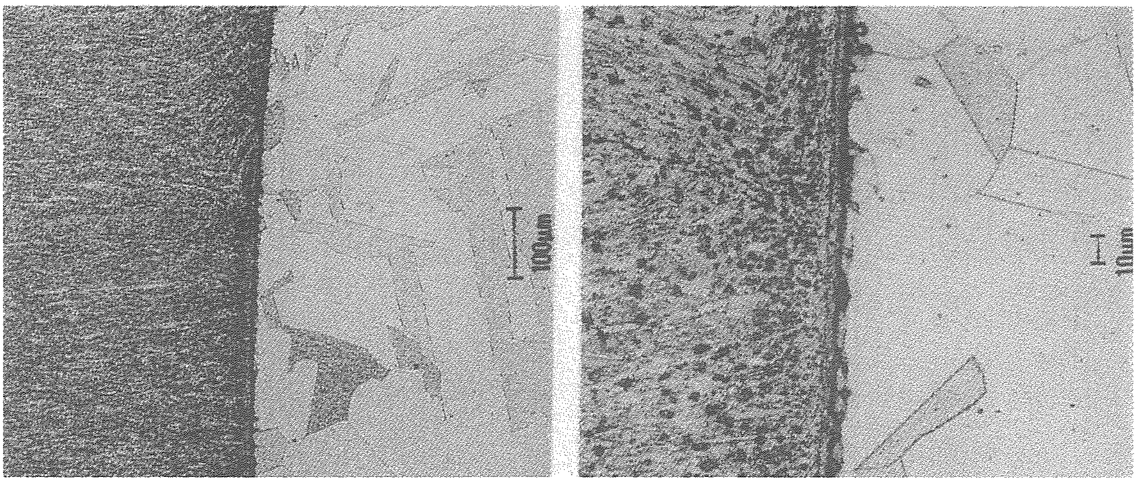


Etching for SS side

Fig. A-6.6 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ① of the cross-section C shown in Figs. A-1 and A-4



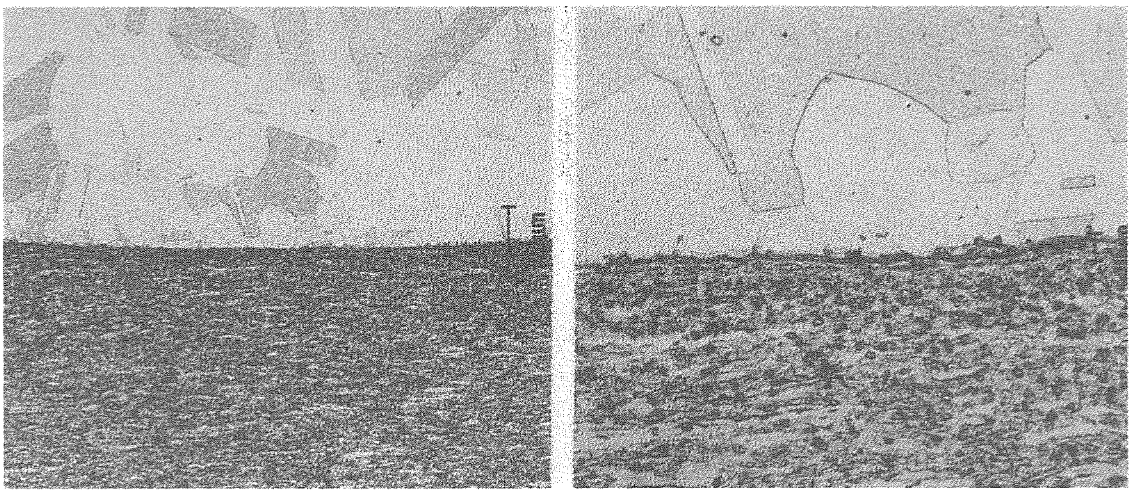
Etching for DSCu side



Etching for SS side

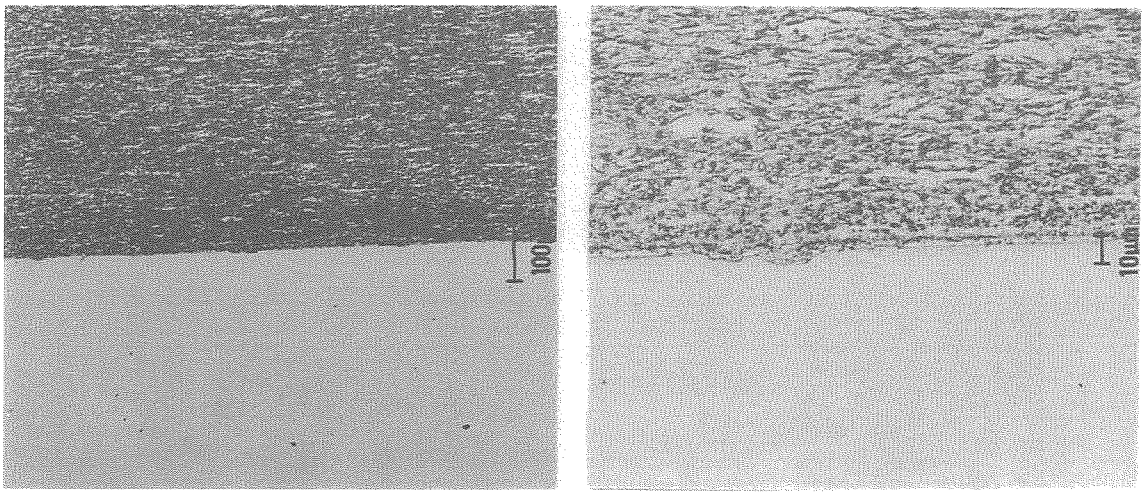
Fig. A-6.7 Micro-scopic images at the DSCu/DSCu/SS HIP bonded interface in the location ② of the cross-section C shown in Figs. A-1 and A-4

Etching for DSCu side

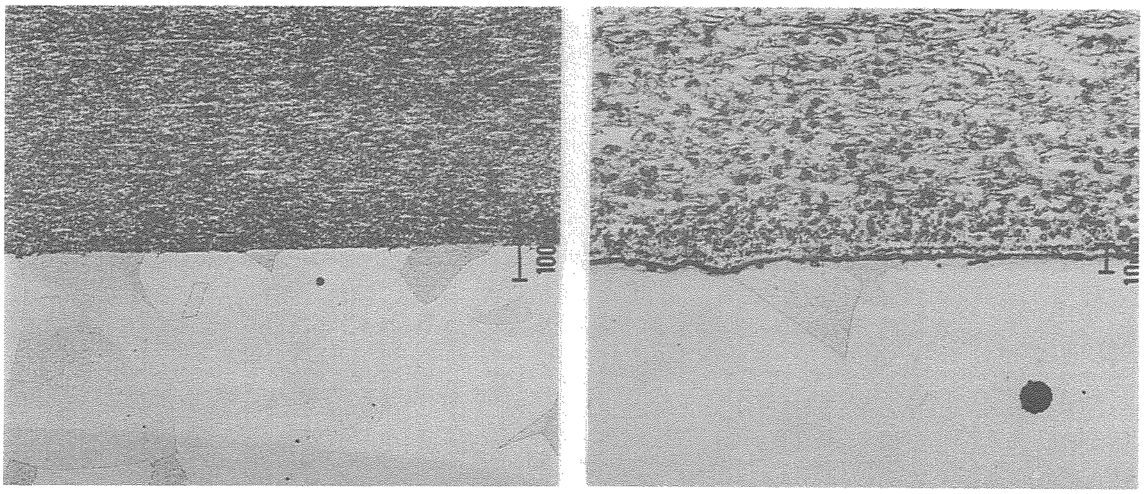


Etching for SS side

Fig. A-6.8.1 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ③-1 of the cross-section C shown in Figs. A-1 and A-4

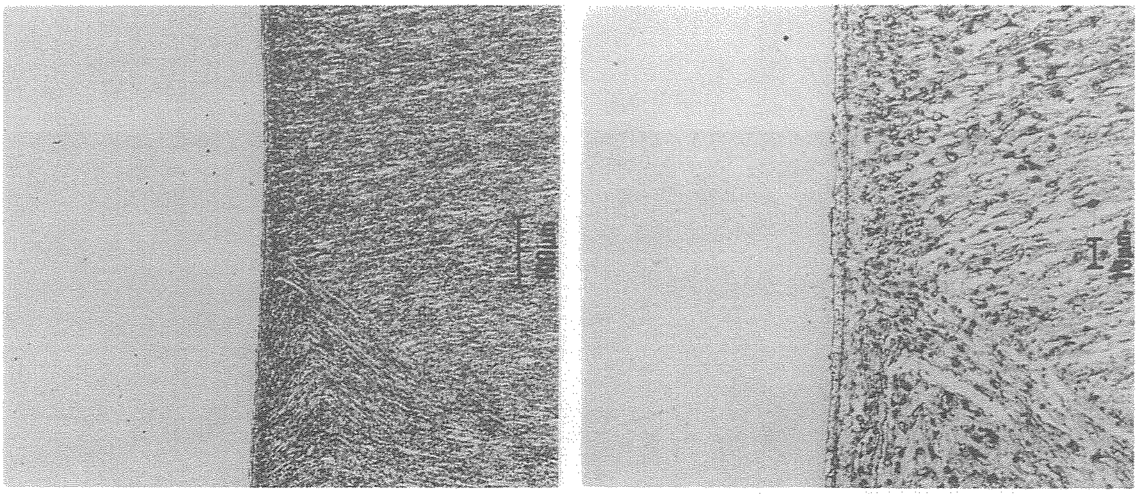


Etching for DSCu side

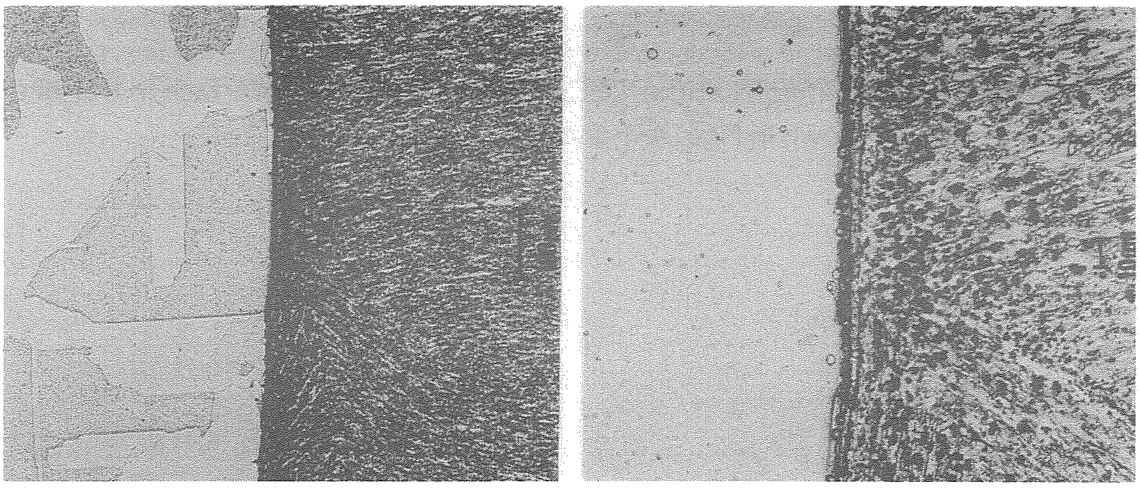


Etching for SS side

Fig. A-6.8.2 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ③-2 of the cross-section C shown in Figs. A-1 and A-4



Etching for DSCu side



Etching for SS side

Fig. A-6.9 Micro-scopic images at the DSCu/DSCu/SS HIP bonded interface in the location ④ of the cross-section C shown in Figs. A-1 and A-4

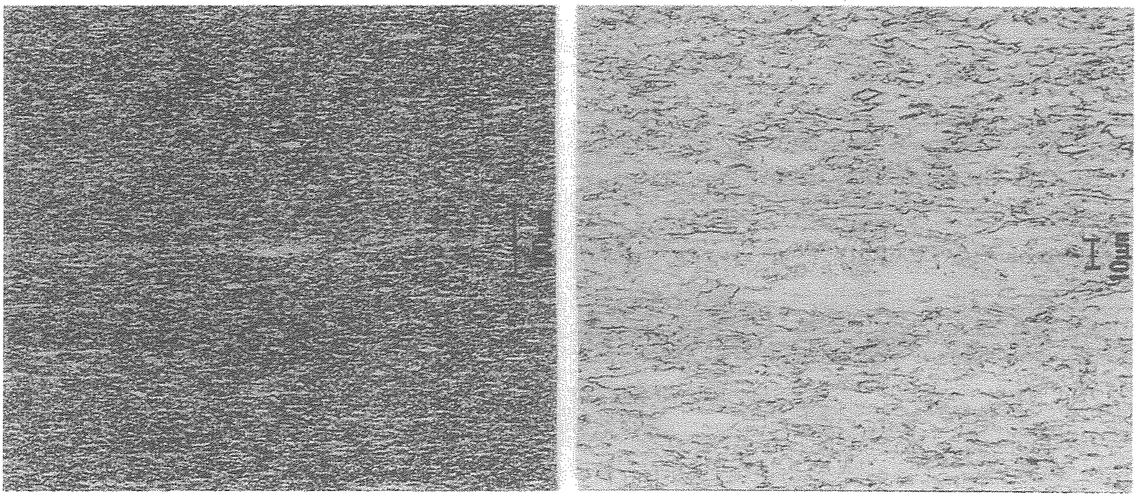


Fig. A-6.10 Micro-scopic images at the DSCu/DSCu HIP bonded interface in the location ⑤ of the cross-section C shown in Figs. A-1 and A-4

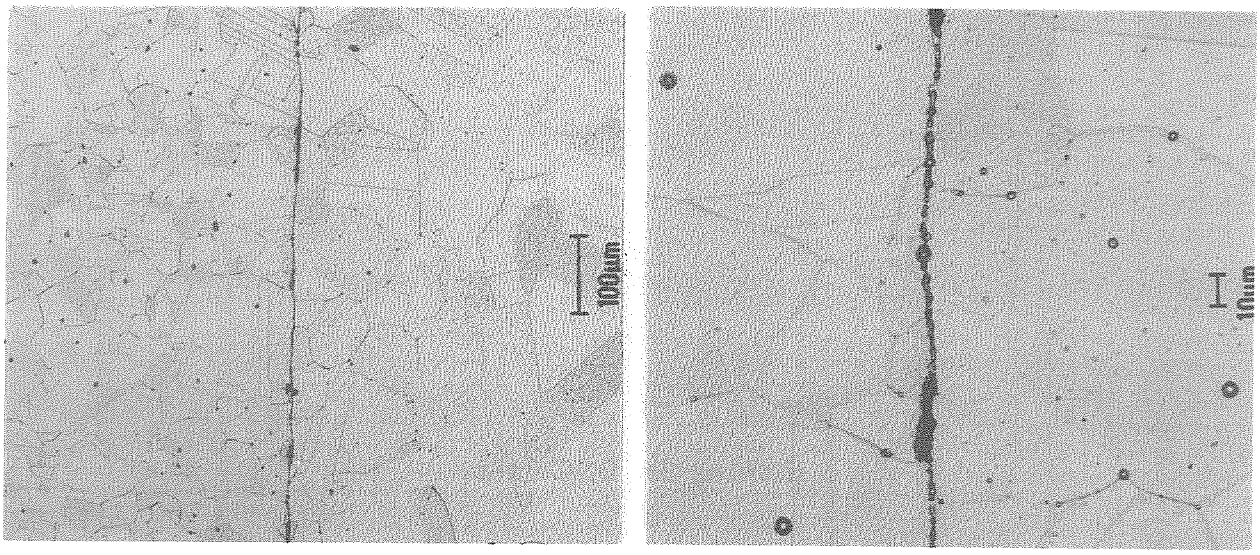
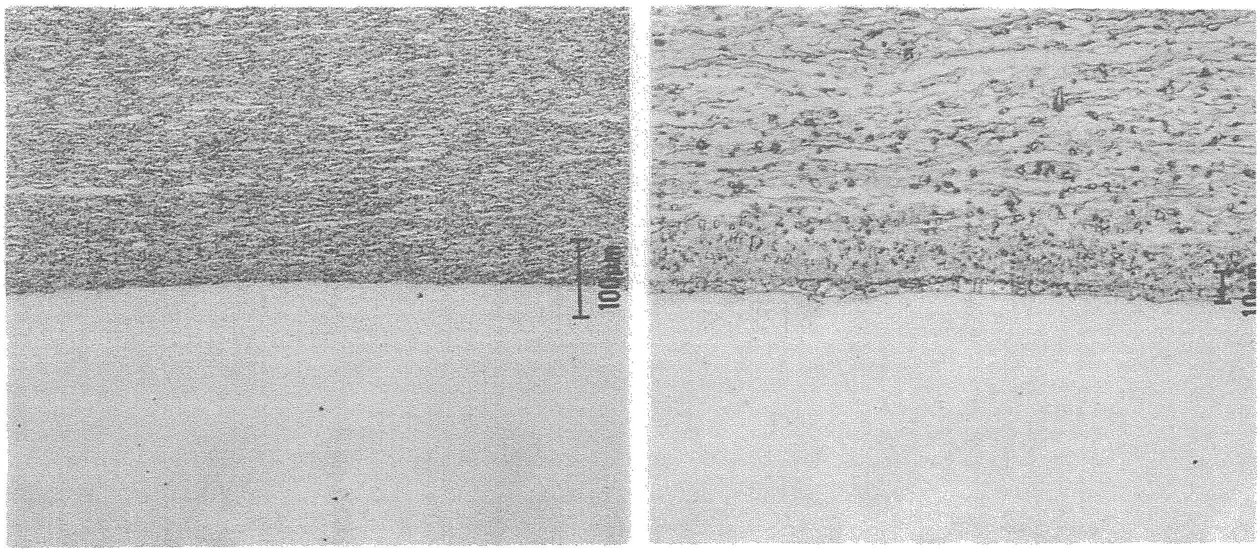
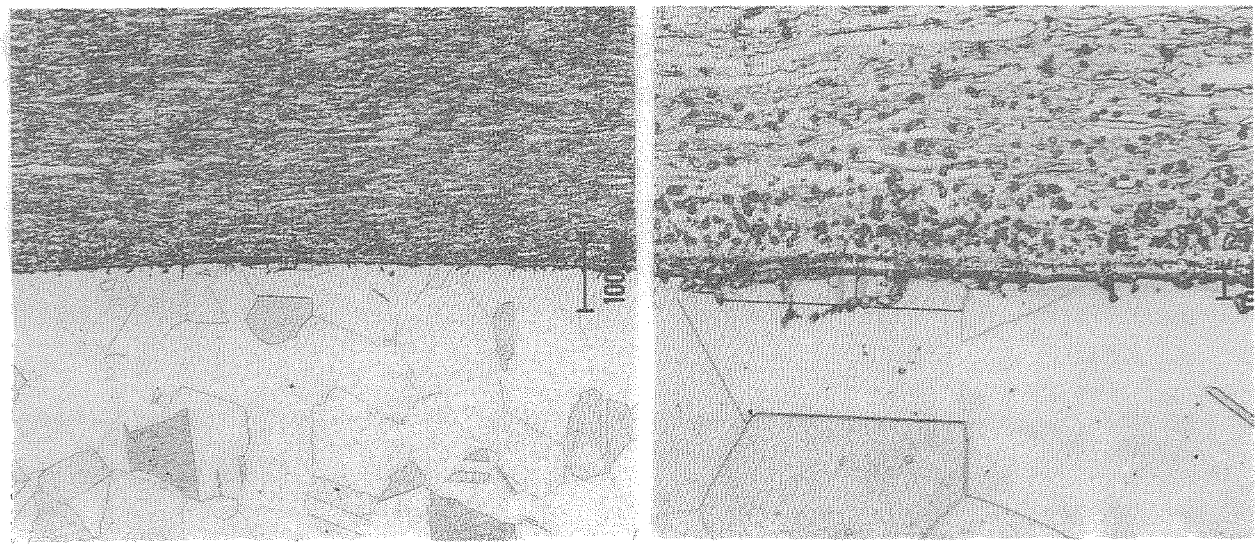


Fig. A-6.12 Micro-scopic images at the SS/SS HIP bonded interface In the location ⑦ shown in Figs. A-6.11 of the location ⑤ of the cross-section C shown in Figs. A-1 and A-4

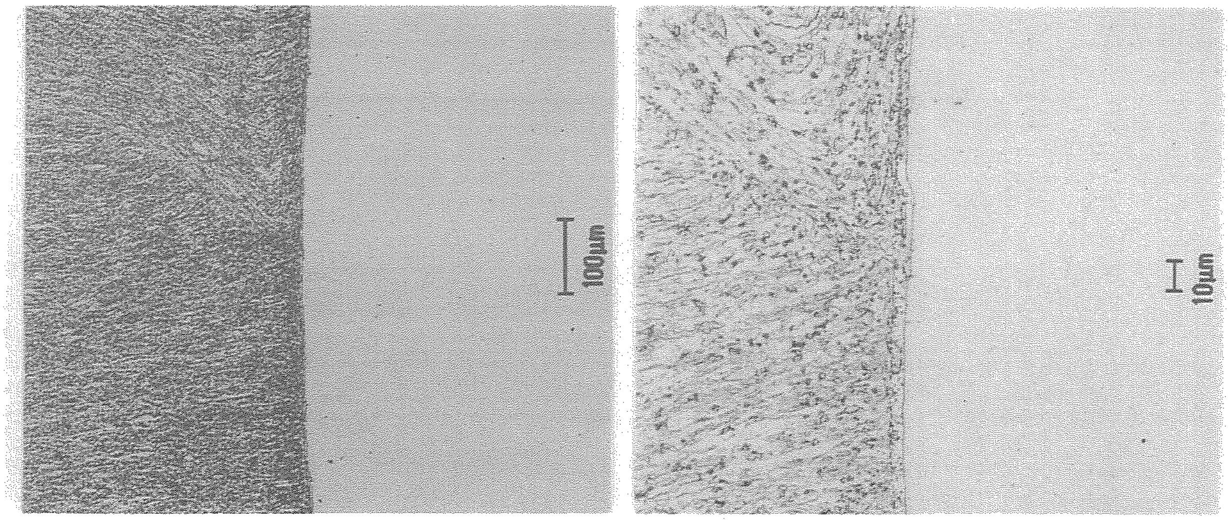


Etching for DSCu side

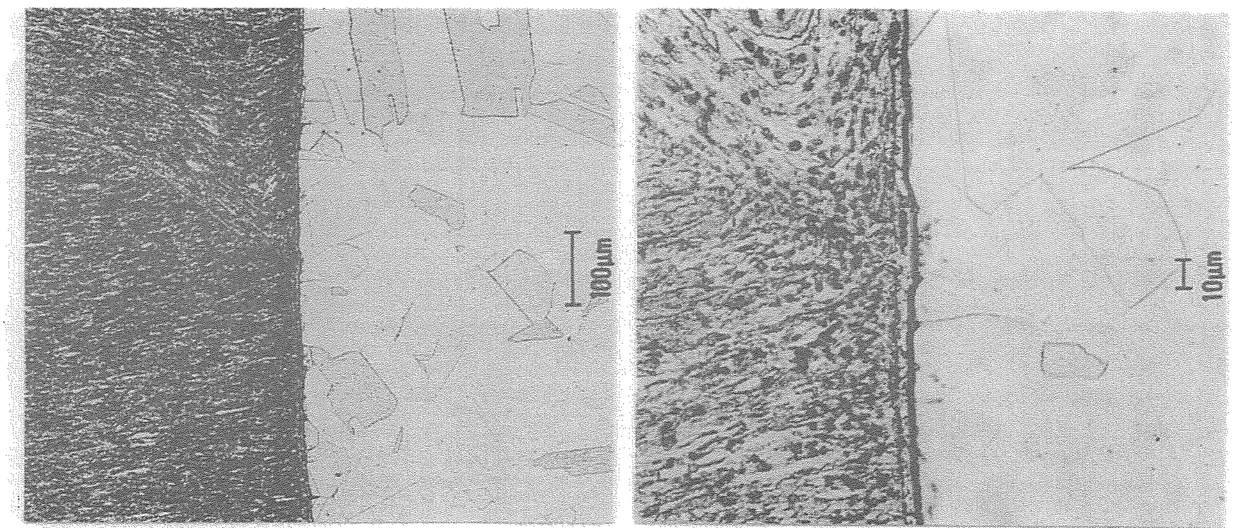


Etching for SS side

Fig. A-6.13 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ① of the cross-section D shown in Figs. A-1 and A-4



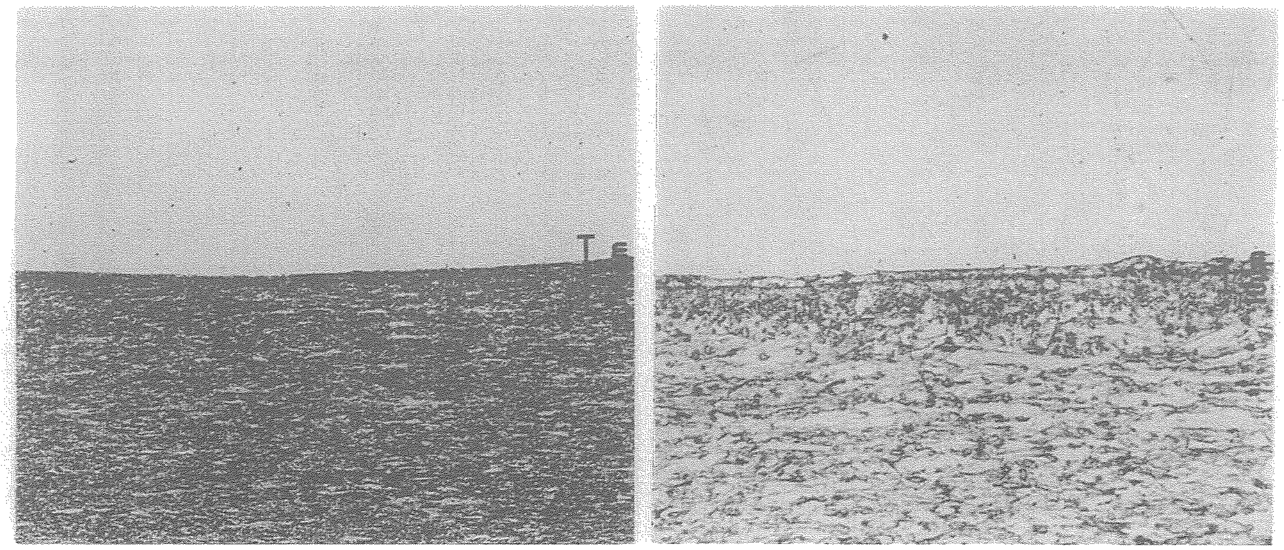
Etching for DSCu side



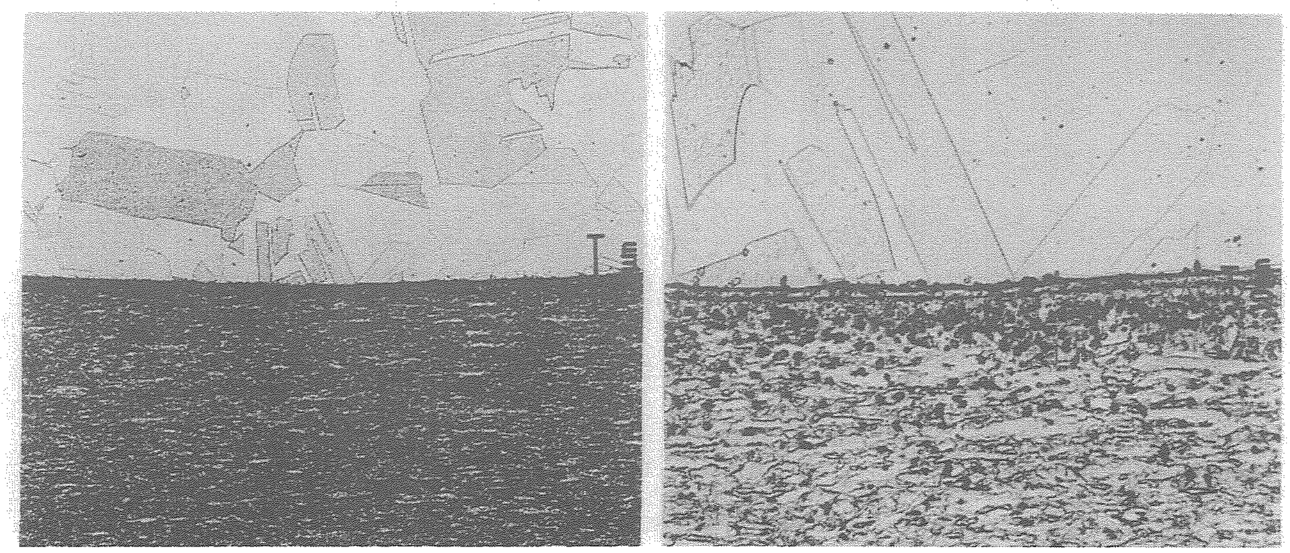
Etching for SS side

① x100 ②①の拡大 x400

Fig. A-6.14 Micro-scopic images at the DSCu/DSCu/SS HIP bonded interface in the location ② of the cross-section D shown in Figs. A-1 and A-4

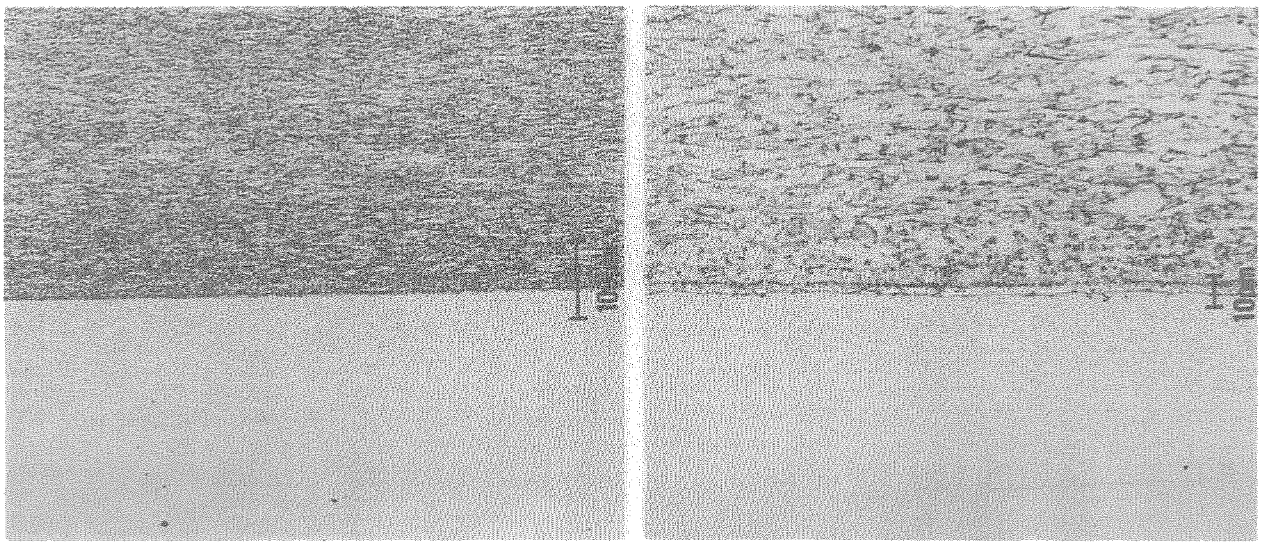


Etching for DSCu side

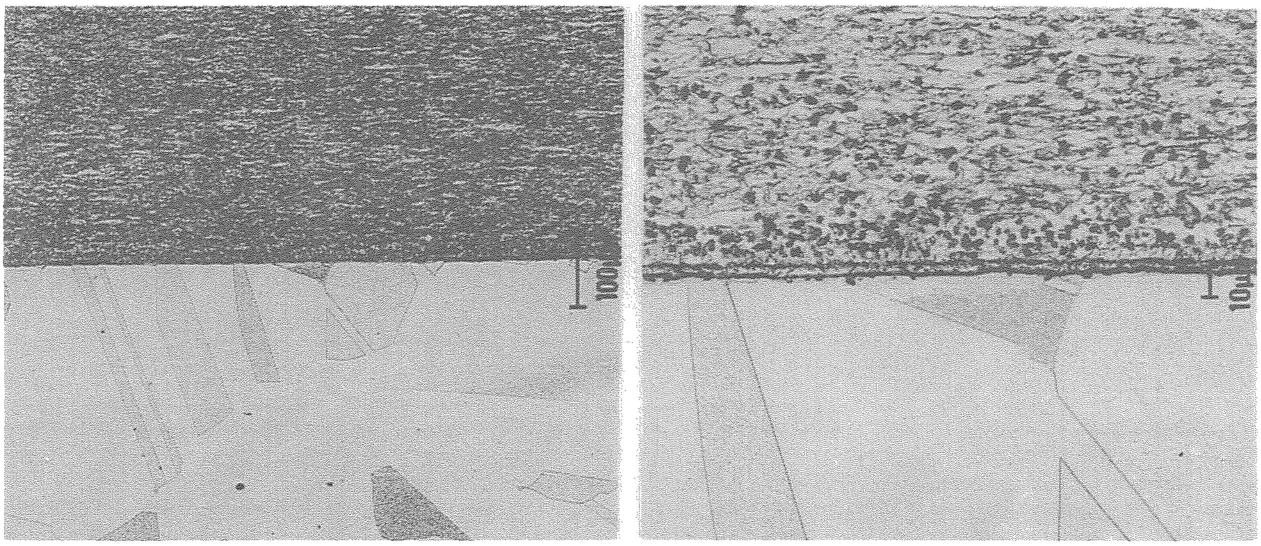


Etching for SS side

Fig. A-6.15.1 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ③1 of the cross-section D shown in Figs. A-1 and A-4

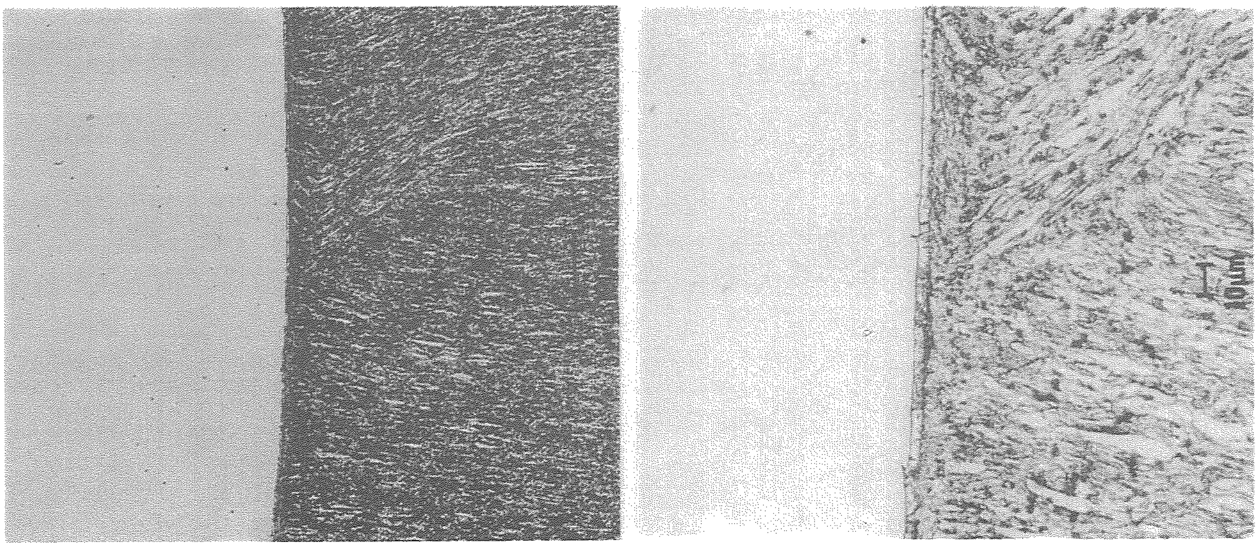


Etching for DSCu side

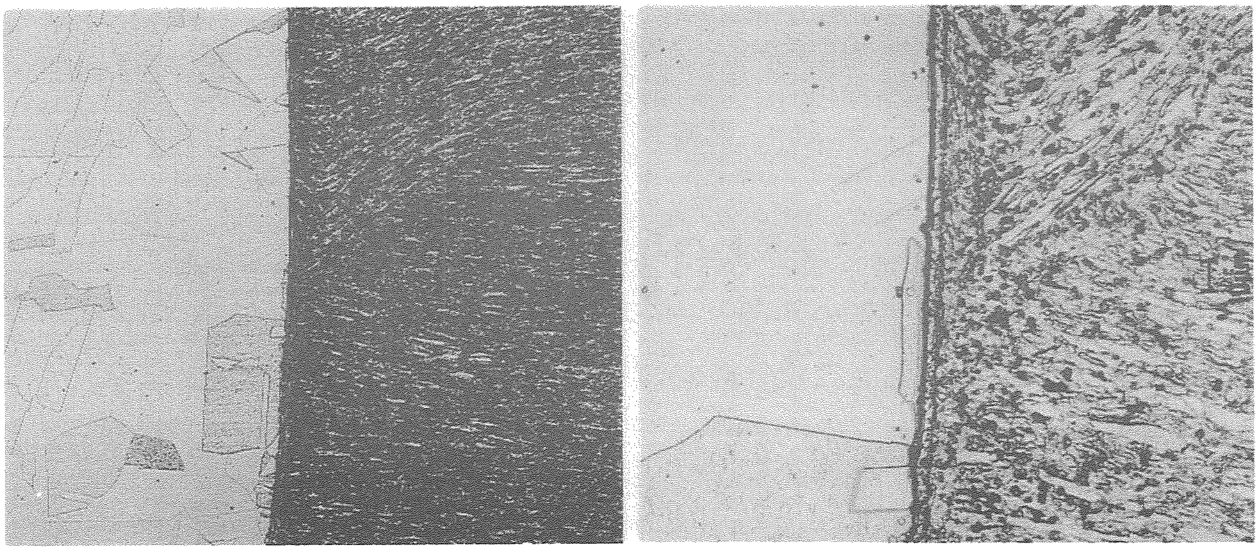


Etching for SS side

Fig. A-6.15.2 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ③-2 of the cross-section D shown in Figs. A-1 and A-4

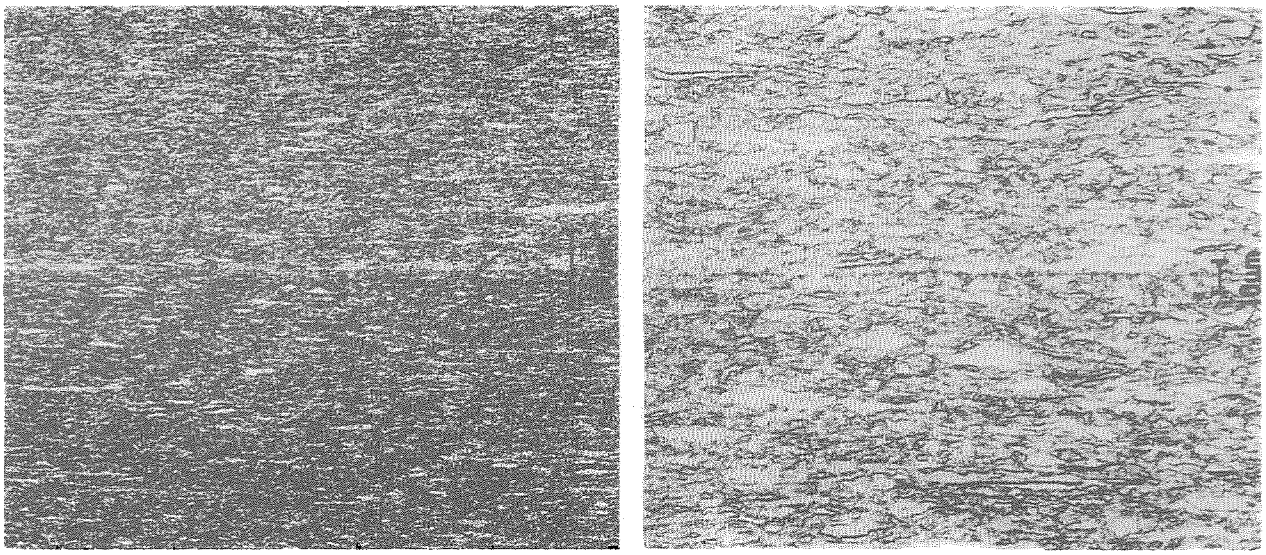


Etching for DSCu side



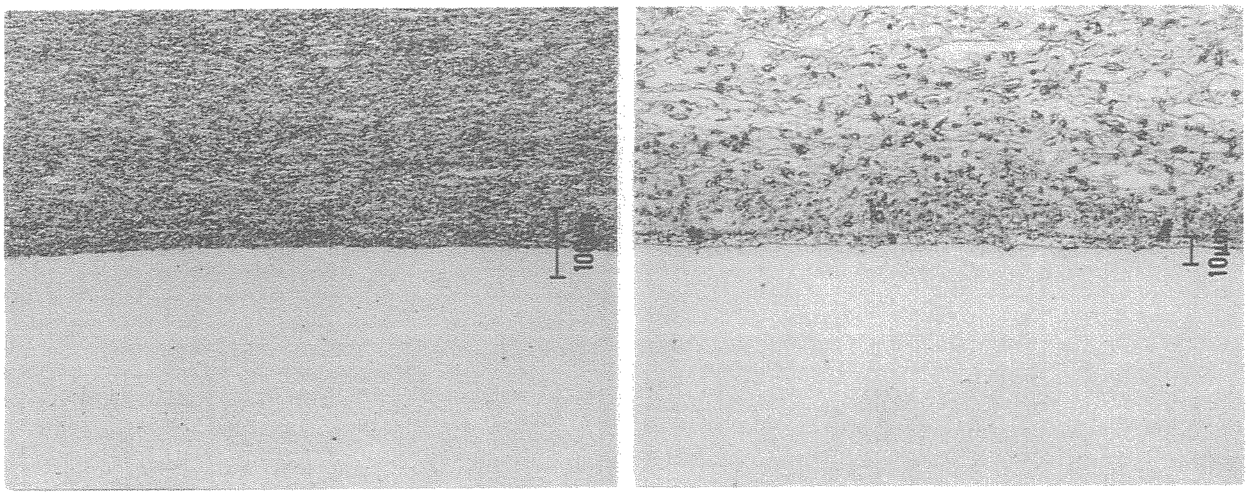
Etching for SS side

Fig. A-6.16 Micro-scopic images at the DSCu/DSCu/SS HIP bonded interface in the locatior ④ of the cross-section D shown in Figs. A-1 and A-4

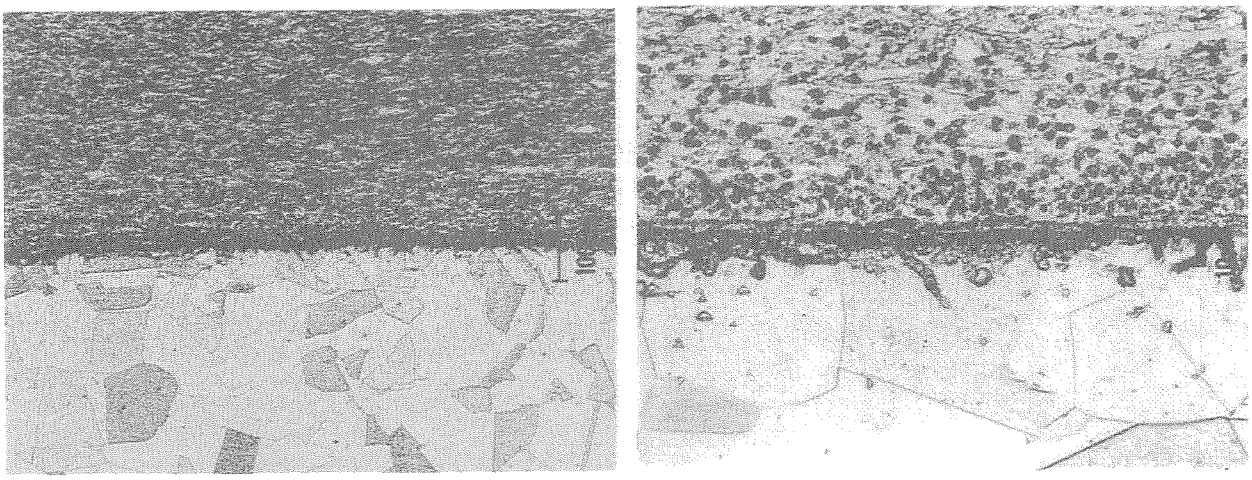


x100 x400

Fig. A-6.17 Micro-scopic images at the DSCu/DSCu HIP bonded interface in the location ⑤ of the cross-section D shown in Figs. A-1 and A-4

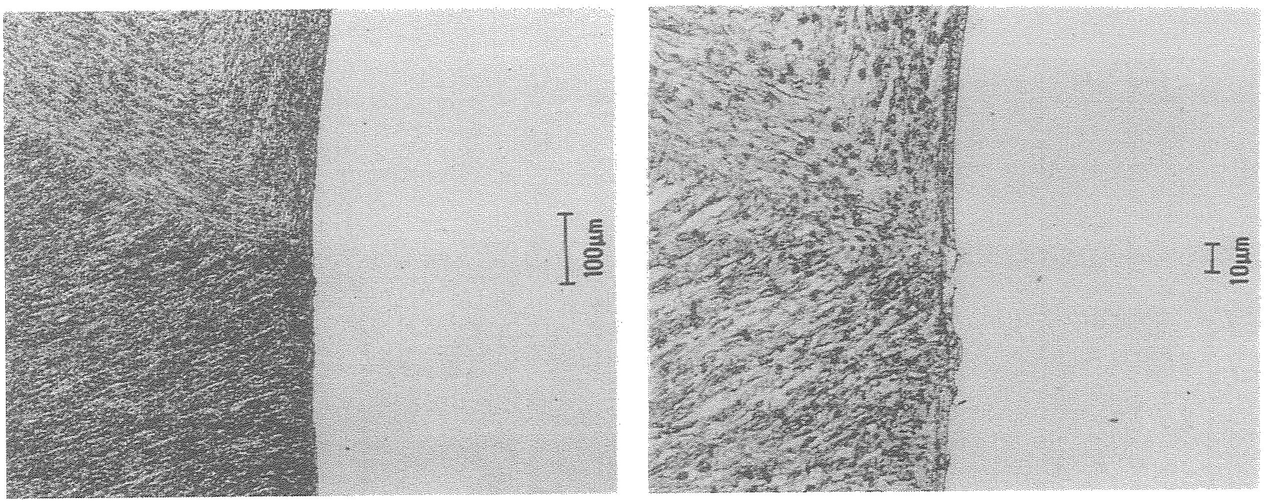


Etching for DSCu side

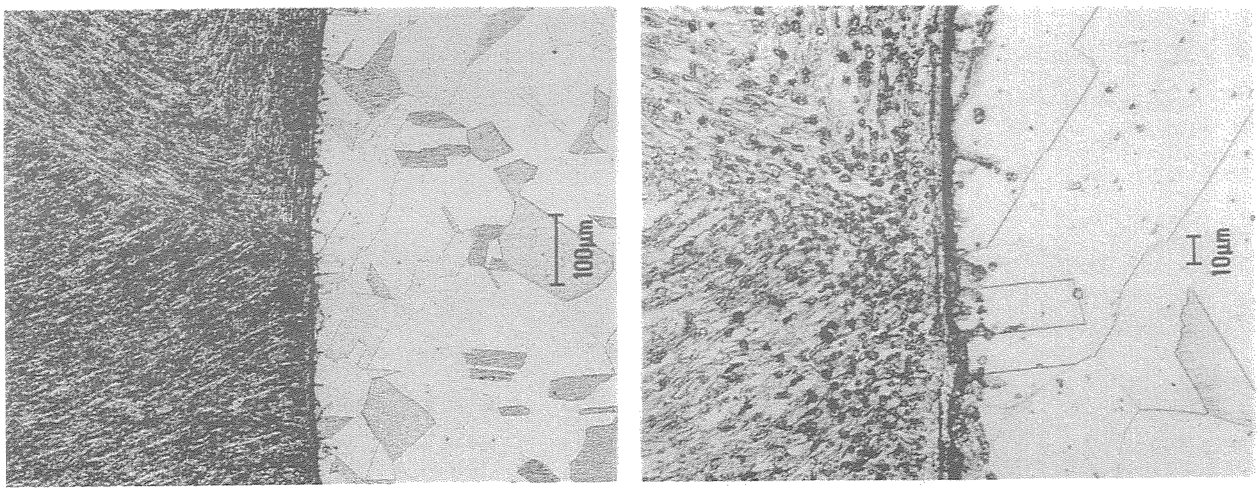


Etching for SS side

Fig. A-6.18 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ① of the cross-section E shown in Figs. A-1 and A-4

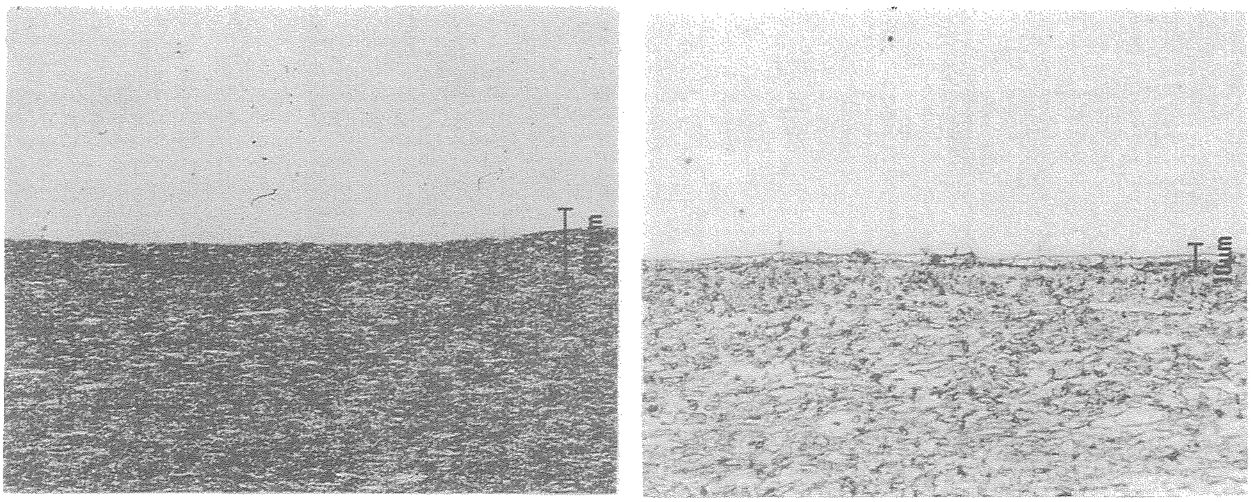


Etching for DSCu side

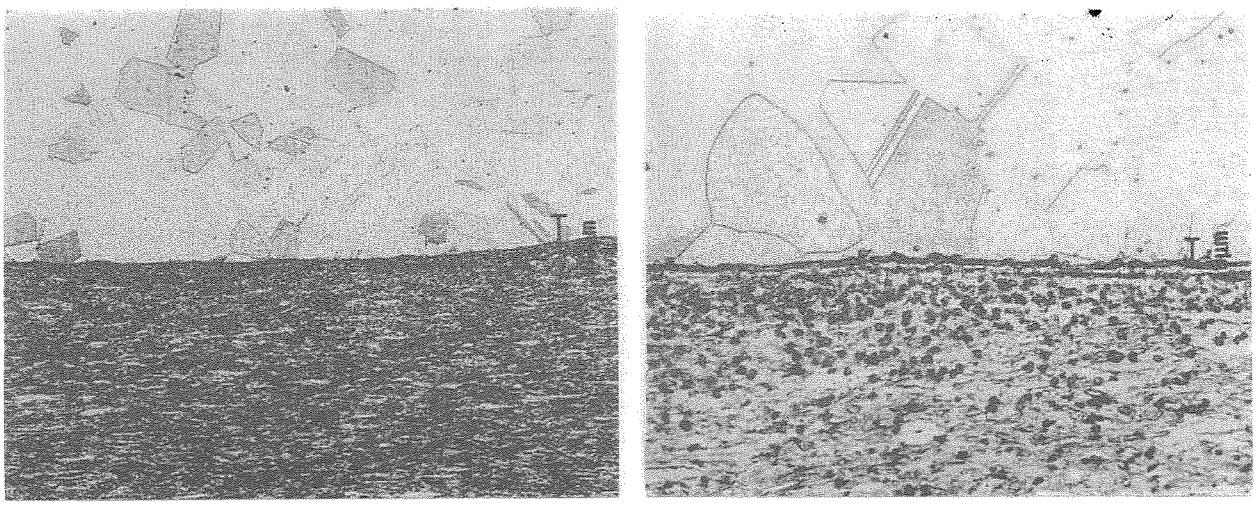


Etching for SS side

Fig. A-6.19 Micro-scopic images at the DSCu/DSCu/SS HIP bonded interface in the location ② of the cross-section E shown in Figs. A-1 and A-4

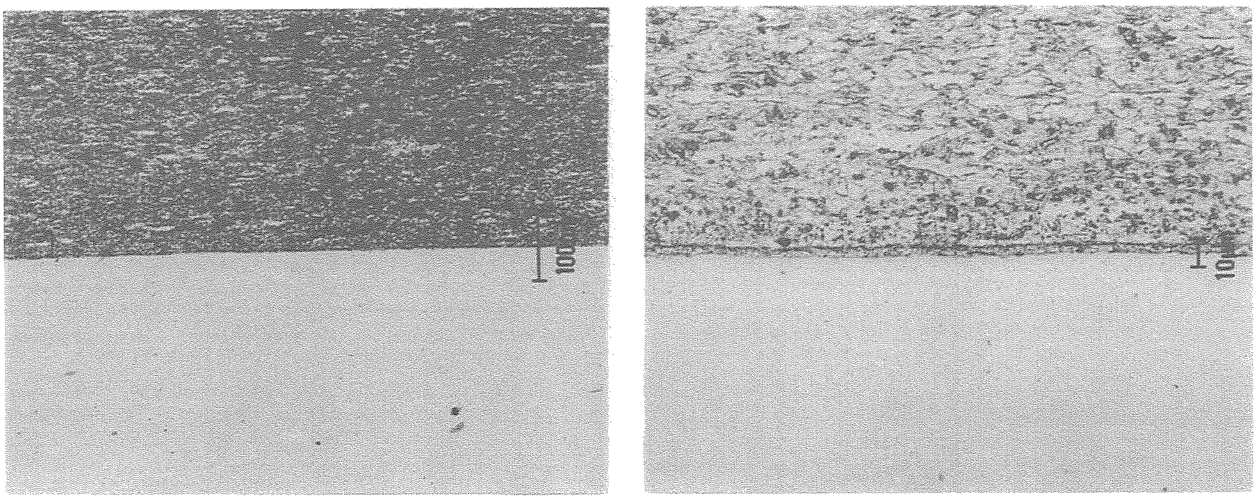


Etching for DSCu side

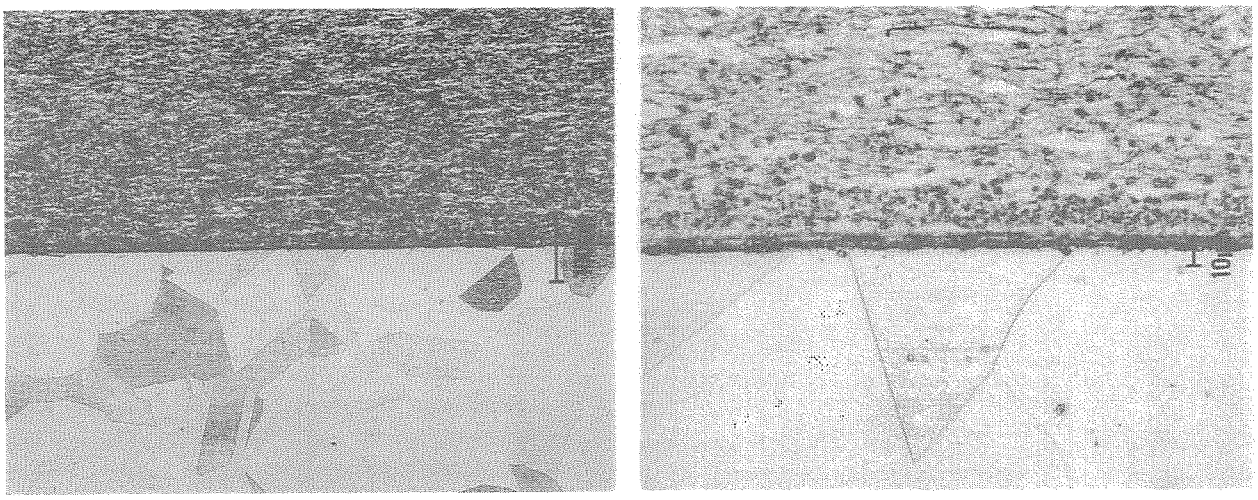


Etching for SS side

Fig. A-6.20.1 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ③-1 of the cross-section E shown in Figs. A-1 and A-4

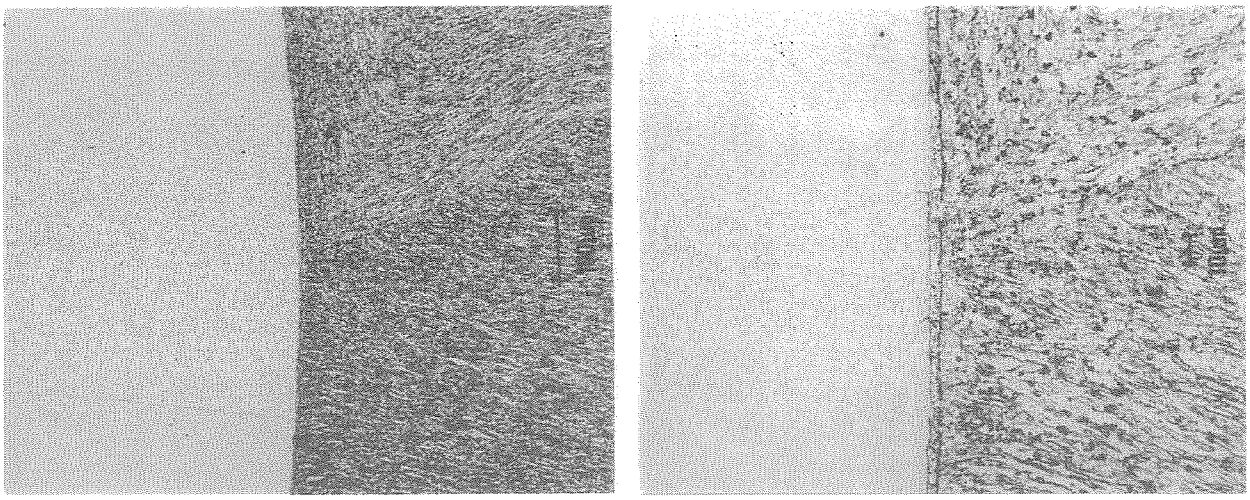


Etching for DSCu side

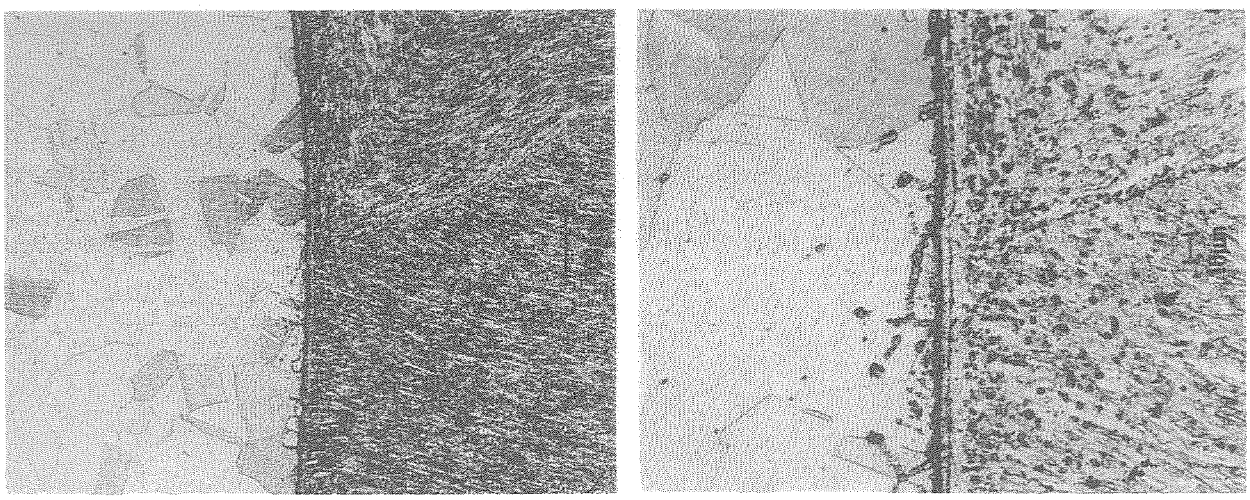


Etching for SS side

Fig. A-6.20.2 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ③-2 of the cross-section E shown in Figs. A-1 and A-4

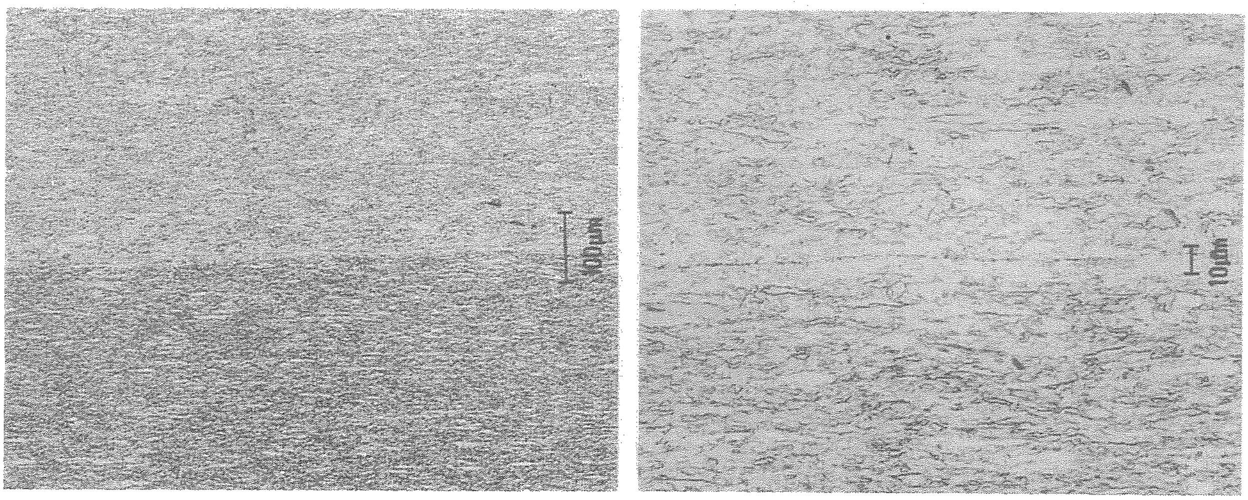


Etching for DSCu side



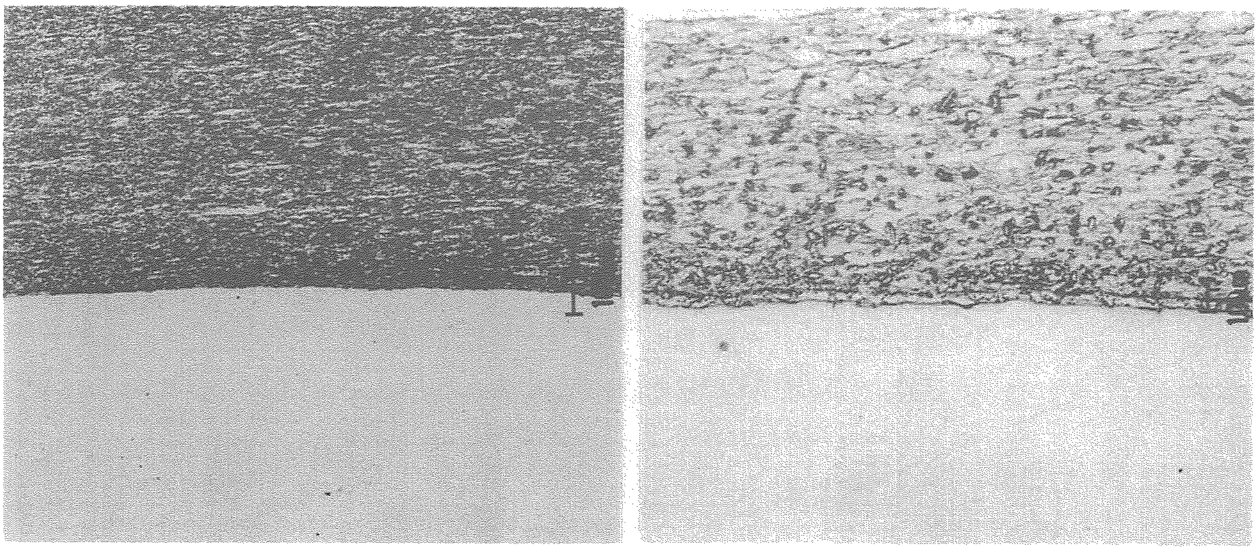
Etching for SS side

Fig. A-6.21 Micro-scopic images at the DSCu/DSCu/SS HIP bonded interface in the location ④ of the cross-section E shown in Figs. A-1 and A-4

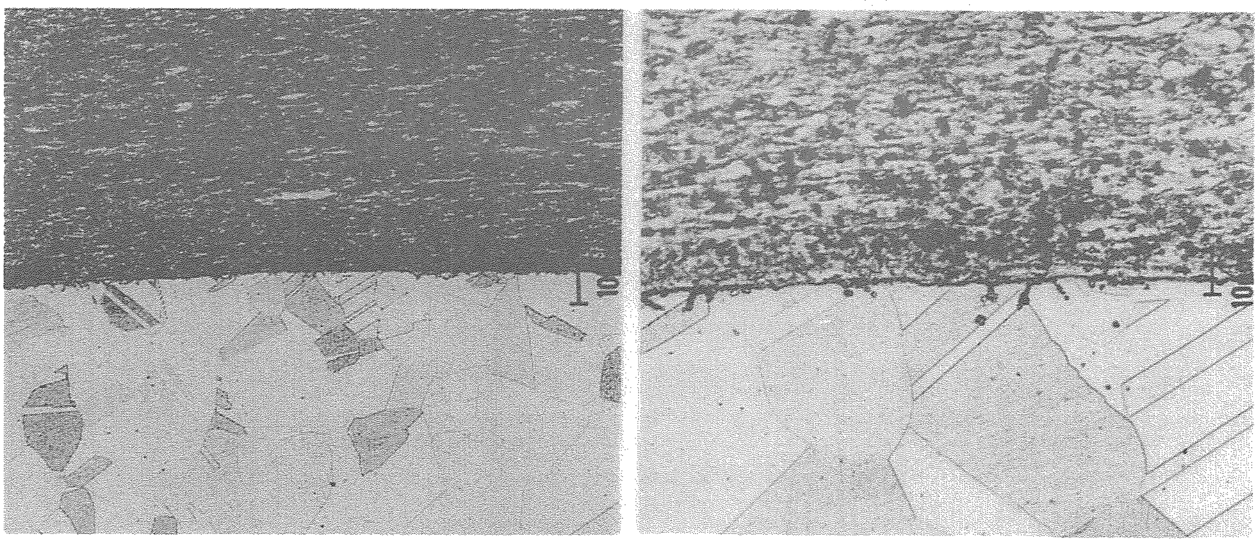


x100 x400

Fig. A-6.22 Micro-scopic images at the DSCu/DSCu HIP bonded interface in the location ⑤ of the cross-section E shown in Figs. A-1 and A-4

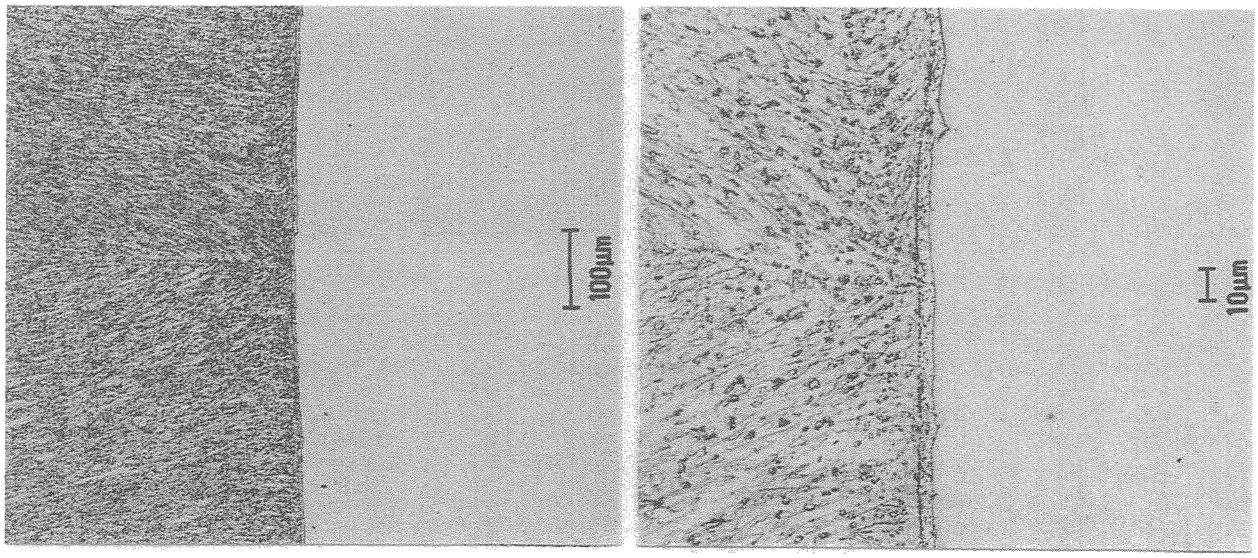


Etching for DSCu side

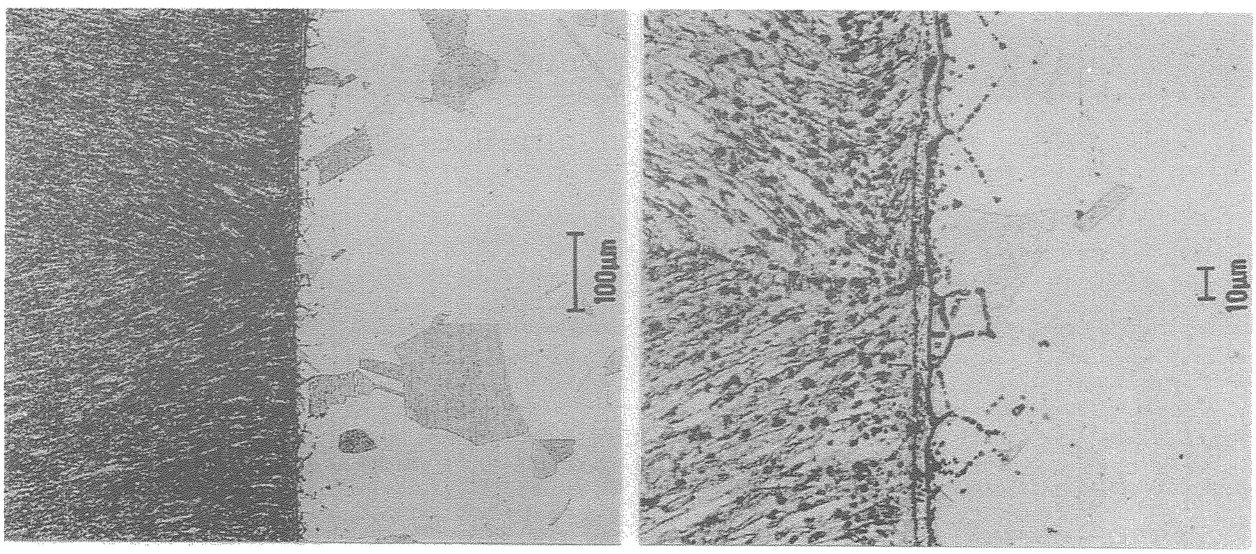


Etching for SS side

Fig. A-6.23 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ① of the cross-section F shown in Figs. A-1 and A-4

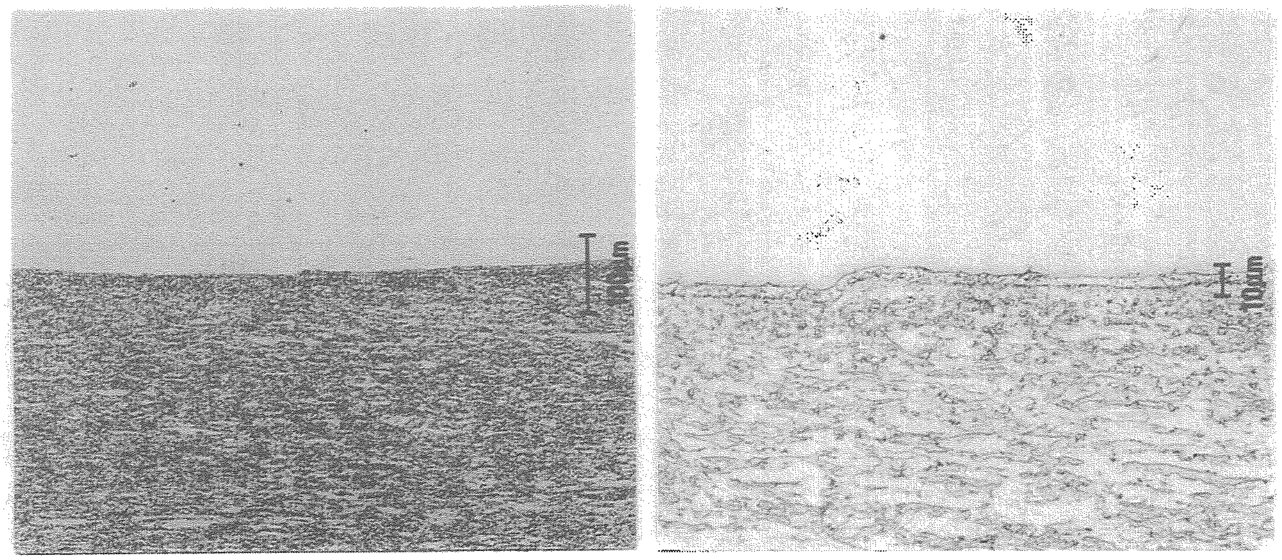


Etching for DSCu side



Etching for SS side

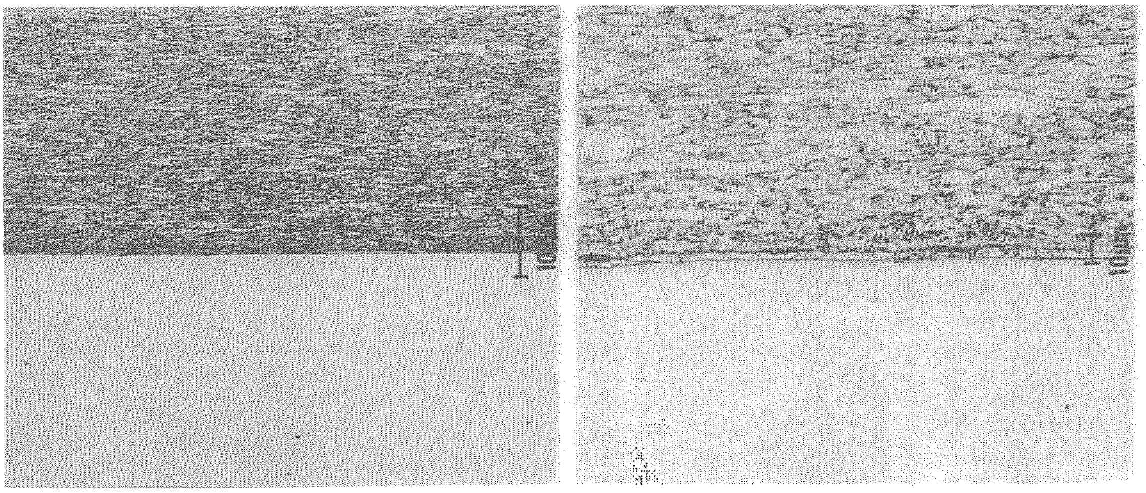
Fig. A-6.24 Micro-scopic images at the DSCu/DSCu/SS HIP bonded interface in the location ② of the cross-section F shown in Figs. A-1 and A-4



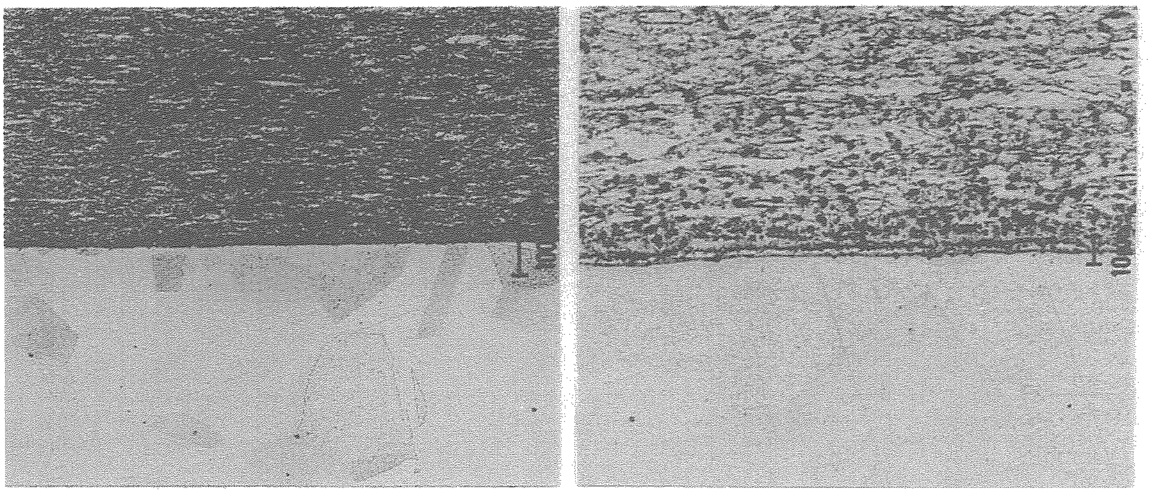
Etching for DSCu side

Etching for SS side

Fig. A-6.25.1 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ③- of the cross-section F shown in Figs. A-1 and A-4

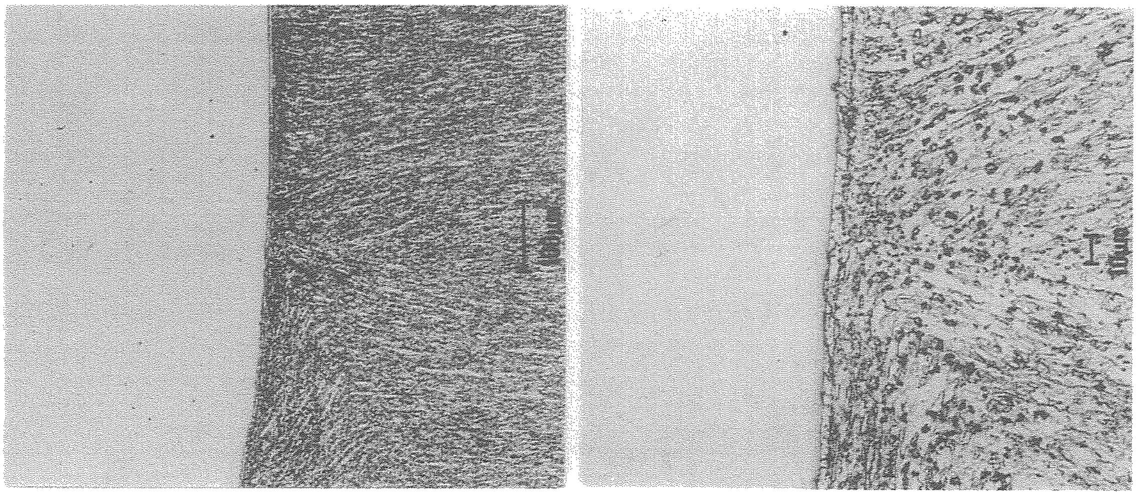


Etching for DSCu side

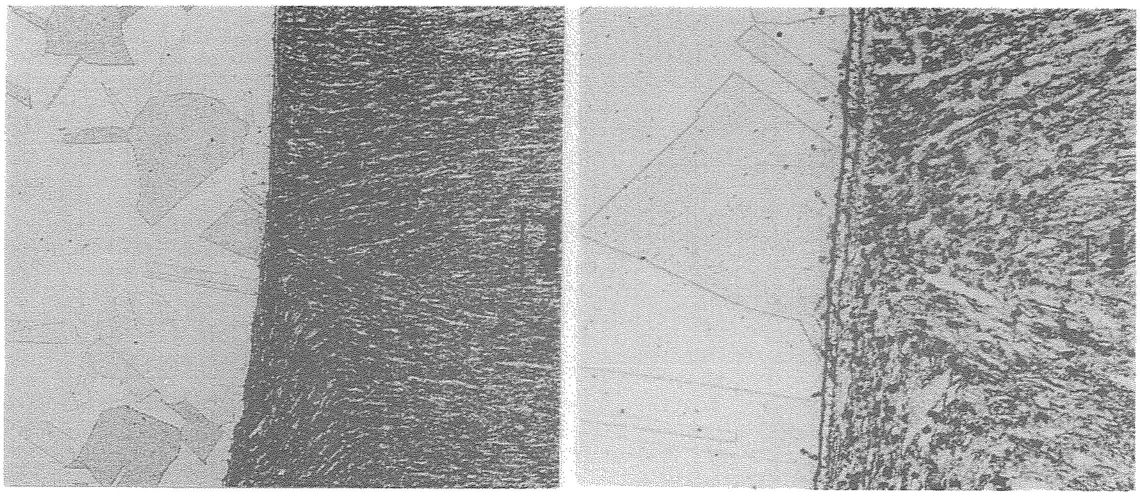


Etching for SS side

Fig. A-6.25.2 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ③-2 of the cross-section F shown in Figs. A-1 and A-4



Etching for DSCu side



Etching for SS side

Fig. A-6.26 Micro-scopic images at the DSCu/DSCu/SS HIP bonded interface in the location ④ of the cross-section F shown in Figs. A-1 and A-4

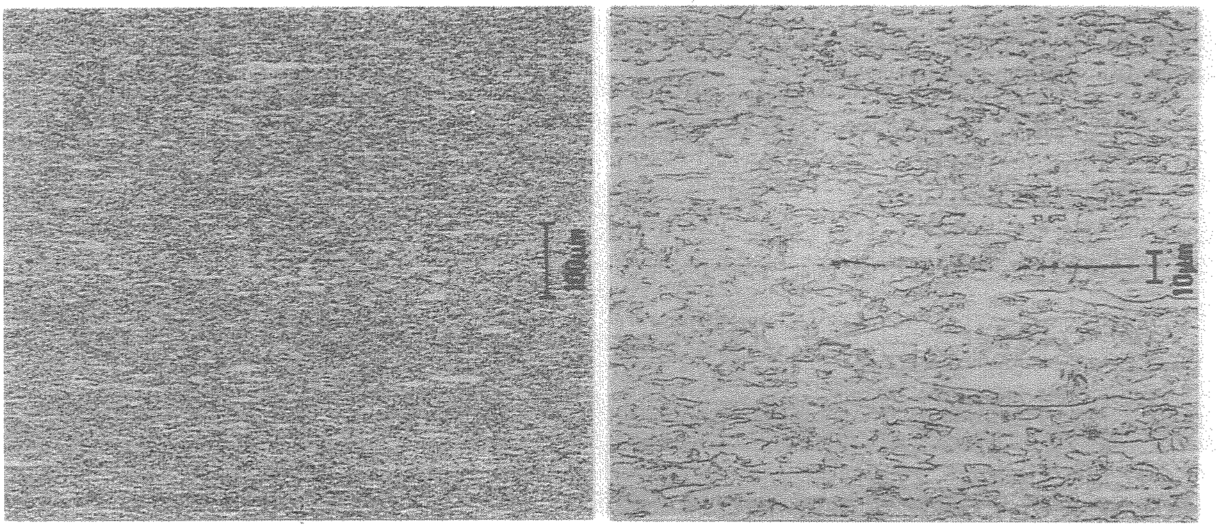


Fig. A-6.27 Micro-scopic images at the DSCu/DSCu HIP bonded interface in the location ⑤ of the cross-section F shown in Figs. A-1 and A-4

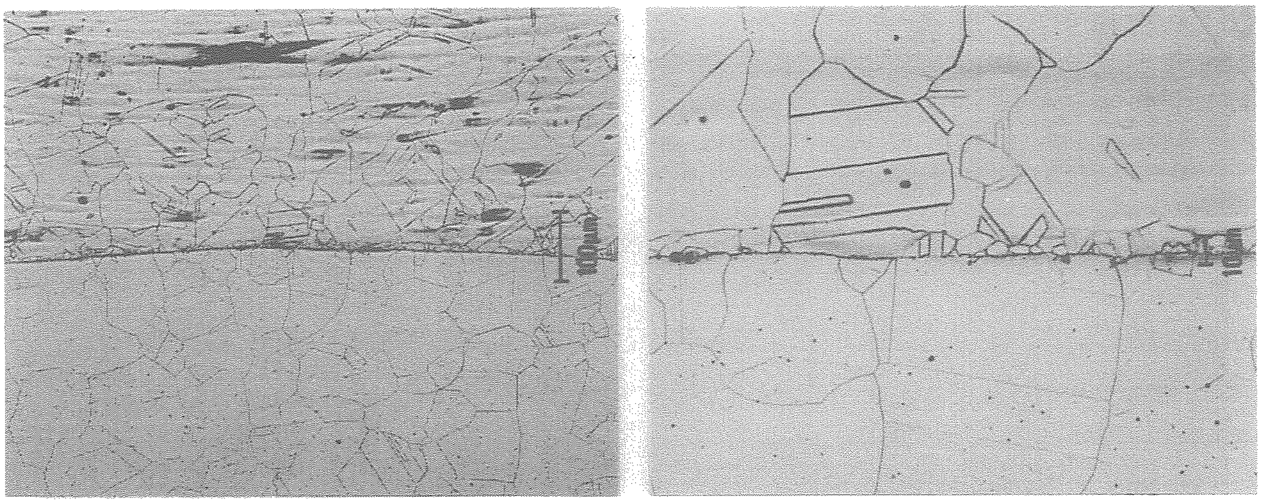


Fig. A-6.28 Micro-scopic images at the SS/SS HIP bonded interface in the location ① of the cross-section G shown in Figs. A-1 and A-4

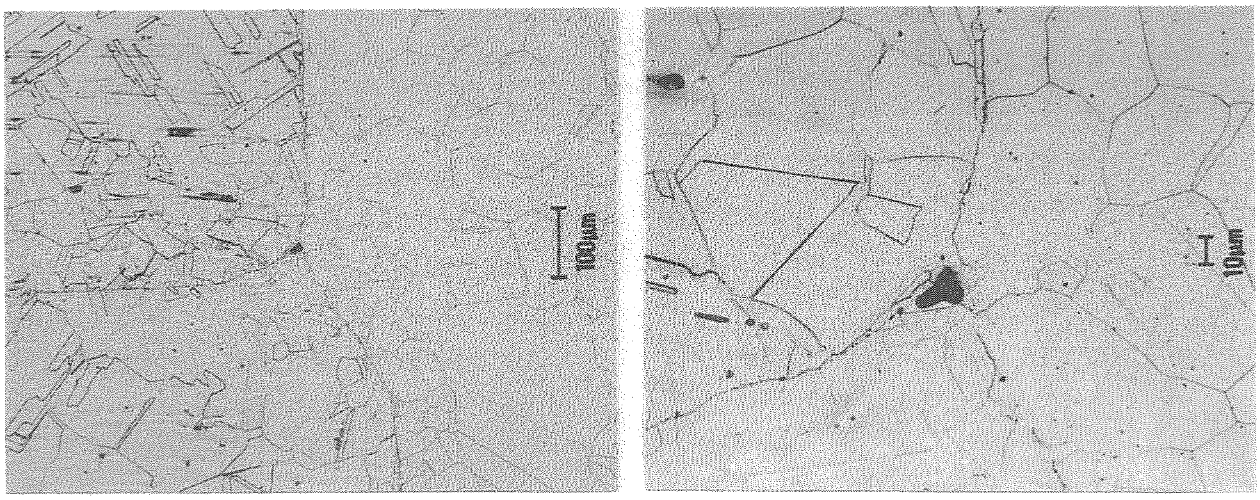


Fig. A-6.29 Micro-scopic images at the SS/SS/SS HIP bonded interface in the location ② of the cross-section G shown in Figs. A-1 and A-4

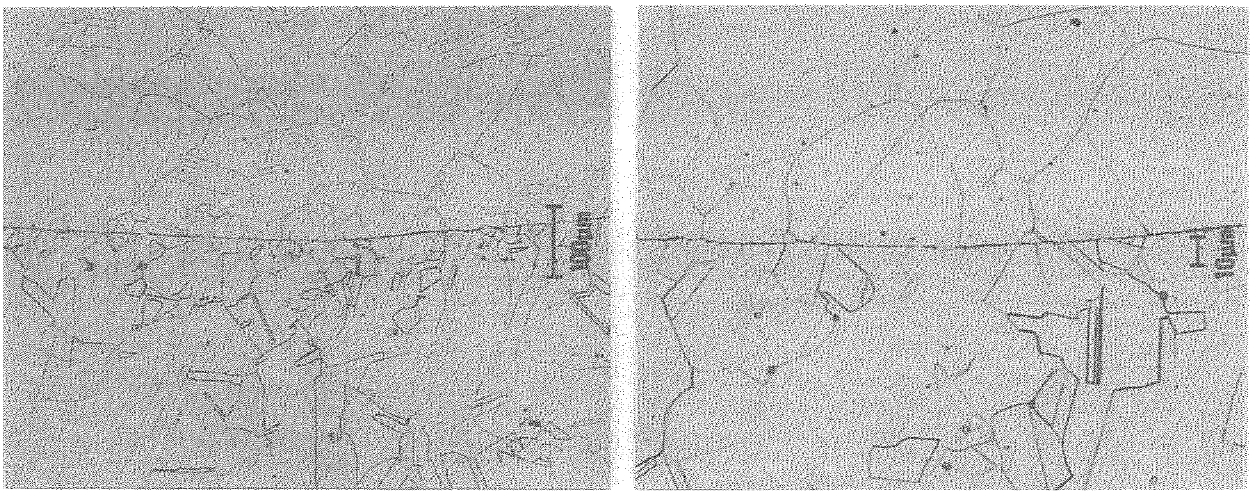


Fig. A-6.30.1 Micro-scopic images at the SS/SS HIP bonded interface in the location ③-1 of the cross-section G shown in Figs. A-1 and A-4

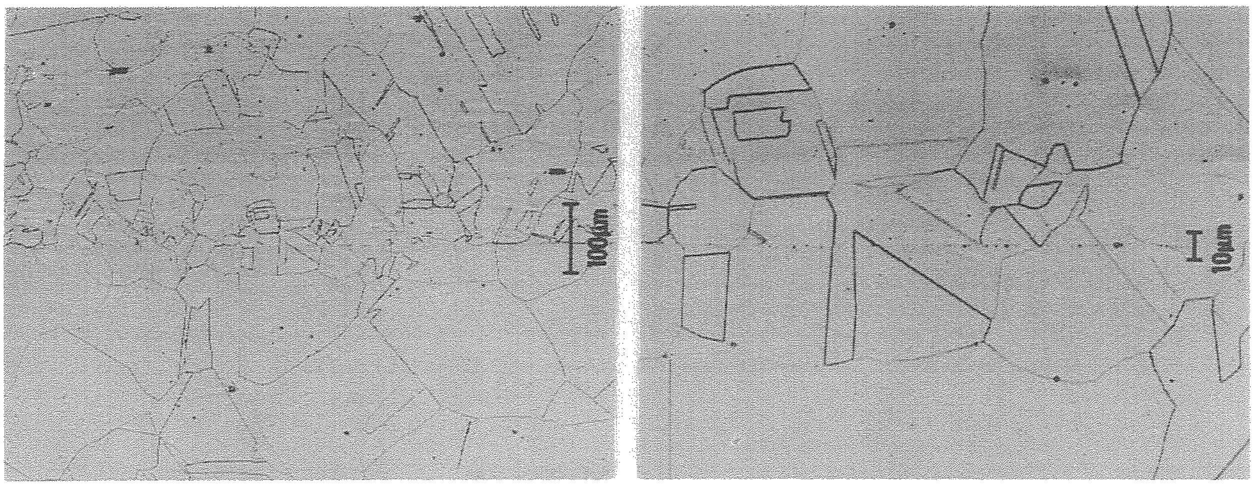


Fig. A-6.30.2 Micro-scopic images at the SS/SS HIP bonded interface in the location ③-2 of the cross-section G shown in Figs. A-1 and A-4

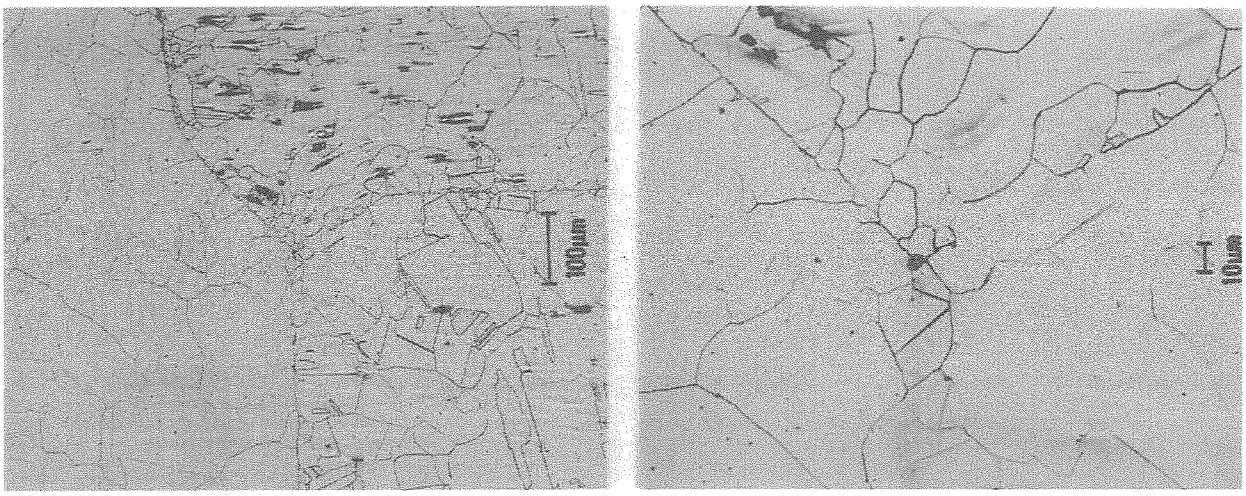


Fig. A-6.31 Micro-scopic images at the SS/SS HIP bonded interface in the location ③-1 of the cross-section G shown in Figs. A-1 and A-4

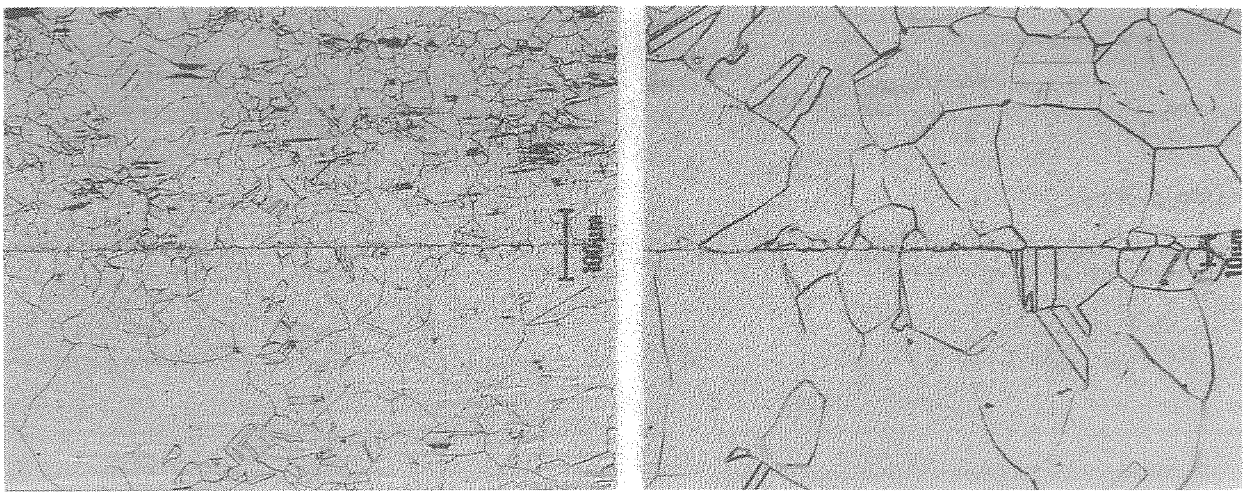
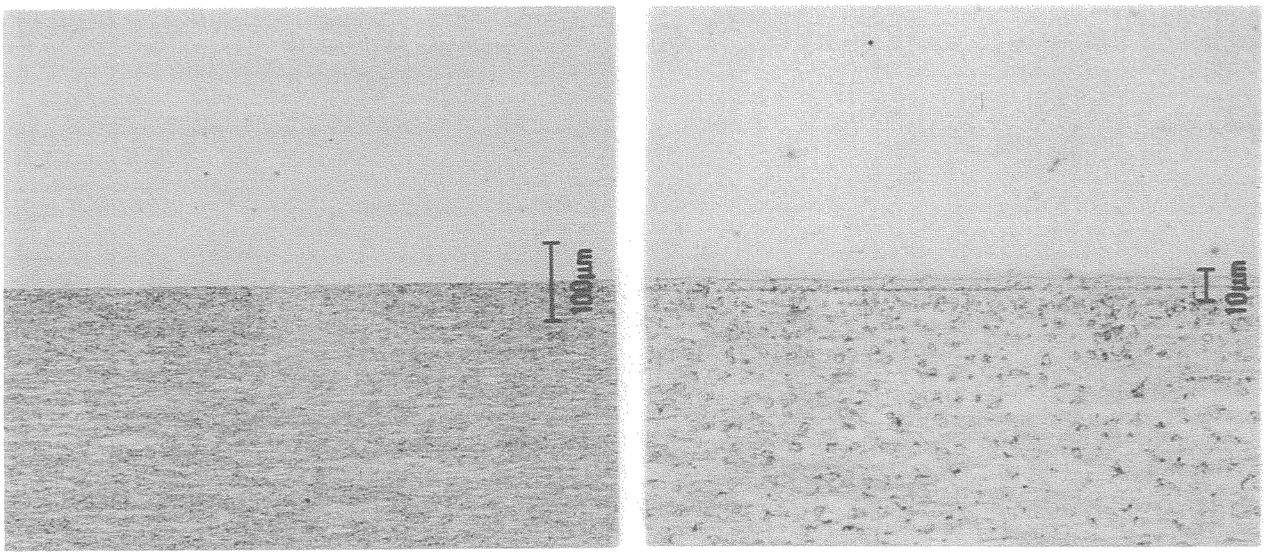
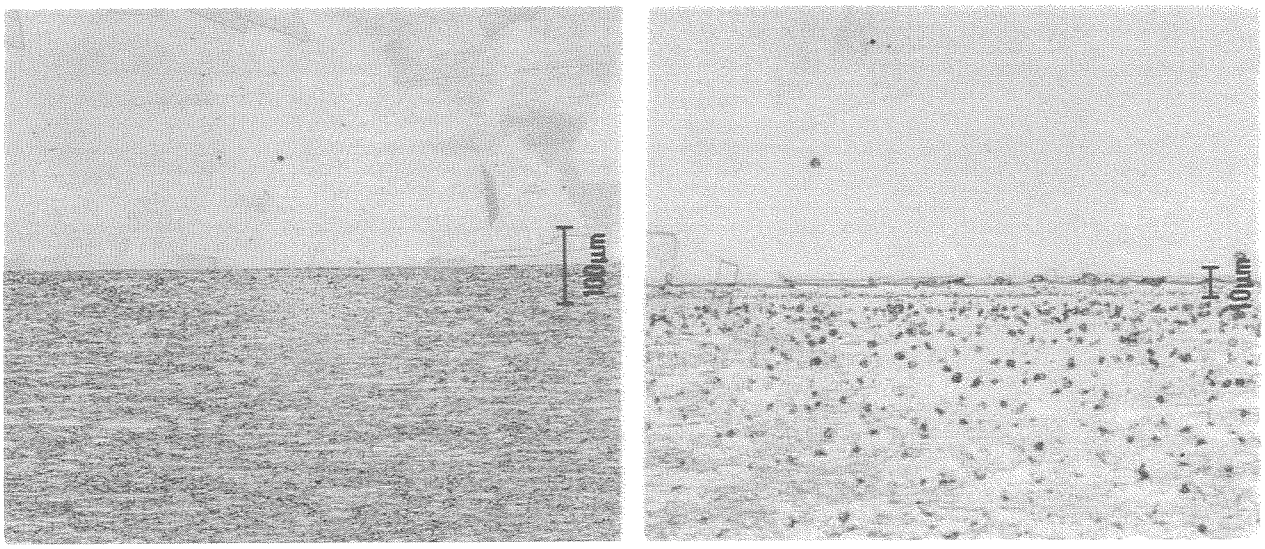


Fig. A-6.32 Micro-scopic images at the SS/SS HIP bonded interface in the location ③-2 of the cross-section G shown in Figs. A-1 and A-4

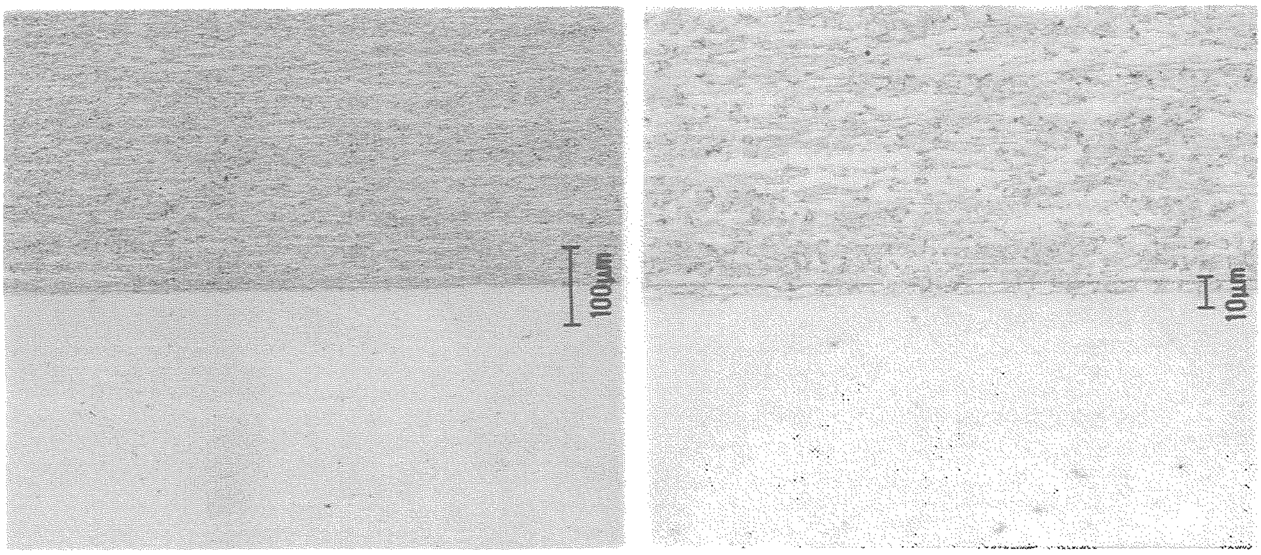


Etching for DSCu side

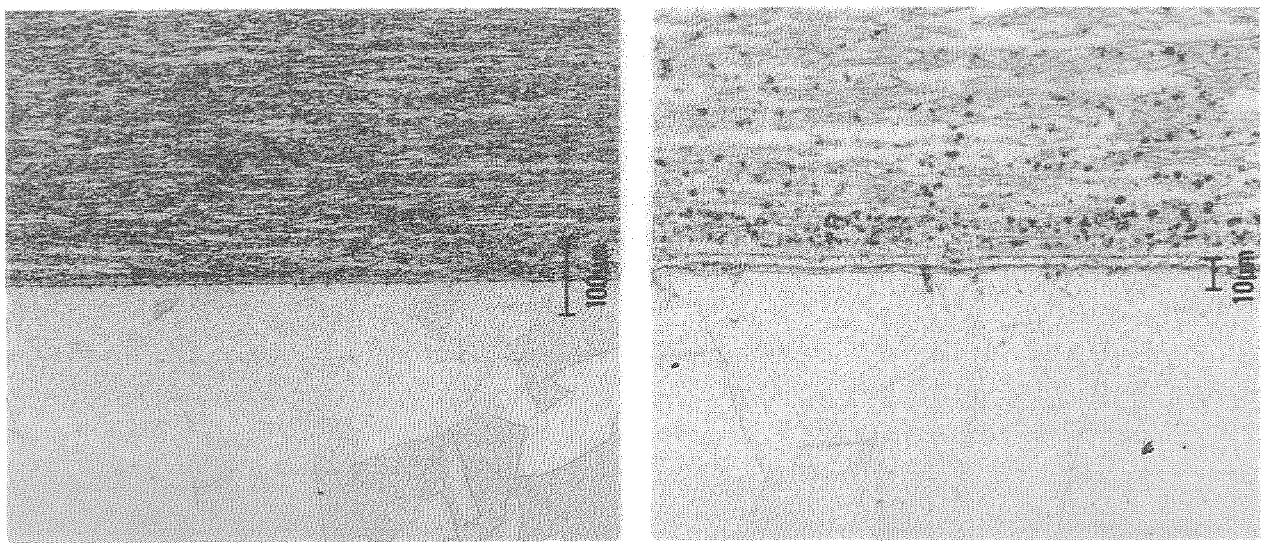


Etching for SS side

Fig. A-7.1 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ⑧ of the cross-section H shown in Figs. A-1 and A-5

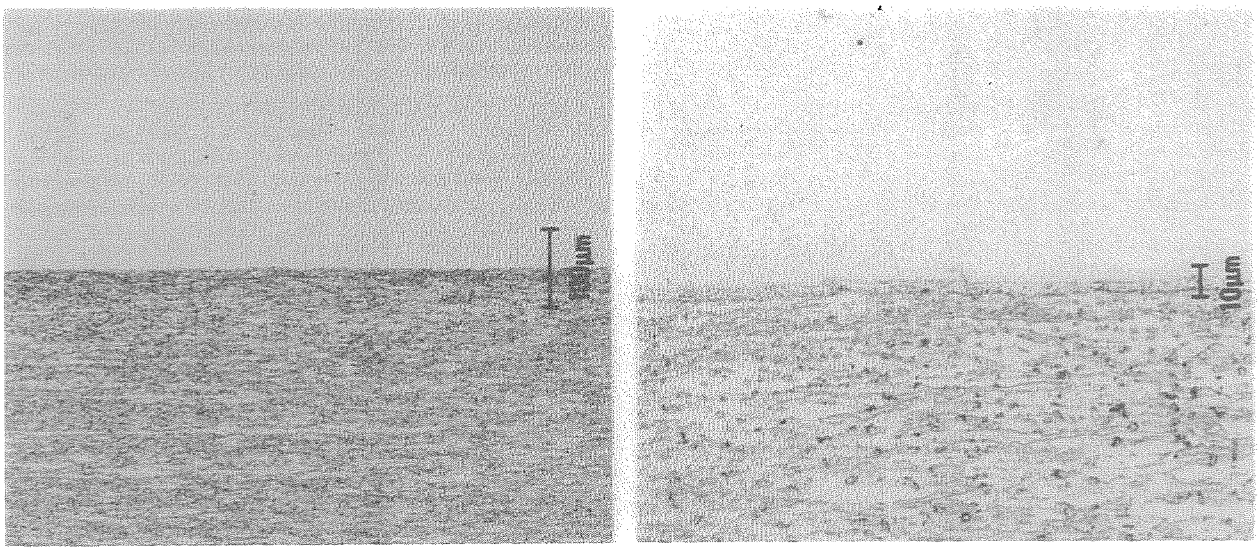


Etching for DSCu side

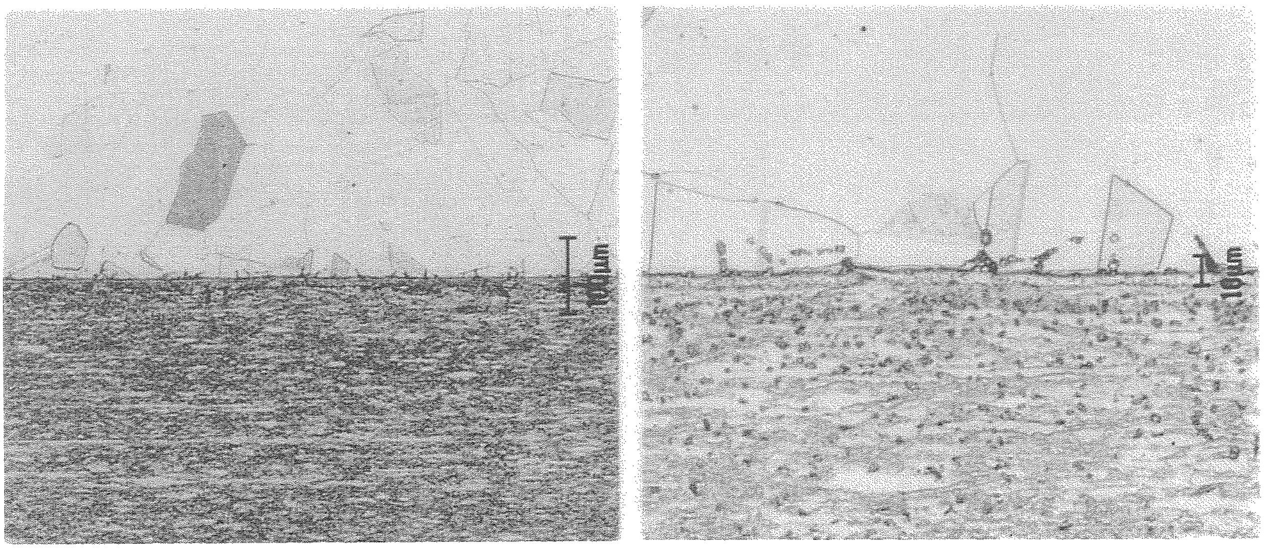


Etching for SS side

Fig. A-7.2 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ⑨ c
the cross-section H shown in Figs. A-1 and A-5

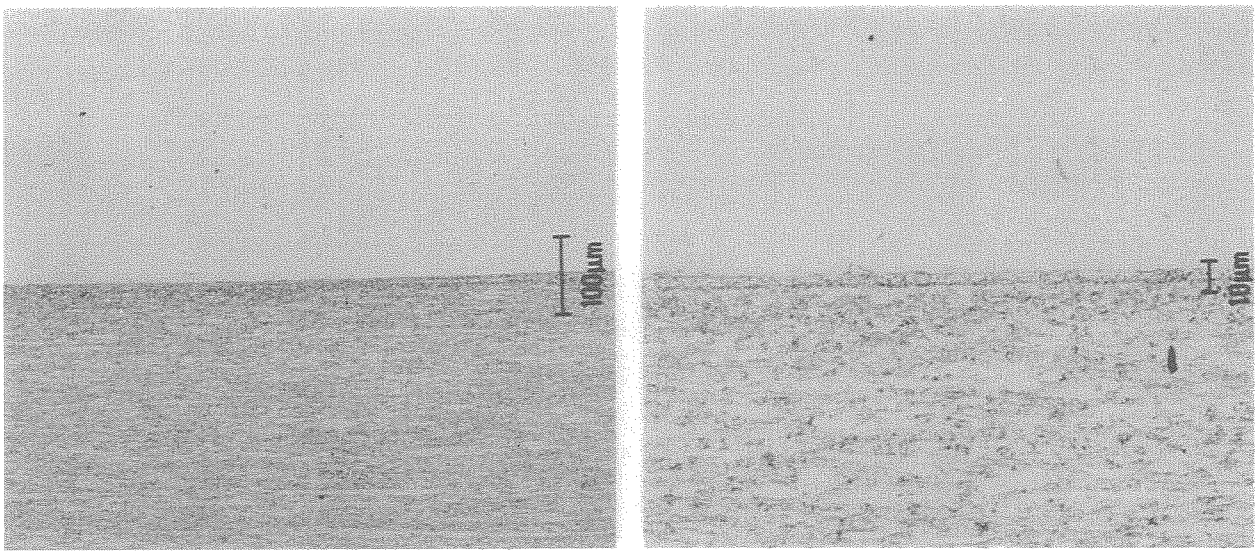


Etching for DSCu side

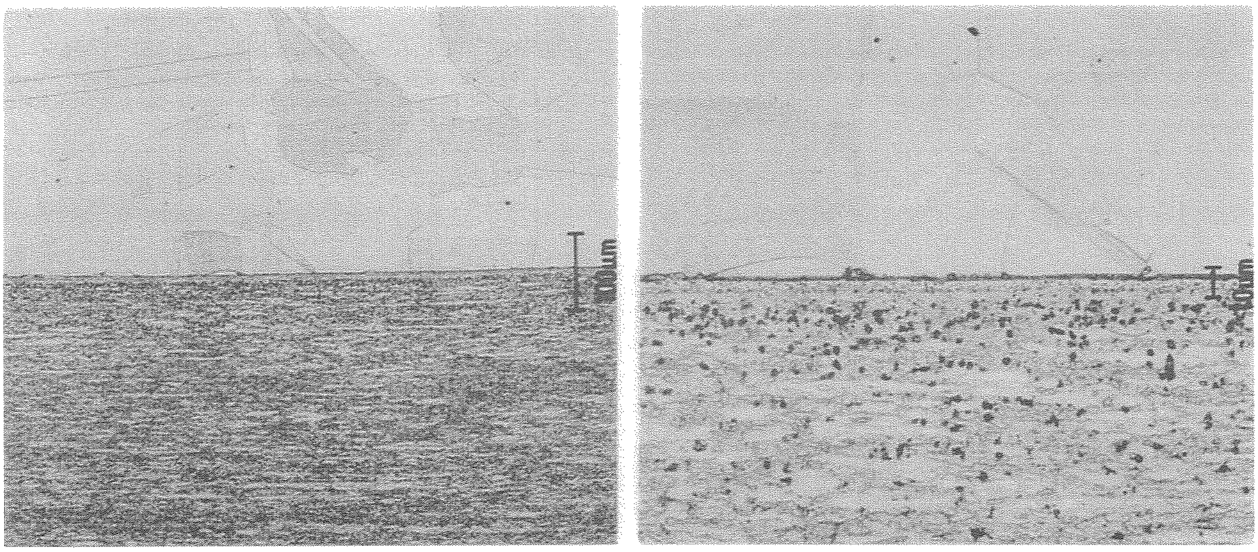


Etching for SS side

Fig. A-7.3 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ⑩ of the cross-section H shown in Figs. A-1 and A-5

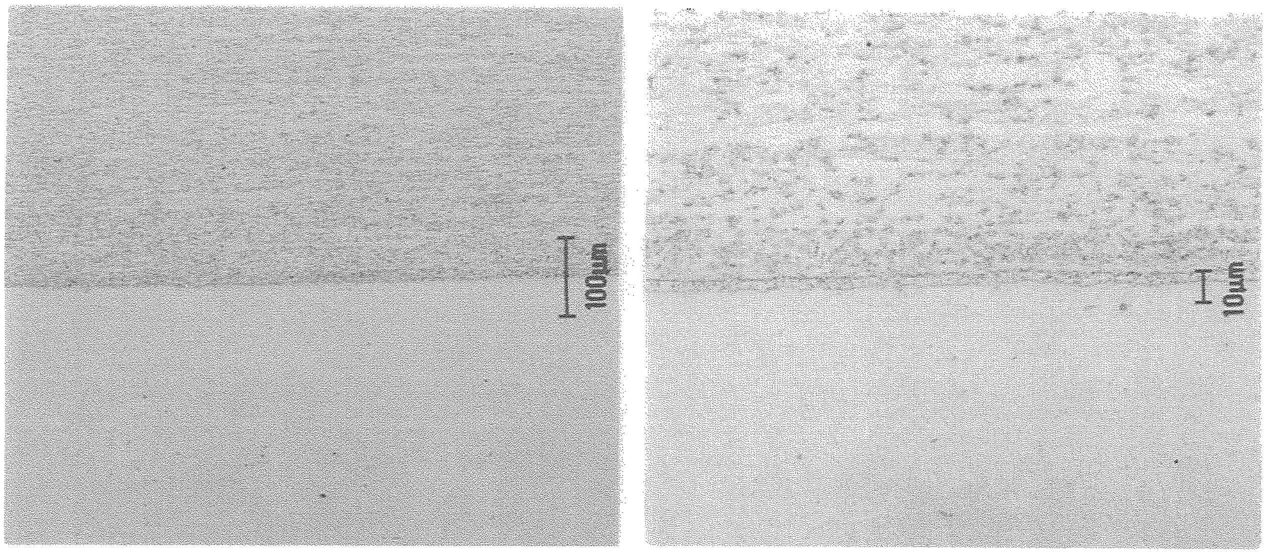


Etching for DSCu side

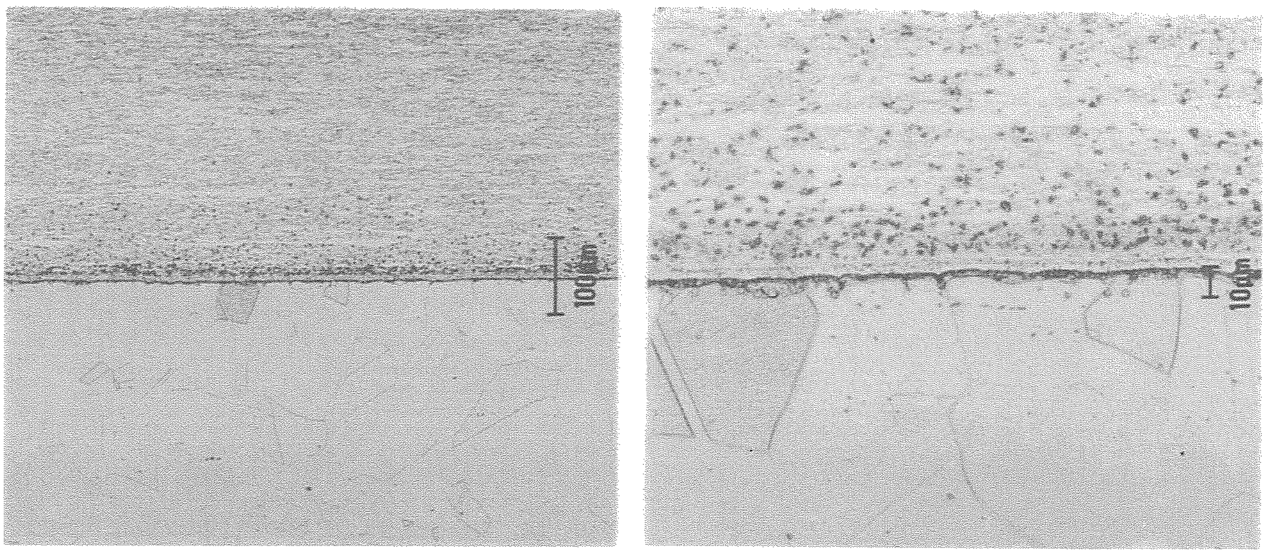


Etching for SS side

Fig. A-7.4 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ⑪ of the cross-section H shown in Figs. A-1 and A-5

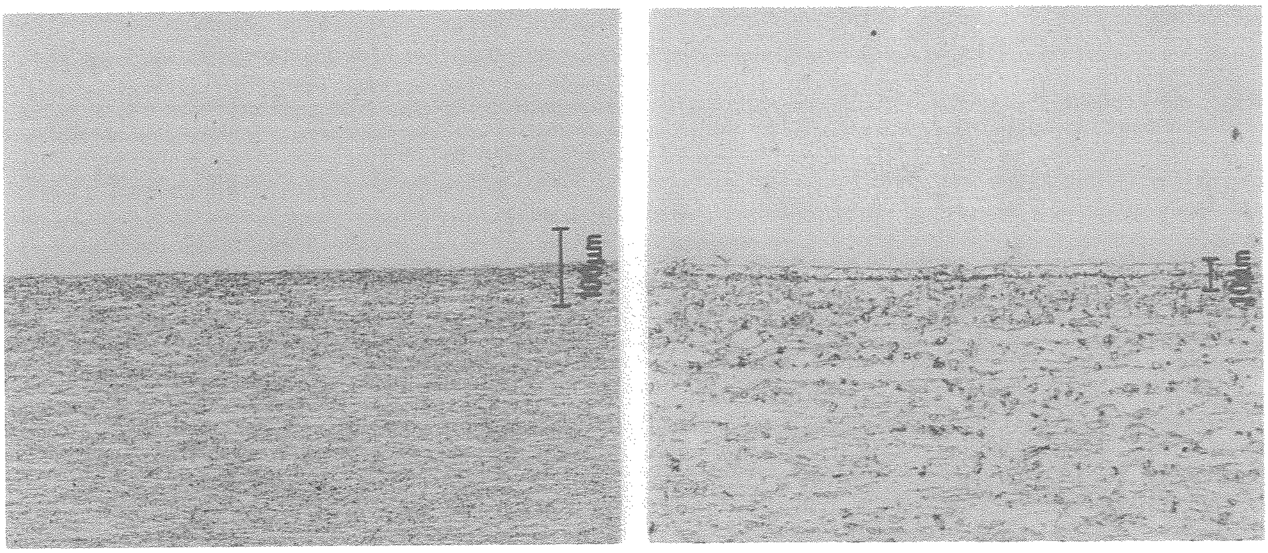


Etching for DSCu side

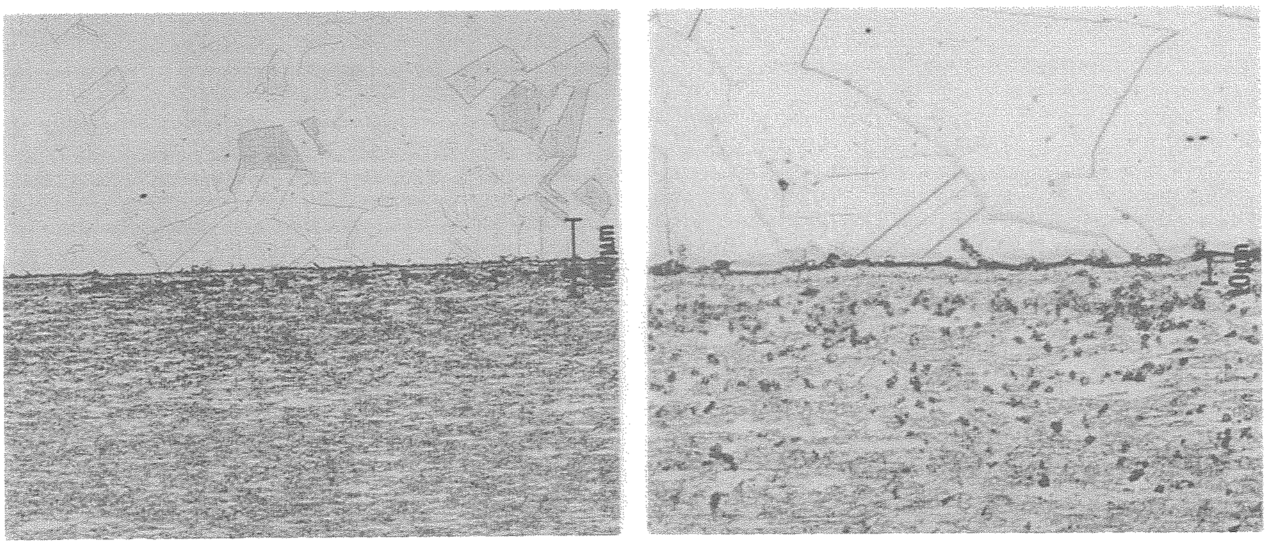


Etching for SS side

Fig. A-7.5 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ⑫ of the cross-section H shown in Figs. A-1 and A-5

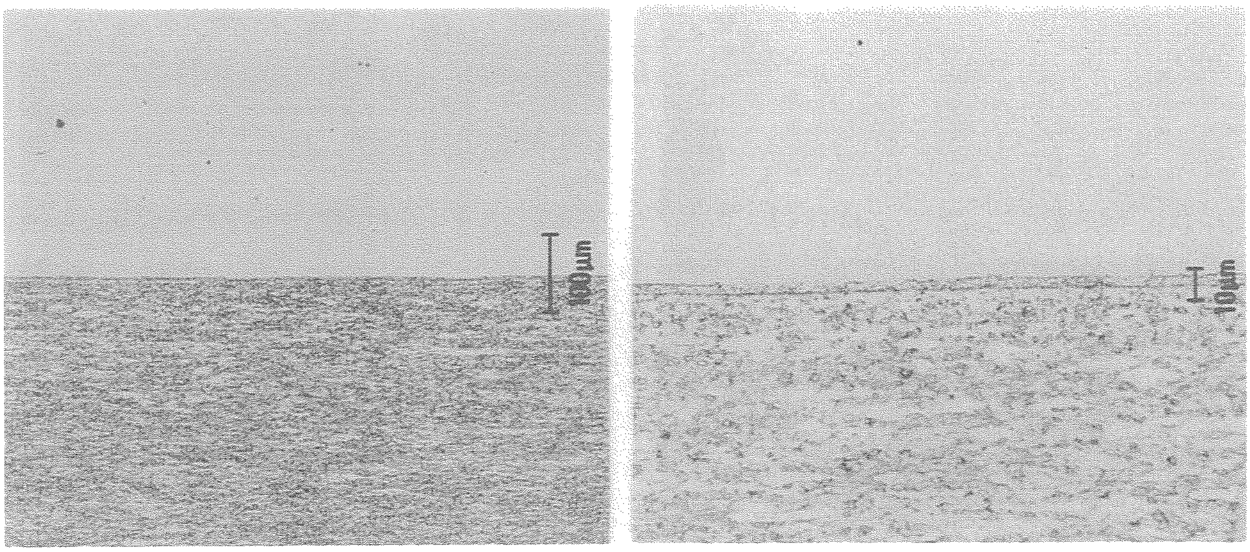


Etching for DSCu side

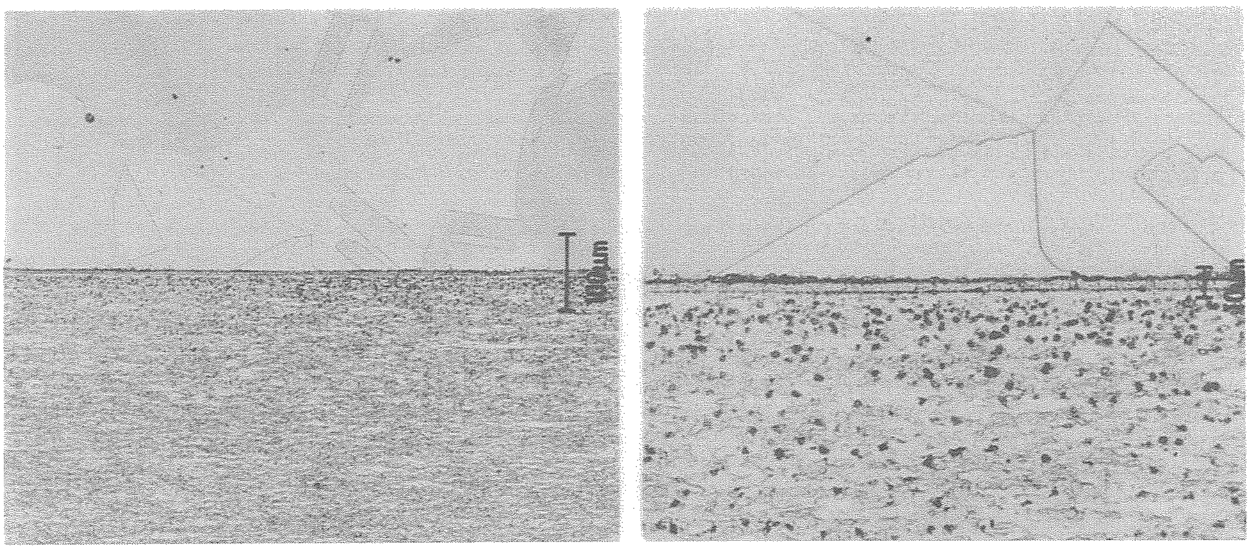


Etching for SS side

Fig. A-7.6 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ⑬ of the cross-section H shown in Figs. A-1 and A-5

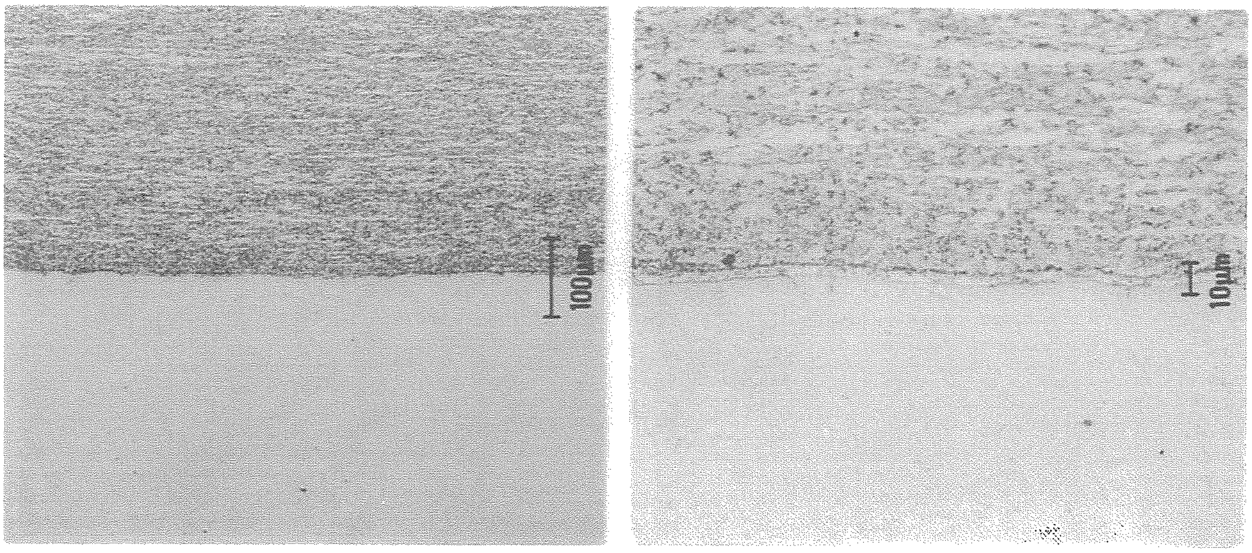


Etching for DSCu side

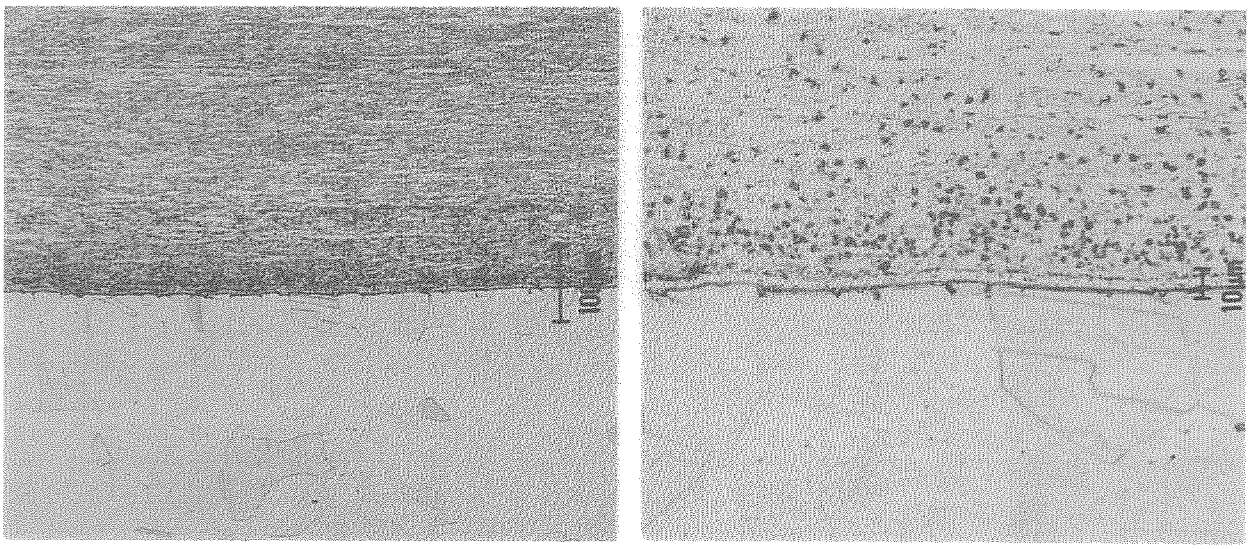


Etching for SS side

Fig. A-7.7 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ⑭ of the cross-section H shown in Figs. A-1 and A-5



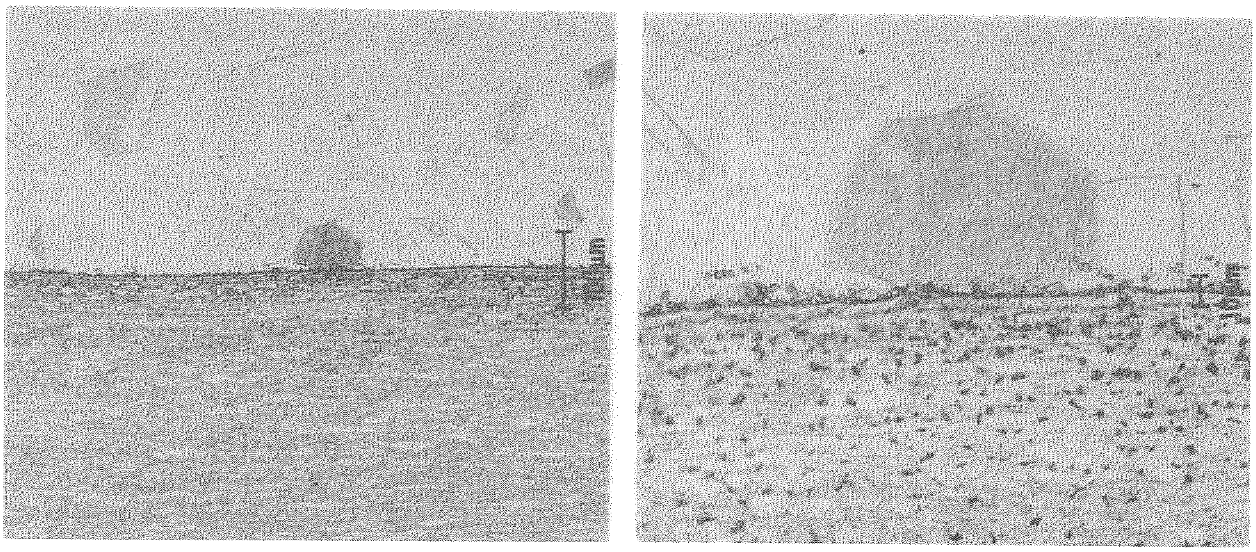
Etching for DSCu side



Etching for SS side

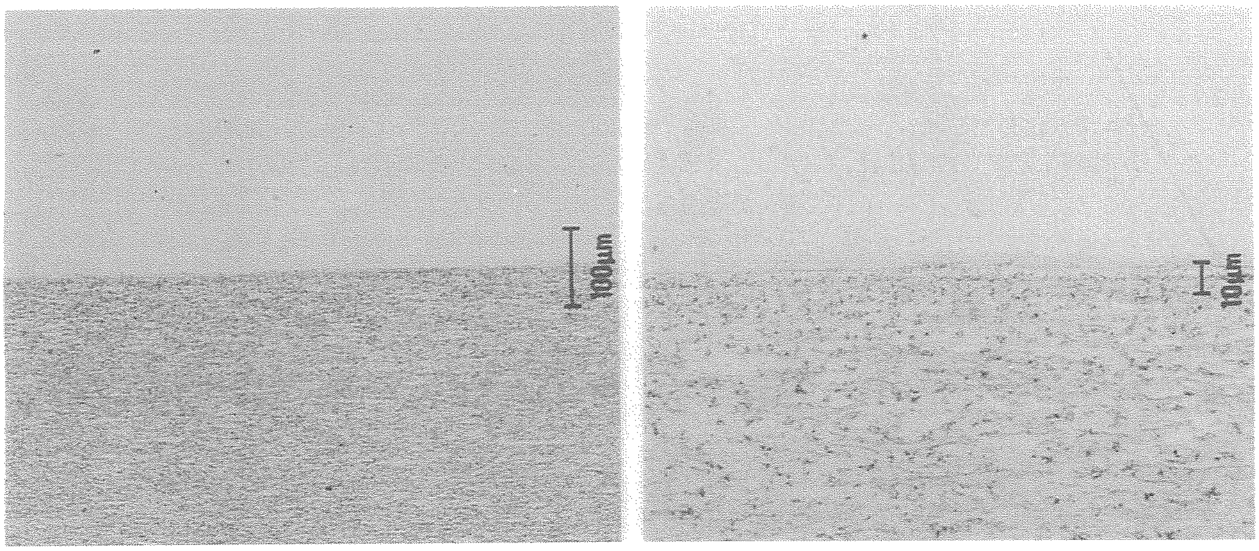
Fig. A-7.8 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ⑮ of the cross-section H shown in Figs. A-1 and A-5

Etching for DSCu side

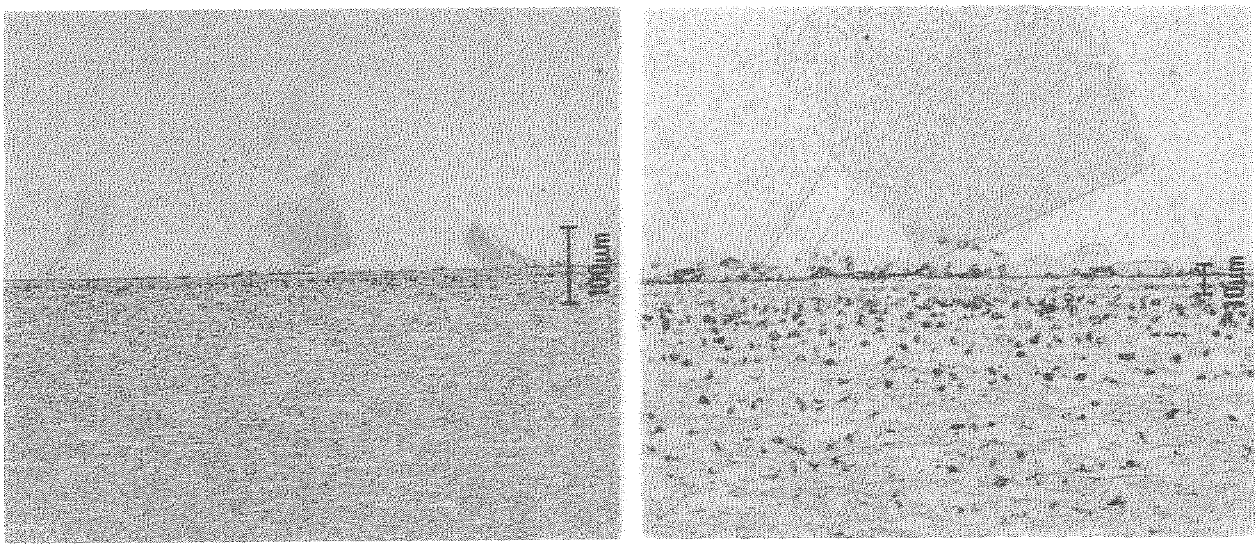


Etching for SS side

Fig. A-7.9 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ⑯ of the cross-section H shown in Figs. A-1 and A-5

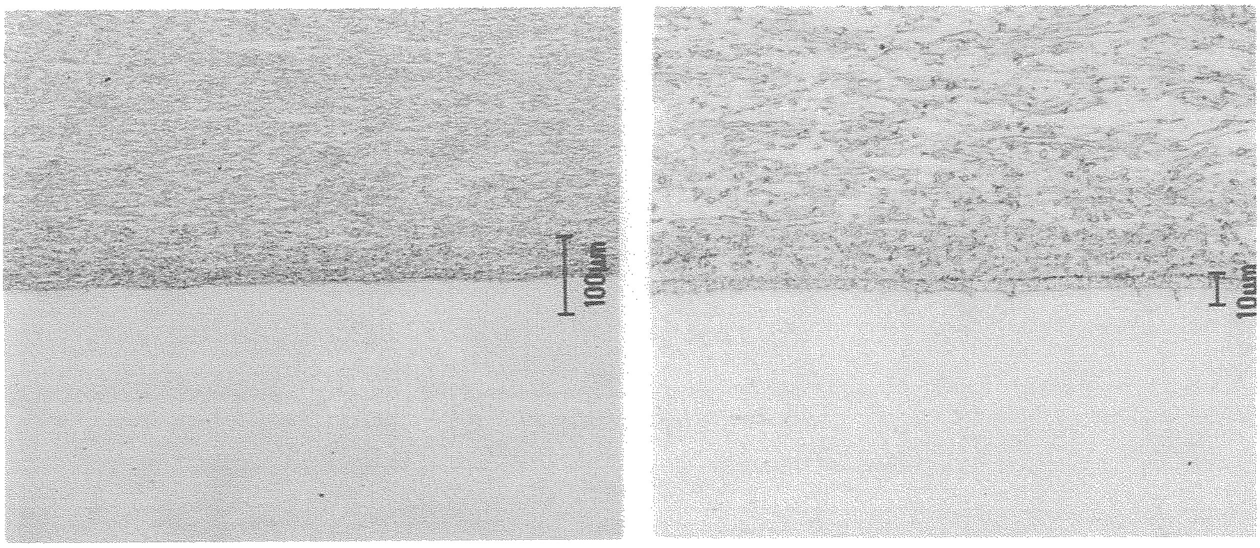


Etching for DSCu side

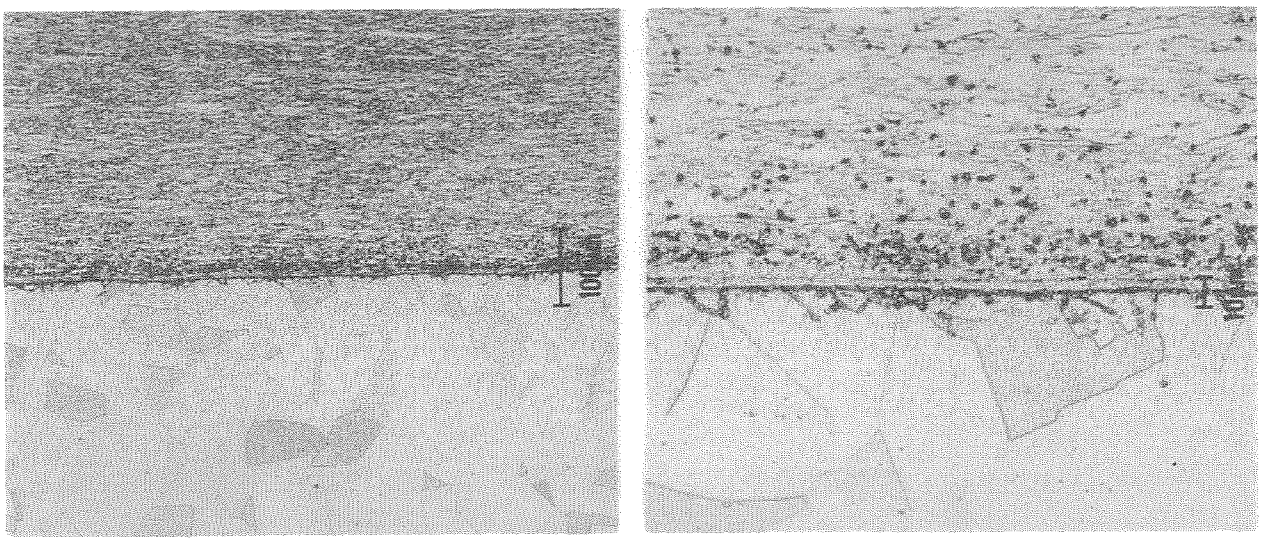


Etching for SS side

Fig. A-7.10 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ⑰ of the cross-section H shown in Figs. A-1 and A-5

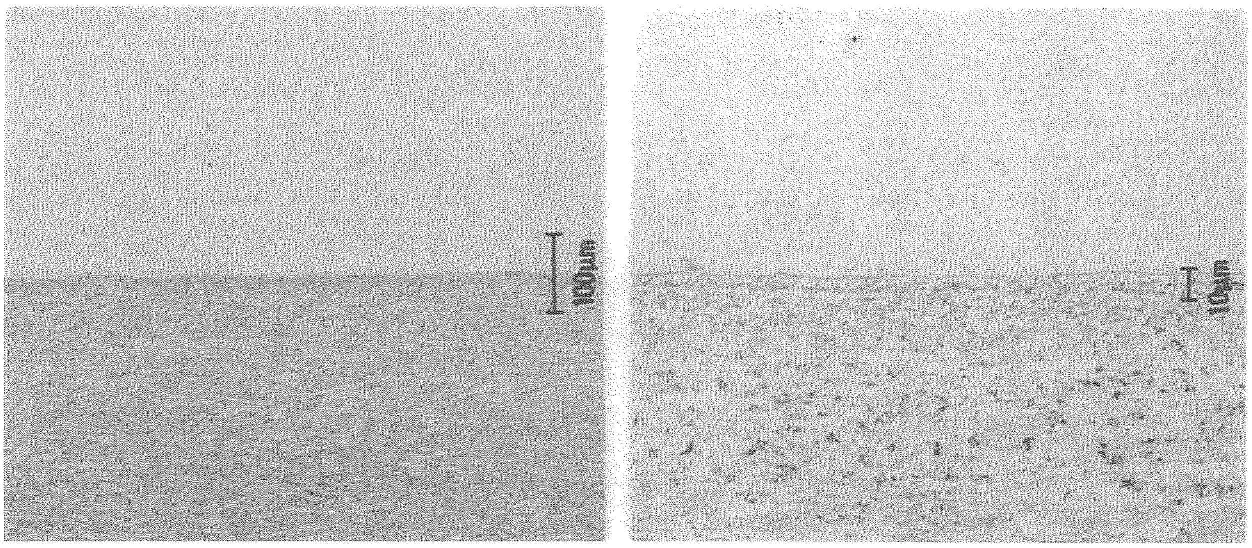


Etching for DSCu side

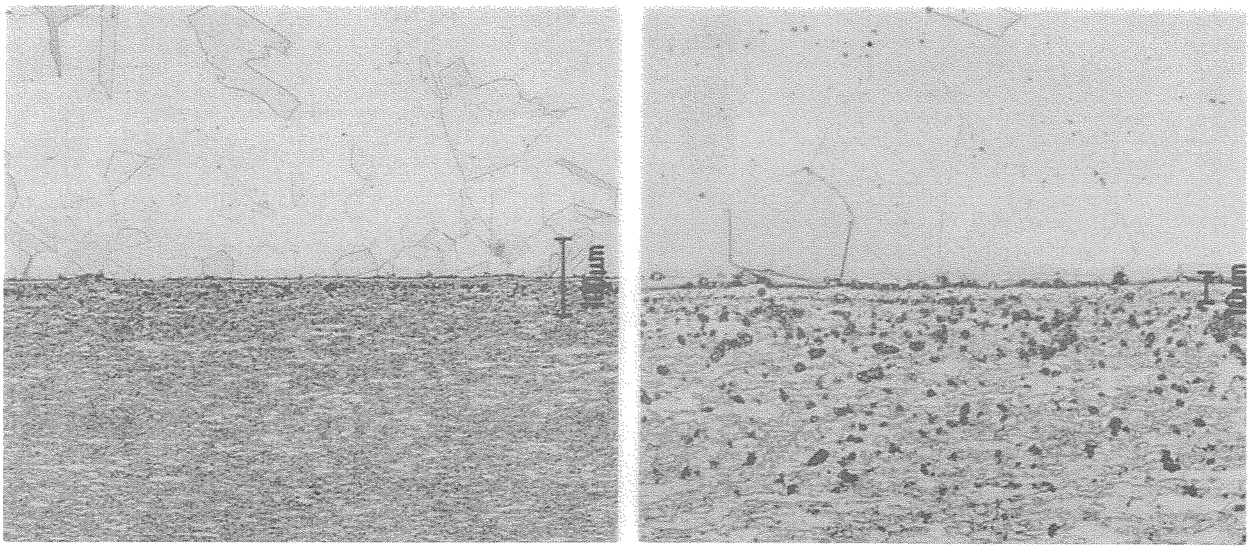


Etching for SS side

Fig. A-7.11 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ⑱ of the cross-section H shown in Figs. A-1 and A-5

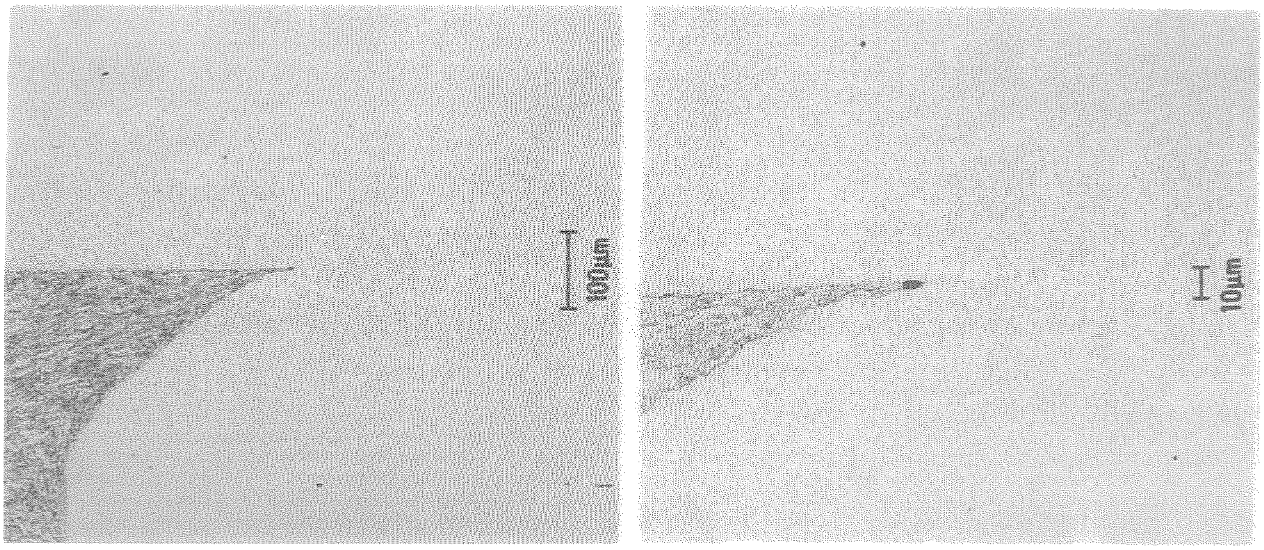


Etching for DSCu side

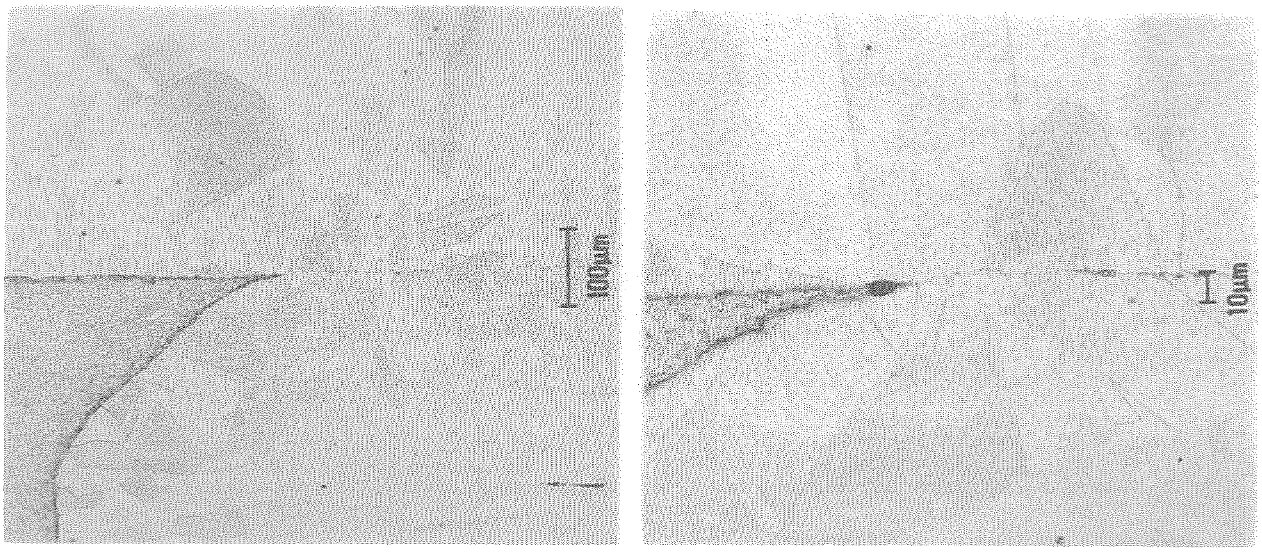


Etching for SS side

Fig. A-7.12 Micro-scopic images at the DSCu/SS HIP bonded interface in the location ⑲ of the cross-section H shown in Figs. A-1 and A-5

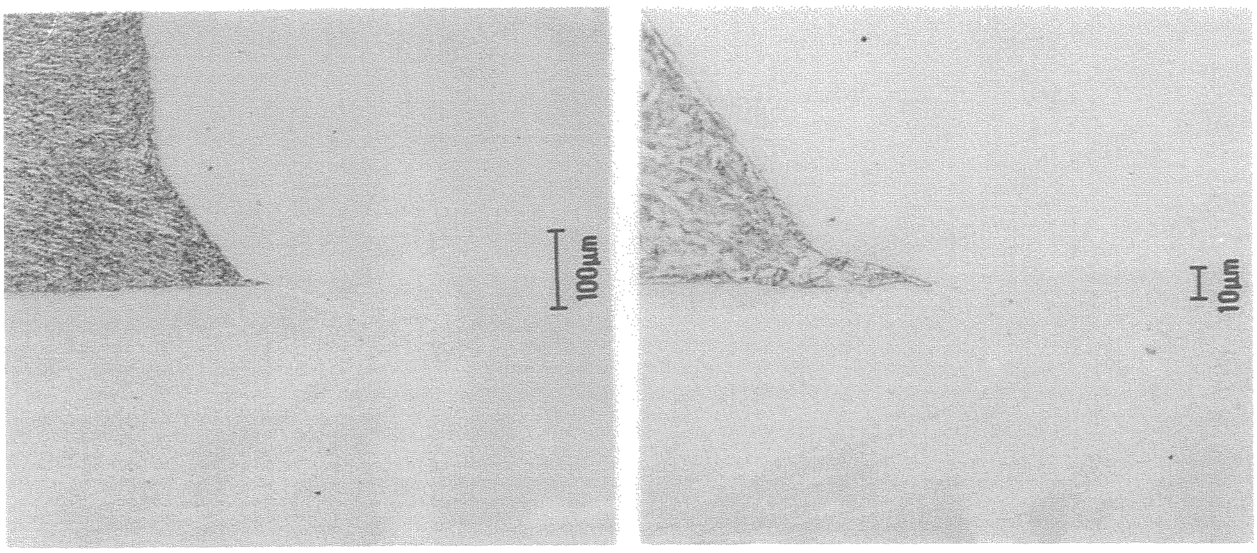


Etching for DSCu side

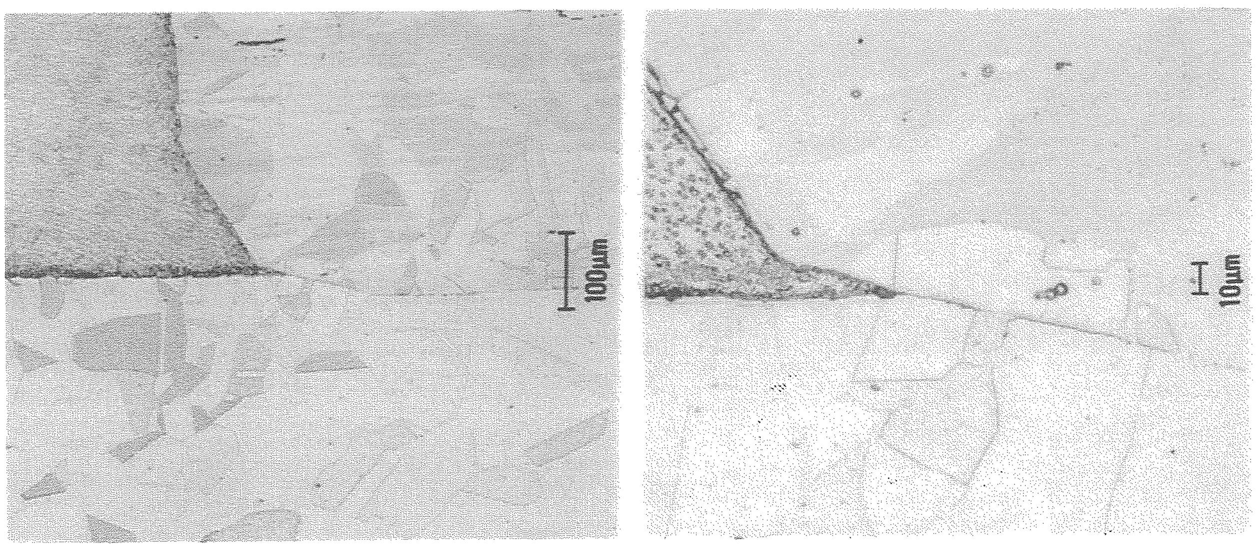


Etching for SS side

Fig. A-7.13 Micro-scopic images at the SS/DSCu/SS HIP bonded interface in the location ⑳ of the cross-section H shown in Figs. A-1 and A-5

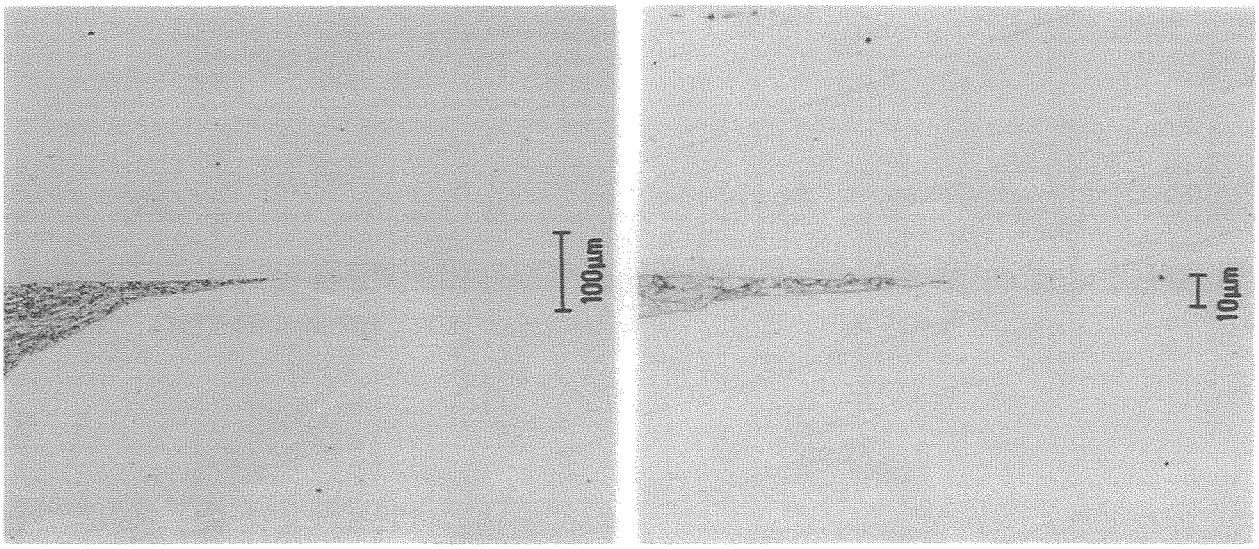


Etching for DSCu side

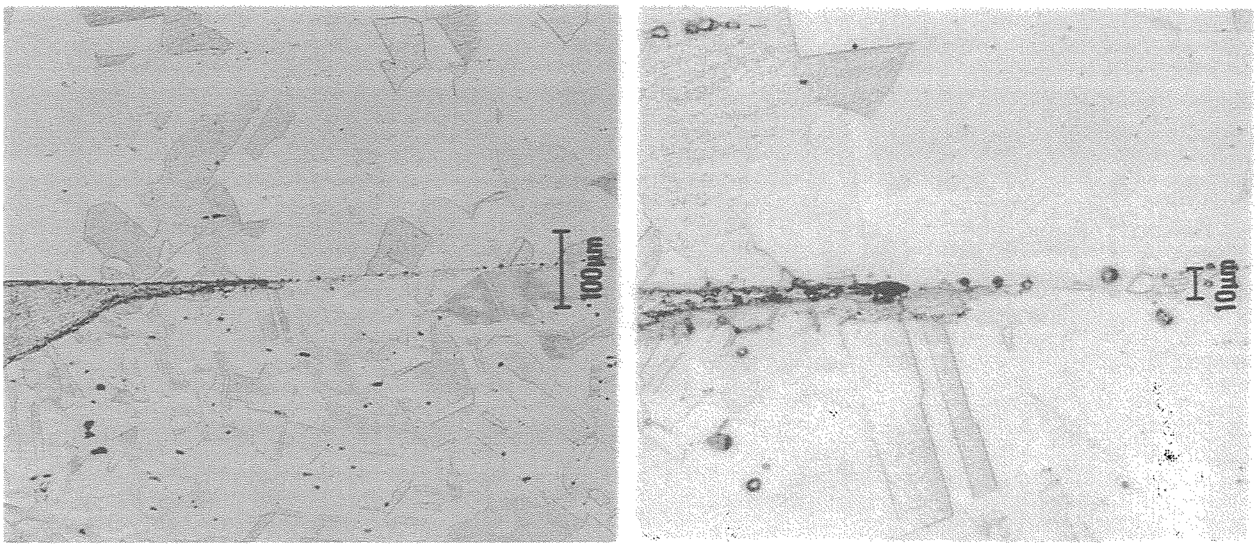


Etching for SS side

Fig. A-7.14 Micro-scopic images at the SS/DSCu/SS HIP bonded interface in the location ① of the cross-section H shown in Figs. A-1 and A-5



Etching for DSCu side



Etching for SS side

Fig. A-7.15 Micro-scopic images at the SS/DSCu/SS HIP bonded interface in the location ② of the cross-section H shown in Figs. A-1 and A-5

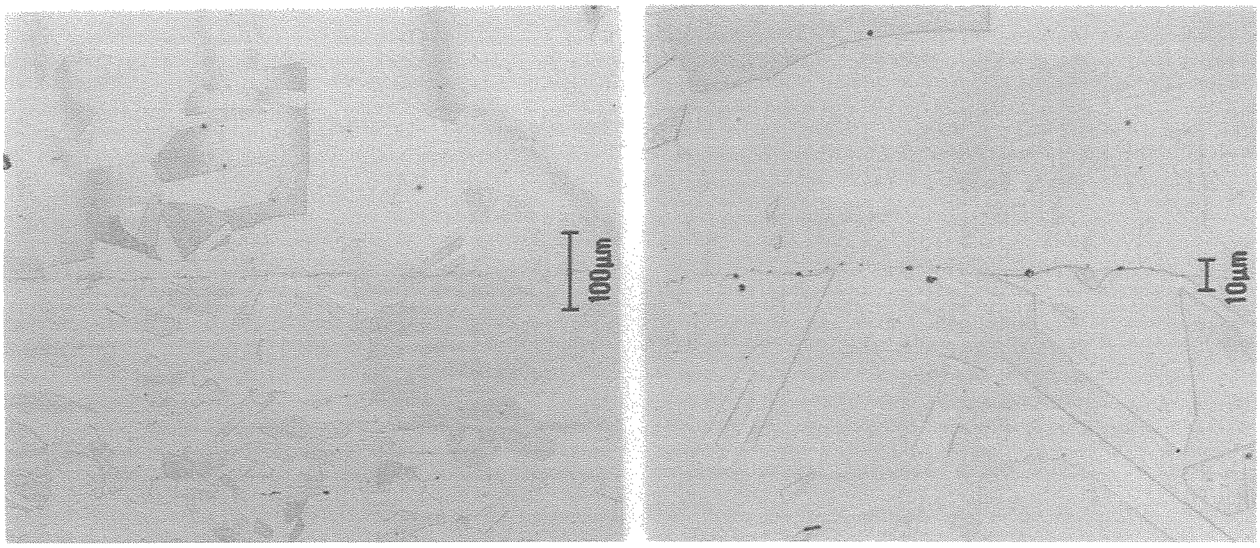


Fig. A-7.16 Micro-scopic images at the SS/SS HIP bonded interface in the location ③ of the cross-section H shown in Figs. A-1 and A-5

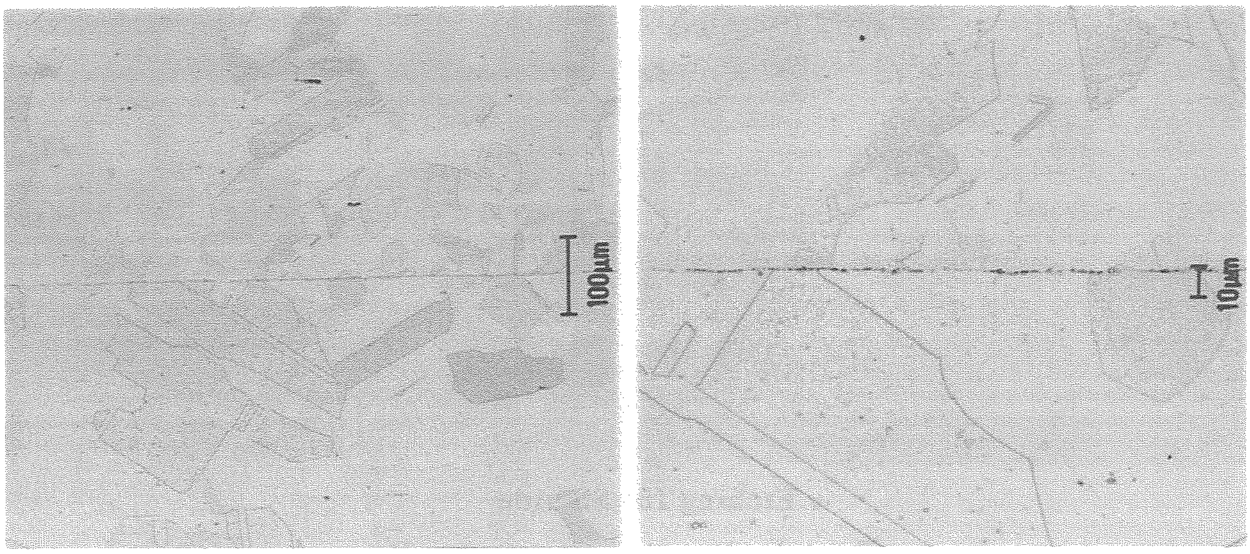


Fig. A-7.17 Micro-scopic images at the SS/SS HIP bonded interface in the location ④ of the cross-section H shown in Figs. A-1 and A-5

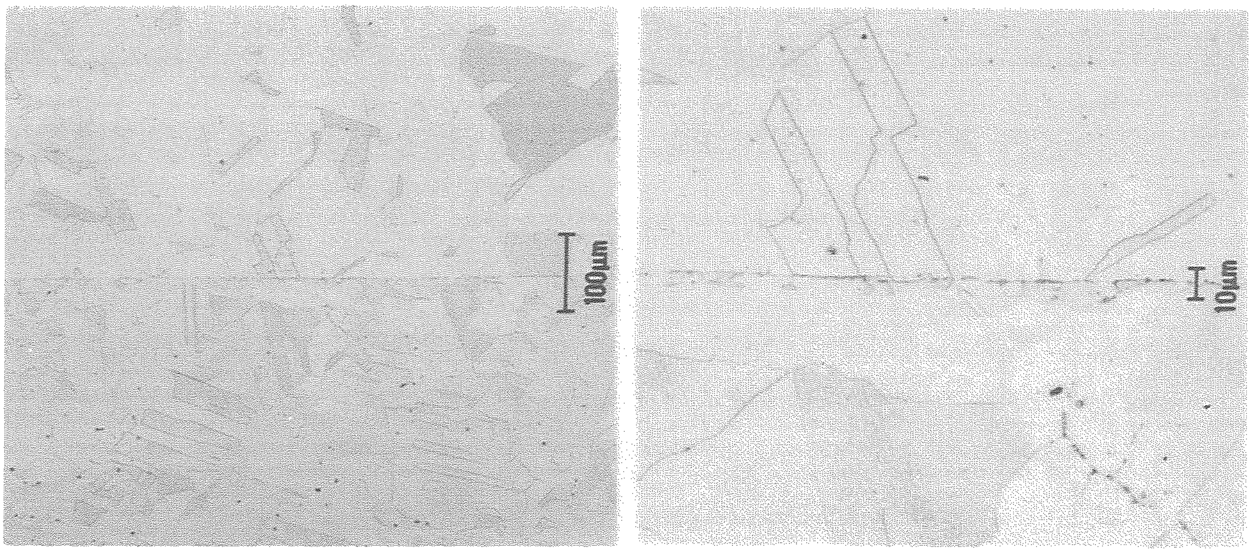


Fig. A-7.18 Micro-scopic images at the SS/SS HIP bonded interface in the location ⑤ of the cross-section H shown in Figs. A-1 and A-5

国際単位系 (SI) と換算表

表 1　SI 基本単位および補助単位

量	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表 2　SI と併用される単位

名称	記号
分，時，日	min，h，d
度，分，秒	°，′，″
リットル	l，L
トン	t
電子ボルト	eV
原子質量単位	u

$1\ \mathrm{eV}=1.60218\times10^{-19}\ \mathrm{J}$

$1\ \mathrm{u}=1.66054\times10^{-27}\ \mathrm{kg}$

表 3　固有の名称をもつ SI 組立単位

量	名称	記号	他の SI 単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	$m{\cdot}kg/s^2$
圧力，応力	パスカル	Pa	N/m^2
エネルギー，仕事，熱量	ジュール	J	N·m
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	A·s
電位，電圧，起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表 4　SI と共に暫定的に維持される単位

名称	記号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

$1\ \mathrm{Å}=0.1\ \mathrm{nm}=10^{-10}\ \mathrm{m}$

$1\ \mathrm{b}=100\ \mathrm{fm^2}=10^{-28}\ \mathrm{m^2}$

$1\ \mathrm{bar}=0.1\ \mathrm{MPa}=10^5\ \mathrm{Pa}$

$1\ \mathrm{Gal}=1\ \mathrm{cm/s^2}=10^{-2}\ \mathrm{m/s^2}$

$1\ \mathrm{Ci}=3.7\times10^{10}\ \mathrm{Bq}$

$1\ \mathrm{R}=2.58\times10^{-4}\ \mathrm{C/kg}$

$1\ \mathrm{rad}=1\ \mathrm{cGy}=10^{-2}\ \mathrm{Gy}$

$1\ \mathrm{rem}=1\ \mathrm{cSv}=10^{-2}\ \mathrm{Sv}$

表 5　SI 接頭語

倍数	接頭語	記号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^{9}	ギガ	G
10^{6}	メガ	M
10^{3}	キロ	k
10^{2}	ヘクト	h
10^{1}	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

(注)

1. 表1－5は「国際単位系」第5版，国際度量衡局 1985年刊行による。ただし，1 eV および 1 u の値は CODATA の1986年推奨値によった。
2. 表4には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した。
3. bar は，JIS では流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。
4. EC閣僚理事会指令では bar，barn および「血圧の単位」mmHg を表2のカテゴリーに入れている。

換　算　表

力	$N(=10^5 dyn)$	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘　度　$1\ \mathrm{Pa{\cdot}s(N{\cdot}s/m^2)}=10\ \mathrm{P}$(ポアズ)$\mathrm{(g/(cm{\cdot}s))}$

動粘度　$1\ \mathrm{m^2/s}=10^4\mathrm{St}$(ストークス)$\mathrm{(cm^2/s)}$

圧力	MPa(=10 bar)	kgf/cm^2	atm	mmHg(Torr)	lbf/in^2(psi)
	1	10.1972	9.86923	7.50062×10^3	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	$J(=10^7 erg)$	kgf・m	kW・h	cal(計量法)	Btu	ft・lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^6	3.67098×10^5	1	8.59999×10^5	3412.13	2.65522×10^6	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal = 4.18605 J (計量法)
　= 4.184 J　(熱化学)
　= 4.1855 J　(15 °C)
　= 4.1868 J (国際蒸気表)

仕事率　1 PS (仏馬力)
　= 75 kgf・m/s
　= 735.499 W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

(86年12月26日現在)