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Impact Property of Low-activation Vanadium Alloy and its weld joint after heavy neutron irradiation
中性子重照射した低放射化バナジウム合金及びその溶接材の衝撃特性

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The reference low-activation alloy, NIFS-HEAT-2, with a composition of V-4Cr-4Ti and its weld joints were neutron-irradiated in JOYO reactor up to 0.98 dpa and 8.5 dpa at 670 K and 720 K, respectively. Impact properties were evaluated by Chrapy V-notch impact test with miniature specimens. The base metal of NIFS-HEAT-2 exhibited superior resistance to neutron-irradiation embrittlement for the present irradiation condition, while the weld metal indicated enhanced irradiation embrittlement. It was found that the embrittlement for the weld metal was caused by not only irradiation hardening but also additional hardening due to dissolution of Ti-CON precipitates during the welding before irradiation. A post-irradiation annealing at 873 K for 1 hr was effective to recover the irradiation hardening in the weld metal.

1. Introduction

Welding is a key technology for low-activation vanadium alloys to fabrication of blanket components for fusion reactors. The Japanese reference V-4Cr-4Ti alloy, NIFS-HEAT-2, have exhibited superior impact properties at annealed condition and also at as-welded condition. Heavy neutron irradiation is necessary to evaluate mechanical performance of the alloy at the blanket irradiation condition. The purpose is to evaluate irradiation embrittlement of the alloy and its weld joints by heavy neutron irradiation and to clarify the mechanism for the embrittlement.

2. Experimental

Material used was NIFS-HEAT-2 plates with a thickness of 4 mm. The plates were annealed at 1273 K for 2 hr. Weld samples were made by bead-on-plate welding with 1.6 kW YAG laser in a high purity Ar. They were machined into Charpy V-notch (CVN) specimens with a size of 3.3 x 3.3 x 25.4 mm (1/3 size CVN) and 1.5 x 1.5 x 20 mm (1.5 size CVN). The V-notch was positioned at the base metal (BM) and the center of the weld metal (WM). The CVN specimens were irradiated in JOYO reactor in Japan. The irradiation conditions were 1.5×10^{25} neutron m^{-2} (E > 0.1 MeV) at 670 K and 1.3×10^{26} neutron m^{-2} at 720 K, which are equivalent to 0.98 dpa and 8.5 dpa, respectively. After irradiation, Charpy impact tests, Vickers micro-hardness tests with a load of 100 g for 30 sec and microstructural observations with a transmission electron microscope (TEM) were conducted.

3. Results and discussion

Figures 1 and 2 show absorbed energy for the Charpy impact tests for the base metal and the weld metal. In the present paper, ductile-to-brittle transition temperature (DBTT) is defined as the temperature where the absorbed energy is half the upper-shelf energy (E_U). DBTT is an important parameter to evaluate the toughness and ductility of the materials. RT (~300 K) is recognized as a limit for DBTT of the structural materials, assuming they are cooled down to RT with some pressure after shutdown of the fusion reactor. DBTT for the base metal and the weld metal before irradiation was 122 and 103 K, respectively, with 1/3 size CVN specimens (Fig. 1), while it was below 77 K for both the base metal and the weld metal with 1.5 size CVNs (Fig. 2). DBTT was shifted to 189 K and 188 K after 8.5 dpa irradiation at 720 K with 1/3 size (Fig. 1) and 1.5 size (Fig. 2) CVNs, respectively. Since the DBTTs were still much lower than RT, the base metal maintained the superior resistance to neutron irradiation embrittlement up to 8.5 dpa at 720 K. The weld metal maintained 188 K in DBTT with 1.5 size CVNs after 0.98 dpa irradiation at 670 K (Fig. 2). Absorbed energy for weld metal after 8.5 dpa irradiation with 1/3 size CVNs was scattered, however DBTT was tentatively estimated as 332 K to estimated the worst one (Fig. 1), while it was above 423 K with 1.5 size CVNs (Fig. 2). These results revealed that irradiation embrittlement was enhanced in the weld metal. Recovery of the absorbed energy and DBTT was examined for the weld metal by a post-irradiation annealing at 873 K. DBTT was successfully recovered to 243 K by the post-irradiation annealing (PIA) as indicated by an arrow in Fig. 1.

Figure 3 presents the relationship between DBTT with 1.5 size CVNs and hardness of the base metal and the weld metal before and after the neutron irradiations. DBTT is increased with increasing hardness. The recovery of DBTT for the weld metal by the post-irradiation annealing is attributed to the recovery of the hardness indicated by an arrow in Fig. 3.

According to TEM observations before irradiation, the base metal contained Ti-CON precipitates (size ~ 100-1000 nm), while no precipitates were observed in the weld metal. It was indicated that the decomposition of the precipitates released the interstitial C, O and N into alloy matrix, and increased hardness of the weld metal by solid solution hardening. After irradiation, dislocation loops and network were produced as irradiation defects. In addition, irradiation-induced precipitates (size ~ 10 nm) were observed. No significant difference was found in dislocation structure between the base metal and the weld metal, while precipitates in the weld metal seemed slightly more than the base metal. The dislocations were partly recovered by the post-irradiation annealing. The larger hardness of the weld metal after irradiation is explained as the combination of the hardening by the decomposition of the precipitates before irradiation, and the irradiation hardening by the

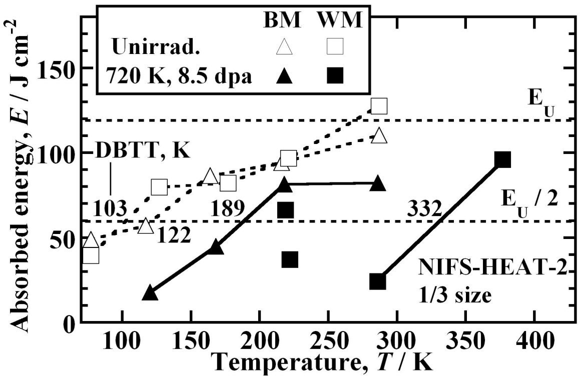

Fig. 1 Absorbed energy for Charpy impact tests with 1/3 size specimens.

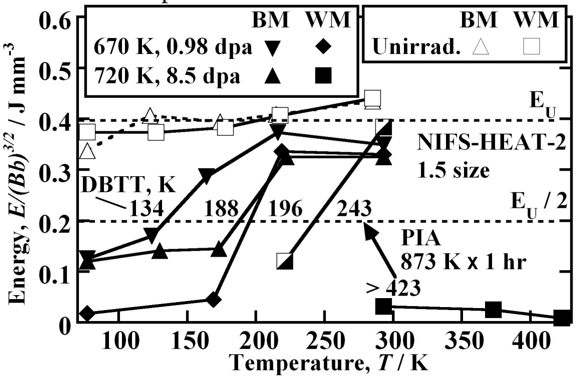

Fig. 2 Absorbed energy for Charpy impact tests with 1/3 size specimens.

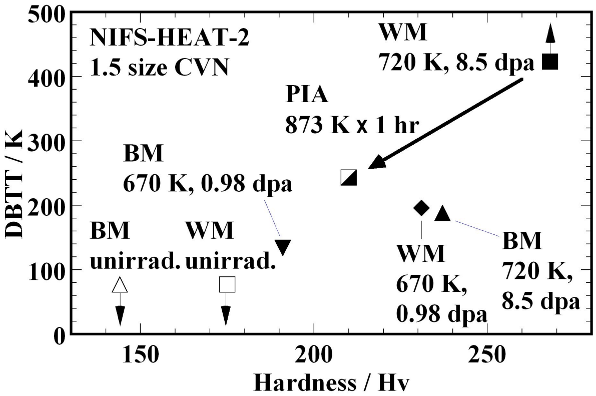

Fig. 3 Relation ship between DBTT and hardness of the base metal and the weld metal before and after the neutron irradiations.

irradiation-induced dislocations and precipitates. It is considered that the recovery of the dislocations resulted in the decrease in the hardness and recovery of DBTT of the weld metal.

4. Conclusion

The base metal of NIFS-HEAT-2 exhibited superior resistance to neutron-irradiation embrittlement, while the weld metal indicated enhanced irradiation embrittlement. A post-irradiation annealing at 873 K for 1 hr was effective to recover the irradiation hardening in the weld metal, mainly due to the recovery of the irradiation-induced dislocations.