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Journal of Nuclear Materials 258–263 (1998) 2023–2029

journal of nuclear materials

Application of HIP bonding to first wall panel fabrication made from reduced activation ferritic steel F82H

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Abstract

As a course of fabrication technology development of DEMO breeding blankets, fabrication of small-scaled first wall panels made from reduced activation ferritic steel F82H has been attempted by applying HIP (Hot Isostatic Pressing) method. By applying the conditions identified in the previous studies, two flat panels with ten cooling channels each have been fabricated. One of the fabricated panels was destructively tested to examine metallurgically sound HIP bonding and to characterize the change of the micro-structure of the F82H steel due to the HIP process. Destructive examination has confirmed sound bonding for all of the HIP interfaces and satisfactory dimensional tolerance, and applicability of HIP bonding to the complex component made from this steel has been demonstrated.

1. Introduction

Reduced activation ferritic steels are the leading candidate structural materials for the blanket and first wall of DEMO reactors. A grade of F82H [1] is the primary candidate structural material of the pebble-bed-type solid breeder blanket of the SSTR (Steady State Tokamak Reactor) [2], and the reference alloy for the Japanese test modules to be tested in the ITER [3]. This steel has been selected as one of the two reference steels for the IEA round robin test on low activation ferritic steels [4], and world-wide efforts are being made on characterization and data accumulation of this steel including irradiation tests [5,6]. In parallel with these efforts, fabrication technologies development and performance tests of the pebble-bed are being conducted by JAERI to provide technological basis for the module testing in the ITER [7], and, as a course of fabrication technology development of the first wall and the blanket box structure, fabrication of small-scale first wall panels made of F82H has been attempted by applying HIP (Hot Isostatic Pressing) method.

The first wall panels of the SSTR and the test module to be tested in the ITER have cooling channels embedded within the wall to assure both of sufficient cooling capability against high thermal loads from plasmas and enough mechanical stiffness against large electromagnetic loads during disruptions. HIP bonding between cooling channels and flat plates is the most promising fabrication method for this type of complicated structures, since it could provide high mechanical integrity and good dimensional tolerances and also eliminate fusion weld from the first wall. In the previous studies [8,9], the optimum HIP conditions and post-heat-treatment conditions after the HIP process have been identified. By applying these conditions, fabrication of flat first wall panels with ten cooling channels each has been attempted.

In the following sections, configuration of the fabricated first wall panel and detailed fabrication procedure are described. One of the fabricated panels was destructively examined, and integrity of the HIP bonded interface and its characterization are discussed.

2. Configuration of fabricated first wall panels

Two first wall panels were fabricated in the present fabrication study: one for destructive test (hereinafter

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0022-3115/98/$19.00
PII: S0022-3115(98)00418-8

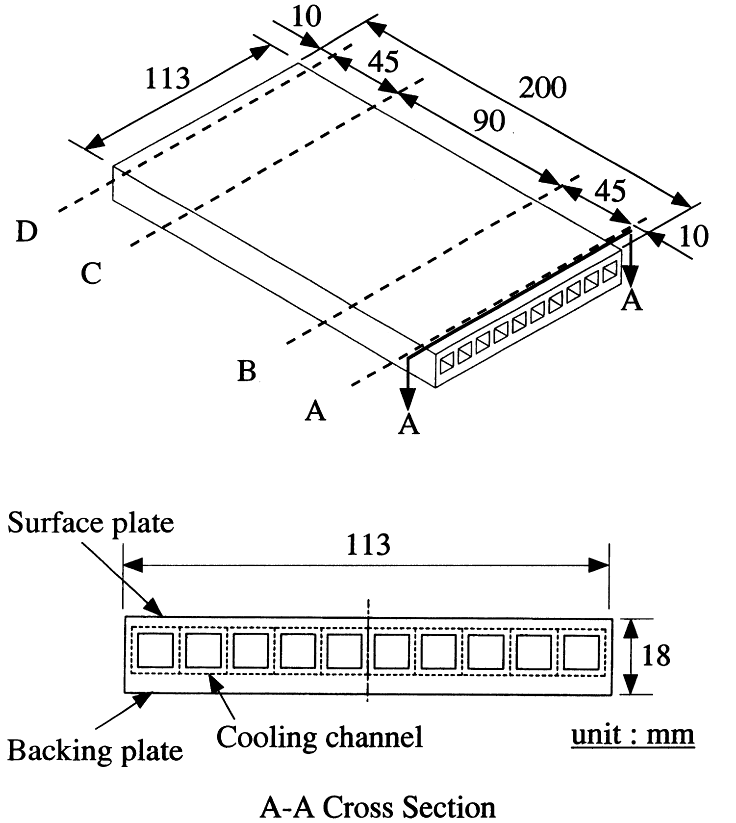

Fig. 1. Configuration of the fabricated first wall panel (destructive test panel). Dotted lines in A–A cross section indicate HIP interfaces, and four broken lines, A–D, show the cut lines for destructive examination.

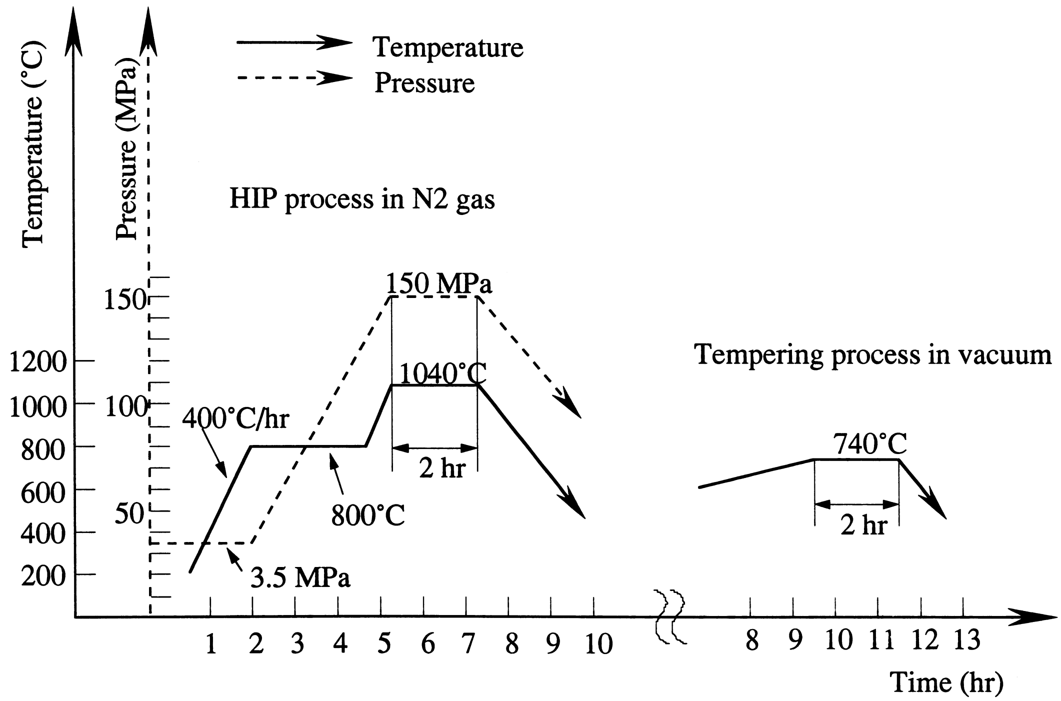

Fig. 2. Time and pressure evolutions during HIP (1040°C) and tempering (740°C) processes after HIP bonding.

referred to as “destructive test panel”) and the other for high heat flux test (“high heat flux test panel”). The former panel was utilized to examine the integrity of the HIP bonded interface, to characterize the change of the micro-structure of F82H steel to obtain internal deformation data due to the HIP process, while the latter is to be thermo-mechanically tested by an electron beam irradiation facility to examine fatigue lifetime of this component under repeated thermal cycles and integrity of the HIP bonded interface under high heat flux loading conditions.

The geometry of the destructive test panel is shown in Fig. 1. It is a rectangular plate with a dimension of 200 mm × 113 mm, and consists of a surface plate 2.5-mm-thick, backing plate 4.5-mm-thick and ten cooling channels with a rectangular cross-section 8-mm-square (inner) and 1.5-mm-thick, resulting in a total thickness of 18 mm. All of these elements are made from F82H steel, and joined by HIP bonding. Broken lines shown in the A–A cross section of this figure indicate the HIP bonding interfaces.

3. Fabrication procedure and conditions

3.1. Preparation

Hot rolled F82H plates taken from the high purity 5-ton heat were used in the present fabrication. Normalizing and tempering heat-treatment processes were applied under the conditions of 1040°C, 30 min and 750°C, 2 h, respectively, leading to a fully tempered martensite and a homogeneous grain size. The surface, backing plates and cooling channels, shown in Fig. 1, were machined from these plates down to the respective geometries. All of the HIP interface surfaces were mechanically polished to get a fine surface. As the roughness of the HIP bonding surface is one of the important factors for high quality bonding [9], it was controlled to be less than 2 μm. Then, the surface and backing plates and ten cooling channels were prebaked in a vacuum furnace at the temperature of 1000°C for 6 h to enhance outgassing from these elements.

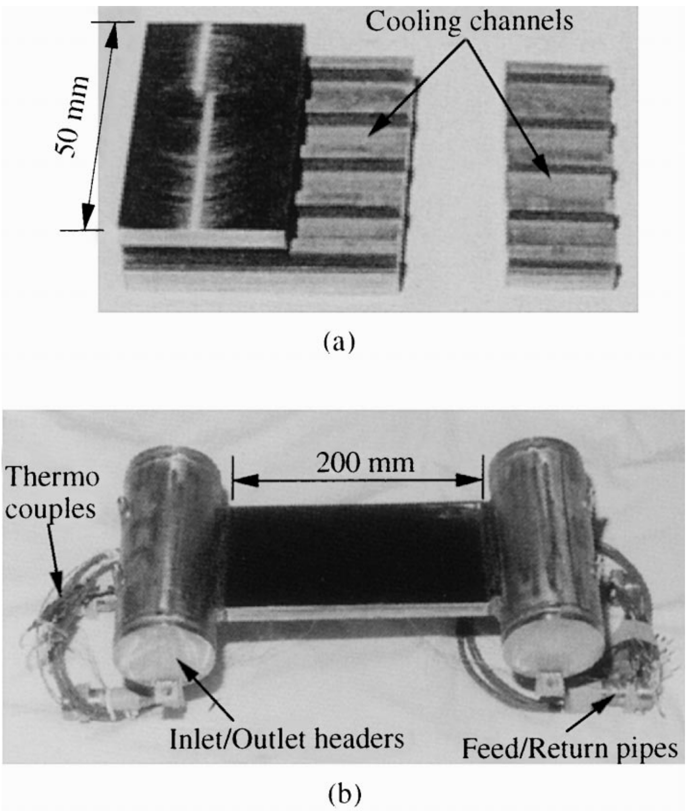

Fig. 3. Final appearance of the fabricated first wall panels; (a) Destructive Test Panel after destructive examination and (b) High Heat Flux Test Panel.

3.2. HIP treatment

After assembling the surface and backing plates and ten cooling channels, all of the HIP interface peripheries were seam welded, and then post-weld heat-treatment was applied to this assembly in a vacuum furnace under the conditions of 720°C and 1 h. After this process, the internal of the assembly was baked out at the temperature of 500°C for 5 h to evacuate the internal pressure down to 10^{-5} Torr.

This assembly was then HIP treated under the conditions selected in the previous studies [8,9], i.e. the temperature of 1040°C (±10°C), pressure of 150 MPa and holding time of 2 h. Time evolutions of the temperature and pressure are schematically shown in Fig. 2. After cooling down to the room temperature, this assembly was removed to the vacuum furnace, and then heat treated at 740°C for 2 h, as shown in Fig. 2. Final appearances of the two panels are shown in Fig. 3.

4. Geometrical inspection and metallurgical examination

4.1. Geometrical inspection

One of the test panels was cut into a number of pieces, and the cross sections were examined along four lines indicated in Fig. 1. Cross sectional view along the

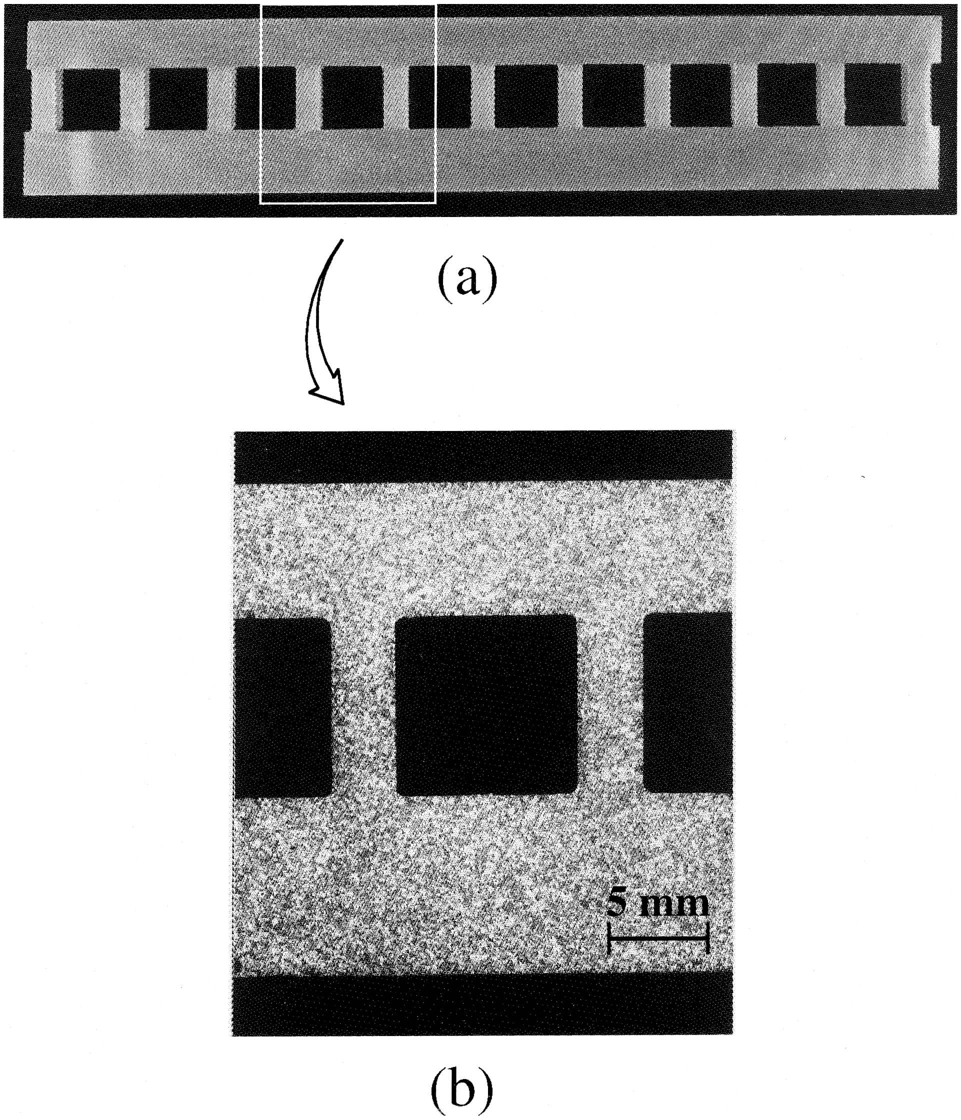

Fig. 4. (a) Cross sectional view of the fabricated panel cut along the line A shown in Fig. 1. (b) Its zoomed-up view after chemical etching.

line A is shown in Fig. 4(a), and zoomed-up view at the center region after chemical etching is given in Fig. 4(b). As revealed in these figures, this panel has a satisfactory geometrical tolerance, and neither insufficient bonding nor excessive deformation can be observed. In particular, four corners of each cooling channel are kept in a good round shape without any crevice or notch, suggesting relaxed corrosion issues.

The dimensions were precisely measured at three locations for each of the four cross sections, and it was found the front wall thicknesses were +0.2/−0.0 mm relative to the nominal values, and the cross section of the cooling channels, 8.0-mm-square as nominal, was found between 8.1 and 8.2 mm inner-square. All of these dimensional data are satisfactory. The low deformation was deduced to result from the fine machining of each element before assembly and negligible initial gap between each element.

4.2. Metallurgical examination

Micro-structure observation and SEM analysis: Micro-structure was examined by an optical microscope at three locations for each of the four observation lines. Typical examples are shown in Fig. 5 for three locations along the line A, as shown in this figure, and (a) and (c) correspond to the triple points, i.e. an intersection point of two HIP interfaces, and (b) is the HIP interface between two adjacent cooling channels. By chemical etching, HIP interfaces are seen from these figures, and sound bonding can be observed without any harmful defect or delamination. Micro-structure of the F82H matrix also shows a good feature without grain coarsening.

SEM examination was also performed at the same locations; three locations for each of the four observation lines, and typical examples are shown in Fig. 6. Fig. 6(b) is a zoomed-up view of (a). Sound bonding was again confirmed by these SEM images, though a submicron-scale void or an interstitial element could be observed in (b). Bonding ratio, an indicative figure showing the quality of the bonding, defined by the formula of $(1 - \sum lvi/\sum Li) \times 100$, where $\sum Li$ and $\sum lvi$ are the summations of the HIP bonded line length and those of the voids observed along the bonded line, respectively, was measured based on these SEM images. By sampling ten different spots ($i = 1$–10) for each of the locations, bonding ratios higher than 96% were confirmed for all of the observed locations.

EPMA line analysis: EPMA line analysis was performed with a beam diameter of 10 mm along three lines transverse the HIP bonded interface. Elements examined

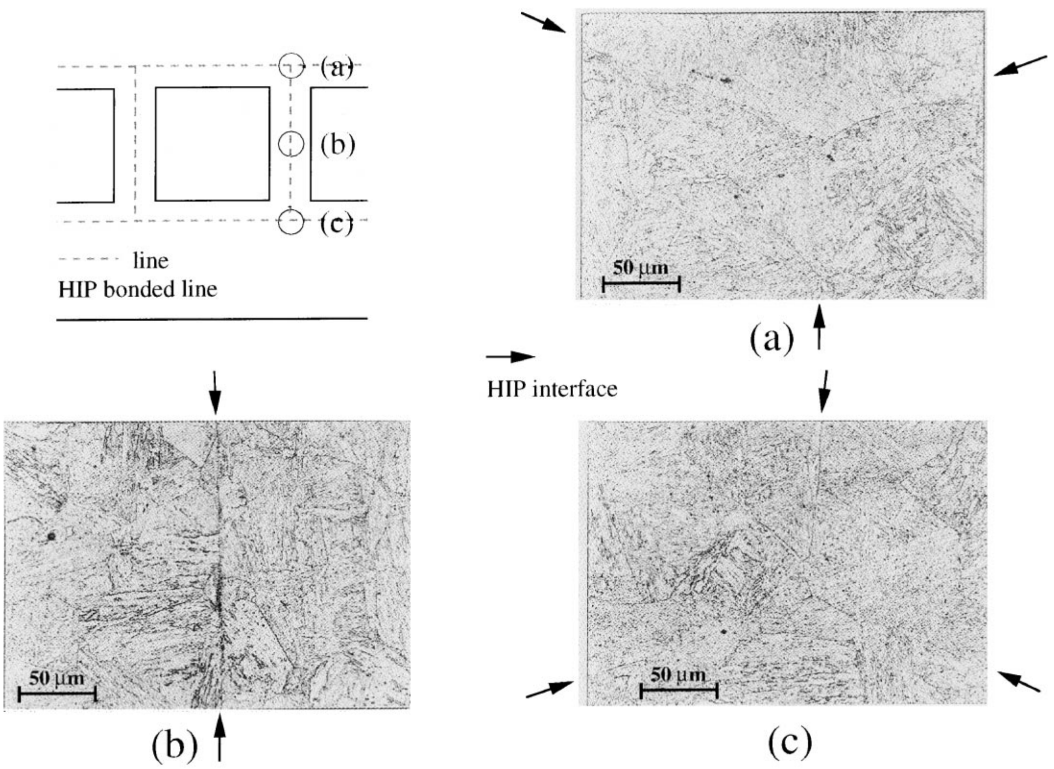

Fig. 5. Optical microscope observation of the HIP bonded interfaces at three locations: (a) upper intersecting point of two HIP interfaces; (b) HIP interface between two adjacent cooling channels; (c) lower intersecting point of two HIP interfaces.

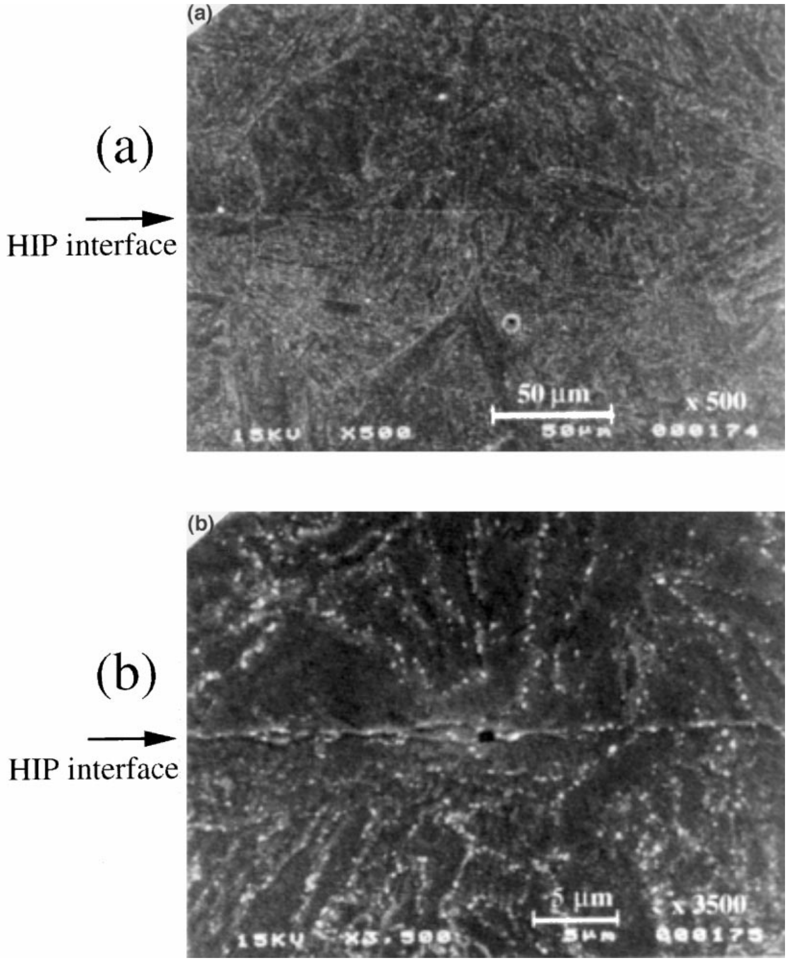

Fig. 6. (a) SEM images taken from the cut line A. (b) A sub-micron-scale void or an interstitial element can be observed in the zoomed-up view.

were iron, chromium, tungsten, carbon and oxygen, and a typical example of the line analysis is shown in Fig. 7. As is shown in this figure, no change in the element distribution was observed, or even fairly uniform distribution of the elements was confirmed along the line over the HIP bonded interface. This suggests a uniform diffusion of the constituting the elements between two F82H plates, and, in particular, constant distributions of carbon and oxygen over the interface imply no decarburization or oxidation at the interface.

5. Conclusion

As a course of fabrication technology development of DEMO breeding blankets, fabrication of small-scale first wall panels made of reduced activation ferritic steel F82H has been attempted by applying HIP method. The fabrication was successfully completed, and one of the fabricated panel was destructively examined to measure the internal dimensions, to examine the bondability of each of the HIP interfaces, and to characterize the HIP bonded region. Through these examinations the following conclusions were obtained:

(1) The fabricated panel has a satisfactory geometrical tolerance with an accuracy better than 0.2 mm, and neither excessive deformation nor delamination has been observed.

(2) Microstructure observation and SEM analysis have confirmed sound HIP bonding at all of the HIP interfaces examined, and bonding ratio more than 96% has been confirmed.

(3) Fairly uniform distributions of the constituting elements (Fe, Cr, W, C and O) have been confirmed by EPMA line analysis along the line over the HIP bonded interface, and no decarburization or oxidation have been observed.

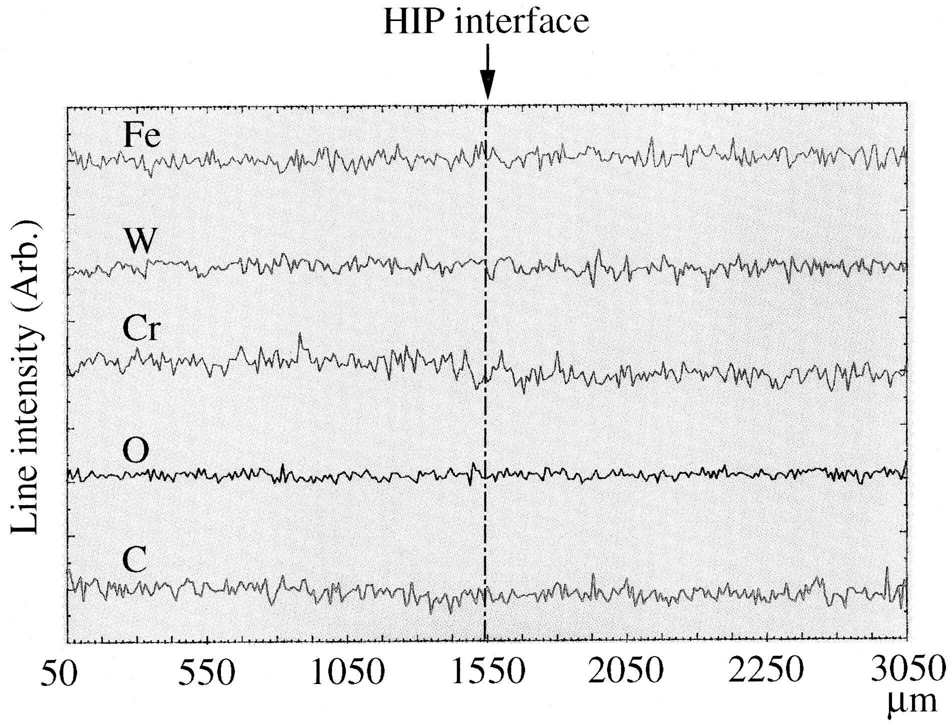

Fig. 7. Results of EPMA analyses along the line transverse to the HIP bonded interface over the length of ±1.5 mm. Elements examined were iron, chromium, tungsten, carbon and oxygen.

(4) Through these fabrication and following destructive examinations, applicability of HIP bonding to a complicated component made from F82H has been demonstrated.

Acknowledgements

The authors would like to express their sincere appreciation to Drs. A. Hishinuma and K. Shiba, JAERI, for providing the F82H plates and fruitful discussions, Prof. M. Tamura, National Defense Academy, for giving a suggestion on heat-treatment process, and Kawasaki Heavy Industries, Ltd. led by Dr. T. Osaki and Kokan-Keisoku Co. led by Dr. Y. Ishizawa for fabricating the panels by their good mutual collaboration. We also would like to acknowledge Drs. M. Ohta and T. Nagashima for their continuous encouragement through this work.

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