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High heat flux test of a HIP-bonded first wall panel of reduced activation ferritic steel F-82H

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Abstract

Reduced activation ferritic steel F-82H is a primary candidate structural material of DEMO fusion reactors. In fabrication technology, development of the DEMO blanket in JAERI, a hot isostatic pressing (HIP) bonding method, especially for the first wall structure with built-in cooling tubes has been proposed. A HIP-bonded F-82H first wall panel was successfully fabricated with selected manufacturing parameters. A high heat flux test of the HIP-bonded F-82H first wall panel has been performed to examine the thermo-mechanical performance of the panel including the integrity of the HIP-bonded interfaces and the fatigue behavior. A maximum heat flux of 2.7 MW/m^2 was applied to accelerate the fatigue test up to 5000 cycles in test blanket inserted ITER. The maximum temperature of the panel was ~450°C under this heat flux. Through this test campaign, no damage such as cracks was observed on the surface of the panel, and no degradation in heat removal performance was observed either from the temperature responses. The thermal fatigue lifetime of the panel was found to be longer than the fatigue data obtained by mechanical testing. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

A grade of ferritic/martensitic steel, F-82H (8Cr–2WVTa) [1–3], is a primary candidate structure material of the DEMO fusion reactor such as steady-state Tokamak reactor (SSTR) [4,5]. Mechanical properties of F-82H including neutron irradiation effects have been investigated [2,3,6–9]. The first wall of the DEMO blanket has cooling tubes embedded within the wall to assure sufficient cooling capability against high thermal loads and enough mechanical stiffness against large electromagnetic loads and internal pressure of the blanket box. As the fabrication method of the DEMO blanket, hot isostatic pressing (HIP) bonding has been proposed as it appears to be most promising, especially for the first wall structure with built-in cooling tubes.

In this study, high heat flux tests with the fabricated first wall panel [10] were performed to investigate the thermo-mechanical performance including the integrity of HIP-bonded interfaces and fatigue lifetime of the panel.

2. First wall panel

An F-82H first wall panel was fabricated with HIP conditions of 1040°C, 140 MPa and 2-h holding time. Heat treatment at 740°C for 2 h was added after HIP [10,11]. Major sizes of the panel are 260 mm in length, 113 mm in width and 18 mm in thickness. Strain gauges were attached on the back of the panel to measure strains during the high heat flux tests. A HIP-bonded F-82H panel is shown in Fig. 1.

3. High heat flux test

3.1. Test condition

High heat flux tests were carried out at the JAERI electron beam irradiation stand (JEBIS) [12]. By performing 3-D finite element method analyses with the model shown in Fig. 2, test conditions were decided for

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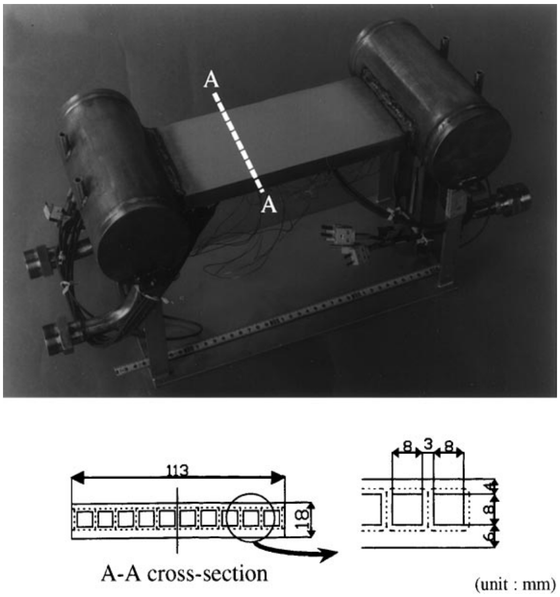

Fig. 1. Appearance of F-82H HIP-bonded first wall panel.

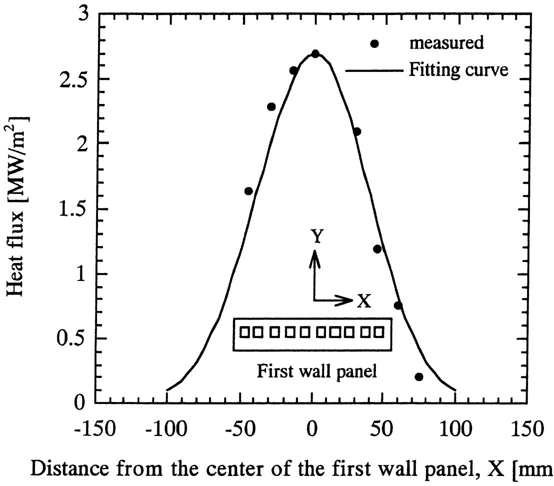

Fig. 3. Heat flux distribution in *X* direction at the center in *X* direction ($Z = 0$).

simulating the expected maximum temperature. These conditions consisted of a temperature of ~450°C under the surface, a heat flux of 0.5 MW/m^2 and a neutron wall load of 3.0 MW/m^2 [4,5]. The heat flux profile applied in the test is shown in Figs. 3 and 4. Since a lower water temperature, 20°C, than in the DEMO condition, 285–325°C, was used and no volumetric heating was simulated in the test, the applied heat flux (2.7 MW/m^2 peak) was higher than the DEMO condition. The heating time in one cycle was 15 s. With these values for heat flux and this heating time, the first wall panel reached steady state with the maximum temperature of ~450°C as shown in Figs. 2–4. By adding a 15-s dwell time after the end of the heating time as shown in Fig. 6, accelerated thermal fatigue testing was performed up to 5000 cycles.

3.2. Test result

Temperature responses at the center of the heated surface in the 500th and 5000th cycles are shown in Fig. 5. Temperatures were measured by an infrared

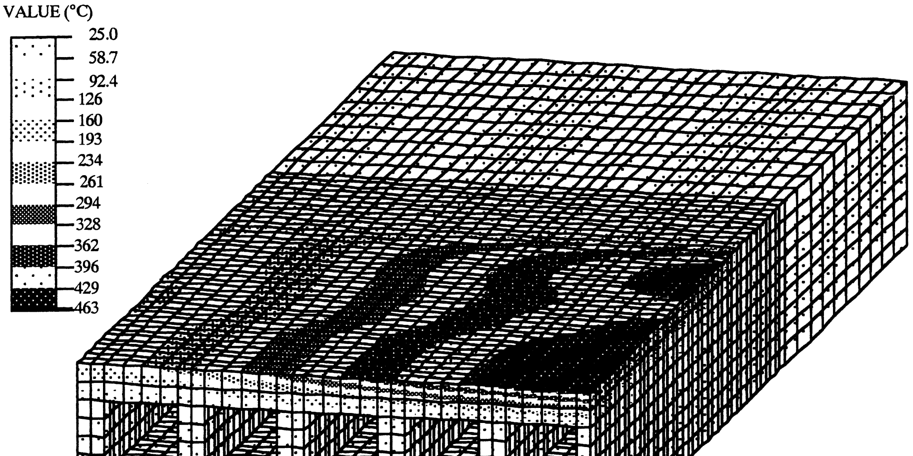

Fig. 2. Analysis model and temperature distribution at heating time of 15 s.

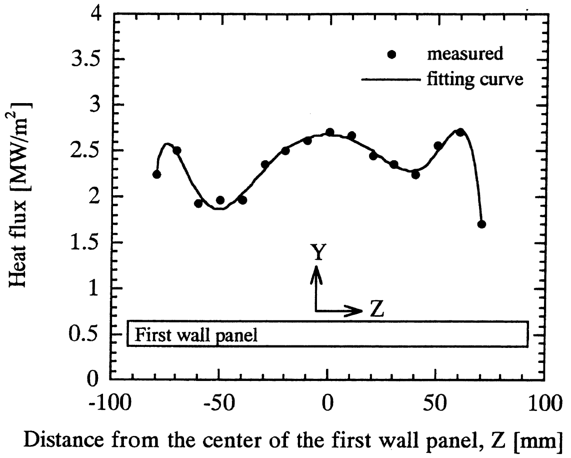

Fig. 4. Heat flux distribution in X direction at the center in Z direction ($X = 0$).

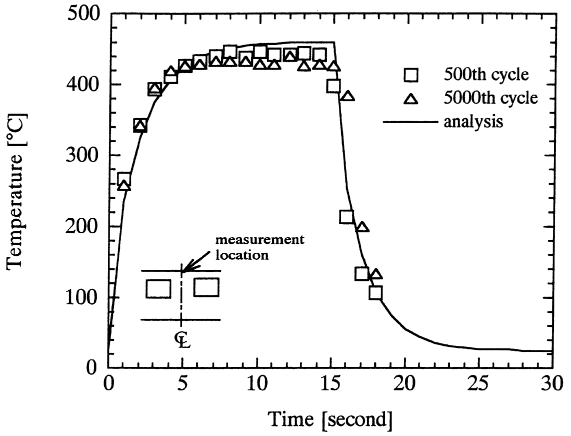

Fig. 5. Representative temperature responses at heated surface measured with infrared camera and calculated by FEM.

camera during the test. The temperature responses in the 500th and 5000th cycles were similar and they also agreed well with the analysis result. As these figures show, no degradation in heat removal performance was observed. In addition, no damage, such as cracks, was observed on the surface of the panel by direct observation using a VTR camera through out the tests.

The measured strains around the 500th cycle are shown in Fig. 6. The strain responses were almost constant through the test.

After this test, postmortem examinations were performed with a test piece cut out from the panel. A microscope image of the HIP-bonded interface is shown in Fig. 7. Exfoliation and crack initiation at the HIP-bonded interfaces were not observed, thus the integrity of HIP-bonded interfaces was confirmed against the high heat flux loads. A series of Vickers hardness tests

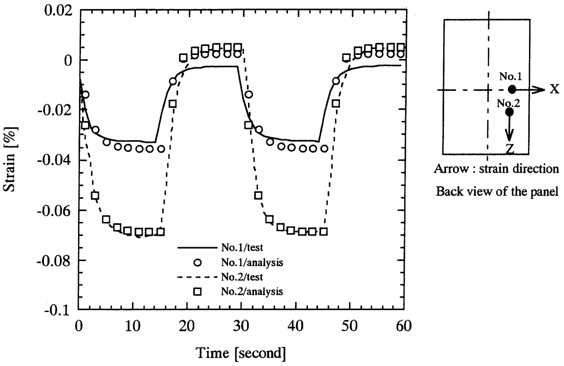

Fig. 6. Strains measured during the high heat flux test and analyzed by FEM.

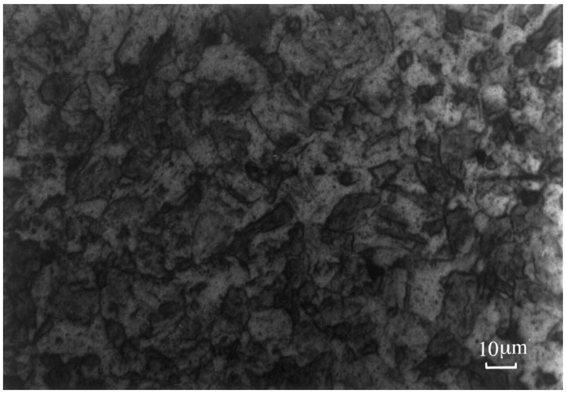

Fig. 7. Microscope image of the HIP-bonded interface 2.5 mm deep from heated surface of the F-82H first wall panel.

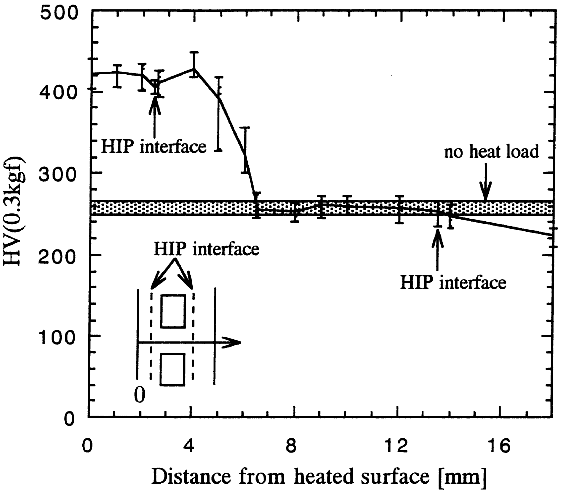

Fig. 8. Hardness distribution across the cross-section of the F-82H first wall panel.

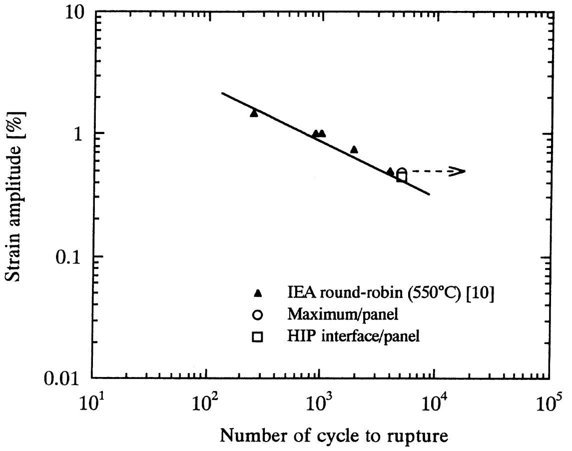

Fig. 9. Low cycle fatigue characteristics of F-82H.

were performed across the cross-section of the panel to evaluate the effect of the heat load. The results of the hardness tests are shown in Fig. 8. The hardness at the heated surface was about two times higher than that near the back where the hardness was not changed from the as-fabricated condition.

4. Discussion

3-D elasto-plastic analyses were performed with the temperature responses obtained in the above-mentioned thermal analysis. The measured strains in Z direction agree with the analysis results very well. On the other hand, the analysis overestimates the strain amplitude in X direction by about 20%. Therefore, fatigue performance of the panel was evaluated by reducing this overestimate from analysis results. The maximum equivalent strain amplitude in the analysis is 0.48% at the center of the heated surface. As shown in Fig. 9, the fatigue lifetime of the F-82H panel is longer than the raw fatigue data of F-82H obtained in the IEA round-robin test [10]. This may be used during the tests due to the distributed strain profile in the panel with a peak strain at the heated surface, whereas the fatigue data were obtained using tension–compression tests with uniform strain distributions. The HIP-bonded joint had similar thermo-mechanical strength and fatigue lifetime, so the equivalent strain amplitude calculated at the HIP-bonded interface was 0.45%.

The results of Vickers hardness tests revealed that the F-82H material near the heated surface was hardened almost like being quenched even though the cooling after the heating time was from ~450°C with ~100°C/s. This hardening would be due to the accumulation of plastic strain. Since the ultimate tensile strength of F-82H would become higher and the elongation lower, a crack may initiate and propagate in this region. Therefore, a more detailed investigation on the mechanism and the effect of this hardening is required.

5. Conclusion

High heat flux tests on a HIP-bonded F-82H first wall panel were performed to investigate its thermo-mechanical performance. Through the present study, the following conclusions were obtained.

1. The first wall panel endured a heat flux of 2.7 $\mathrm{MW/m^2} \times 5000$ cycles simulating the maximum temperature of the water-cooled DEMO blanket.
2. Integrity of the HIP-bonded interfaces in the F-82H first wall panel was confirmed by measuring a temperature response during and after the test.
3. Thermal fatigue lifetime of the panel was longer than the raw mechanical fatigue of F-82H. In addition, the HIP-bonded F-82H first wall panel has sufficient heat removal and thermo-mechanical performance to be applied to the DEMO blanket.
4. Further investigation on the mechanism and the effect of the hardening at the heated region is necessary.

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