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Swelling behavior of TIG-welded F82H IEA heat

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Abstract

Tungsten-inert-gas weld joints prepared from the IEA heat of F82H were irradiated with 10.5 MeV Fe ions and 1.05 MeV He ions at 450 °C. Transmission electron microscopy observation revealed a marked cavity growth up to 30 nm at 50 dpa in the over-tempered portion of the heat-affected zone (HAZ), while cavities in the quenched portion of HAZ remained smaller (up to 10 nm). Base metal results also showed that a specimen tempered at 780 °C contained larger cavities than those tempered at 750 °C. Cavities in cold-worked specimens were the smallest. Initial dislocation densities in F82H, which are affected by heat treatment and/or mechanical treatment, dominate the cavity growth.

1. Introduction

A reduced activation ferritic/martensitic (RAF/M) steel, F82H [1,2], is one of the most promising candidates for the structural material of future fusion energy systems. The importance of the welding technique for the fabrication of fusion reactor core components is well recognized and efforts have been devoted to characterize the welded F82H in IEA round robin tests [3]. Weld metal and some portions of the heat-affected zone (HAZ) are heated above the Ac3 temperature (at which the microstructure becomes completely austenitic) during welding, and this will lead to quench-hardening in the subsequent cooling process. Post-welding heat treatment (PWHT) is, therefore, necessary to temper such portion. On the other hand, some portion of HAZ remaining below the Ac1 temperature (at which the ferritic microstructure starts to transform into austenite) receives additional tempering during welding. Softening in over-tempered HAZ is more easily detected by microhardness tests in tungsten-inert-gas (TIG) welding than in electron beam (EB) weld due to the higher energy deposition in the former method [4]. A weld joint of F82H thus includes complicated microstructure.

The neutron irradiation data suggest that the radiation response of F82H is strongly affected by its heat treatments [5]. In this study, specimens taken from welds were irradiated using the multiple beam irradiation facility in the Takasaki Ion Accelerators for Advanced Radiation Application (TIARA). Base metal specimens with controlled heat and mechanical treatments were also irradiated.

2. Experimental

Plates of F82H IEA heat 25 mm thick were TIG welded. The base metal was in a normalized (at 1040 °C for 40 min) and tempered (at 750 °C for 60 min) condition. A 15 mm narrow gap was filled with 10–12 layers using an oscillating arc method with the electrode swinging. PWHT was performed at 720 °C for 1 h. Further details of welding are described elsewhere [4]. Small pieces of base metal specimens were also normalized and tempered in evacuated quartz tubes. Tempering time was 1 h. Microhardness measurements with 10 kgf load were made on the polished surface of heat-treated blocks, which are more than 3 mm thick. Irradiated base metal specimens include as normalized and tempered (as-N&Ted) ones and cold-worked

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Table 1
Heat and mechanical treatments of F82H base metal used in this study

Normalizing*		Tempering*		As N&Ted	20% CW	40% CW
1040 °C	40 min	750 °C	1 h	a	–	e
			2 h	b	–	–
		780 °C	1 h	c	d	–

Letters ‘a’ through ‘e’ are materials data in Fig. 3.
* After normalizing and tempering, specimens were air-cooled.

(CW) ones, as shown in Table 1. As-N&Ted plates were cold-rolled and the degree of cold work is referred to as the reduction of thickness. Microhardness of these specimens were again measured with a smaller load (500 gf) on thin plates, which are typically 0.5 mm thick.

Specimens were irradiated with 10.5 MeV Fe^{3+} and 1.05 MeV He^{+} ions using the multiple beam irradiation facility in TIARA. A triple-beam irradiation including 380 keV H^{+} was also made. The depth profile of displacement damage by Fe ions peaks at 1.8 μm. From the surface He and H ions were used for irradiation through degraders to widen the implantation depth. Microstructural data were obtained at the depth of 1.0 μm, where the profiles of displacement damage and injected gas ions are relatively flat. The irradiation temperature was 450 °C and the damage rate was about 1.6×10^{-3} dpa/s. The He/dpa ratio in dual beam irradiation was almost 10 appm/dpa, and the triple-beam experiment was performed at higher gas injection rates; 100 appm He/dpa and 2000 appm H/dpa. Further details of ion-irradiation are given elsewhere [6].

Cross-section TEM specimens were prepared with a focused ion beam (FIB), FB-2000A attached with a micro-sampling system. The FIB also enabled accurate sampling of specimens in HAZ, where the microstructure changes according to the distance from the fusion line. A Hitachi HF-2000 electron microscope operated at 200 kV was used for the observation.

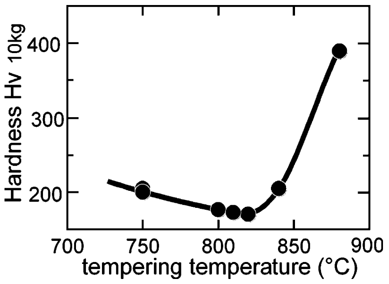

Fig. 1. Microhardness of F82H tempered for 1 h at 750–880 °C. The indentation load is 10 kgf.

3. Results and discussion

3.1. Base metal

Results of microhardness tests on tempered base metal are summarized in Fig. 1. The hardness of F82H base metal showed a general decrease with increasing tempering temperature between 750 and 820 °C, after which a sudden increase in hardness was observed. The latter is caused by the formation of austenite during tempering, which will change into martensite in the following cooling process and remains as-quenched. The Ac1 temperature of F82H is thus determined to be 820 °C from Fig. 1, which is somewhat lower than the value determined by volume change (856 °C) [7].

Cavities formed in the 780 °C-tempered F82H steel dual-beam-irradiated at 450 °C up to 50 dpa are shown in Fig. 2. Cavities up to 13 nm are observed in as-N&Ted material (a), while most cavities are less than 5 nm in 20% CW material (b). The growth of radiation induced cavities is suppressed by cold working. Fig. 3 shows the plots of microhardness and the maximum cavity size as a function of dislocation density determined by TEM observation. Due to smaller load (500 gf) in these measurements, hardness values are somewhat higher than those in Fig. 1. Dislocation densities of cold-worked specimens were higher than those of as-N&Ted. Higher tempering temperature results in lower dislocation density, while longer tempering time has limited effects on dislocation density and hardness. Anyhow, a good proportionality is shown between dislocation density and microhardness data (Fig. 3(a)). Fig. 3(b) also shows a good proportionality between dislocation density and the maximum cavity size. The higher dislocation densities due to lower tempering temperature or cold-working suppress the cavity growth. This result is consistent with the HFIR irradiation data [5], where as-normalized F82H doped with Ni showed little swelling. On the other hand, degradation of swelling resistance in welds is anticipated, especially at HAZ where softening was detected.

The cavity swelling detected in the present work is still small. It is estimated that the largest swelling measured in dual-beam irradiated base metals is less than

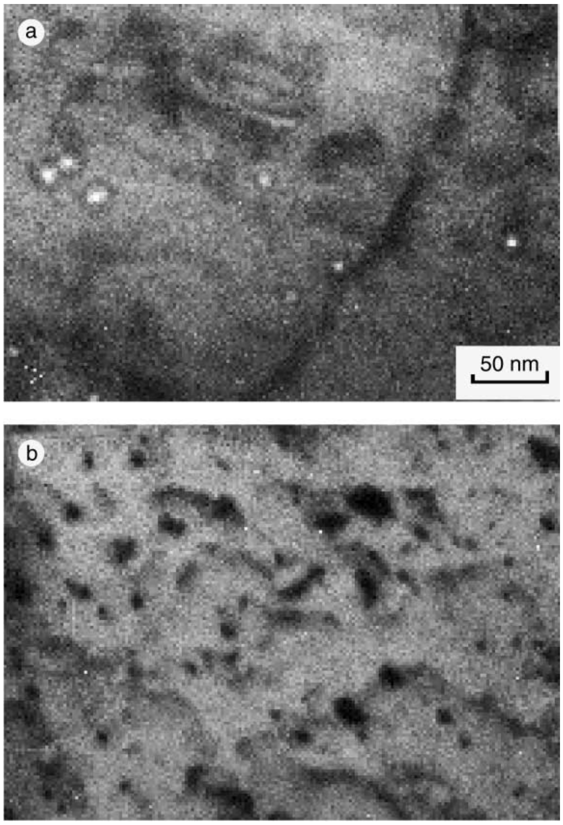

Fig. 2. Cavities formed in 780 °C-tempered F82H base metal irradiated at 450 °C up to 50 dpa. Cavities up to 13 nm are observed in as-N&Ted material (a), while most cavities are less than 5 nm in 20% CW material (b).

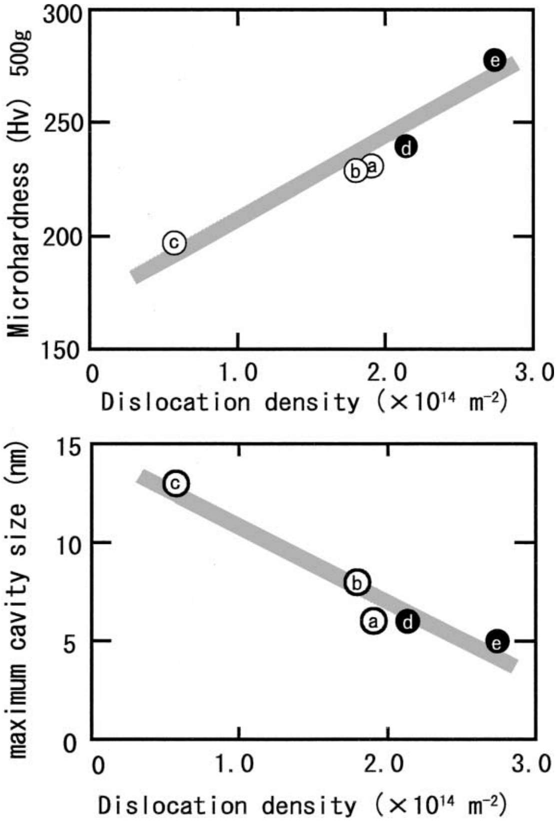

Fig. 3. Plots of hardness (a) and maximum cavity size (b) as a function of dislocation density. Hardness data are obtained with 500 gf indentation load. Open circles are data obtained with as-N&Ted material, while solid ones are with cold-worked material.

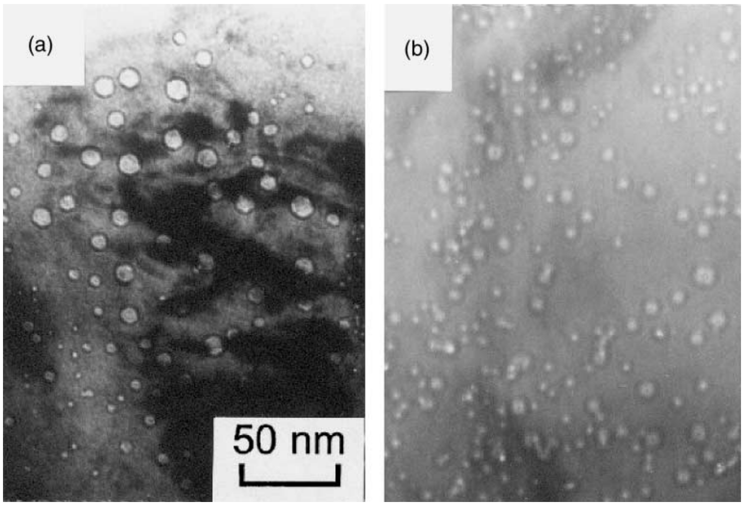

Fig. 4. Cavities formed in 750 °C-tempered F82H base metal irradiated with triple beams. The irradiation was made at 450 °C up to 50 dpa with higher gas injection rates (100 appm He/dpa and 2000 appm H/dpa) than dual-beam irradiation. Many large cavities (>15 nm) are observed in as-N&Ted material (a), while most cavities are less than 10 nm in 40% CW material (b).

0.1%. The swelling of ion-irradiated F82H becomes much larger with co-implanted hydrogen [6]. Increased dislocation density introduced by cold-working suppresses the growth of cavities under such irradiation conditions (Fig. 4). Indeed many large cavities larger than 15 nm are observed in the as-N&Ted material (a), while most cavities are less than 10 nm in the 40% CW material (b).

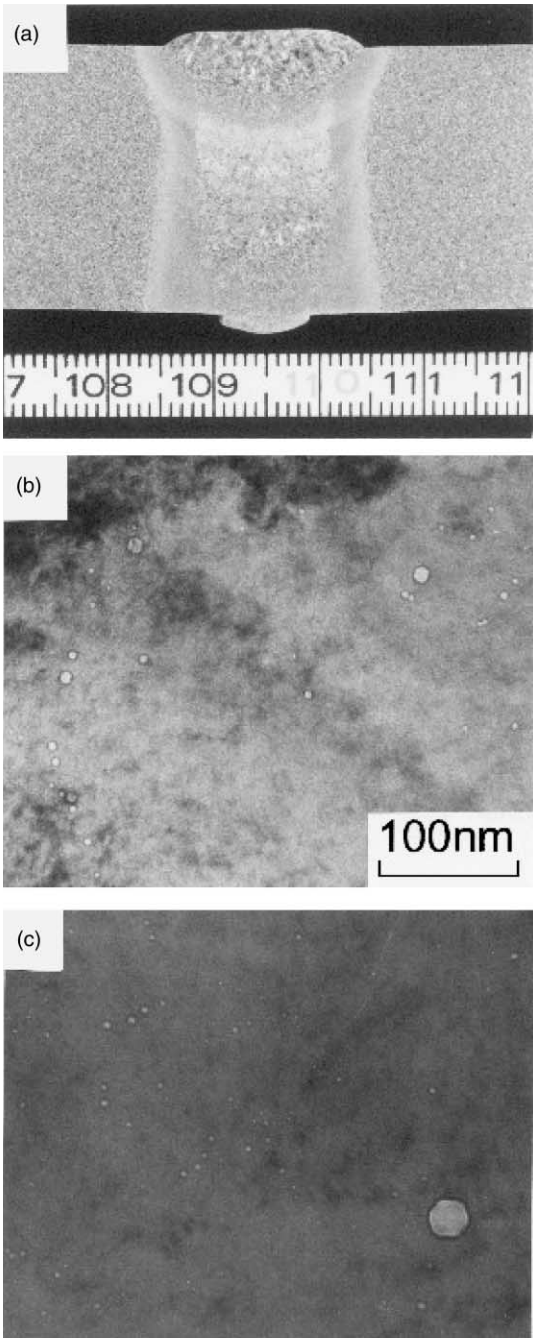

Fig. 5. Cross-section of TIG welded F82H plates (a) and cavities formed in irradiated HAZ (b, c). HAZ within the transformation line contained cavities less than 15 nm (b), while larger cavities were observed in HAZ beyond the transformation line (c).

3.2. Weld

A marked transformation line appears in HAZ at 3–5 mm distance from the fusion line (Fig. 5(a)). Weld metal and HAZ within this line are heated over the Ac1 temperature and the outer side of this line has remained below the Ac1 temperature during weld. Although the weld joint was heat-treated at 720 °C for 1 h (PWHT) to reduce the hardness of the former region, hardening of the former region and softening of the latter region still remain [4]. Two types of HAZ specimens were sampled from irradiated weld using a FIB micro-sampling system. One was obtained at 0.5 mm inside the transformation line and the other at 0.5 mm outside the line. These specimens are, hereafter, designated as quenched HAZ and tempered HAZ according to the typical thermal history, respectively. These specimens were taken from the upper quarter of the plate thickness, so that the effect of multi-layer deposition is small. As shown in Fig. 5, the maximum size of cavities in quenched HAZ is less than 10 nm (Fig. 5(b)), while the tempered HAZ contained cavities up to 30 nm (Fig. 5(c)). The enhanced growth of cavities in the tempered HAZ is well understood from the results obtained from the base metal (Fig. 3(b)). The cavity size observed in the tempered HAZ was the largest in dual-beam-irradiated specimens in the present work. The Ac1 temperature of F82H determined in the present work is 820 °C and the tempered HAZ was heated up to very close to this temperature. This is higher than the highest tempering temperature in base metal experiments.

The temperature of PWHT, 720 °C, is lower than the typical tempering temperature of F82H (750 °C). The maximum cavity size in quenched HAZ (10 nm) is, however, still larger than that of 750 °C-tempered base metal (6–8 nm). According to the tempering behavior of F82H shown in Fig. 1, hardening occurs rapidly above Ac1 but still requires some overheat (880 °C) to reach the full hardness of as-normalized condition. It should be also noted that Fig. 1 was obtained with specimens tempered for 1 h. The time when the HAZ stayed above Ac1 during weld is apparently much shorter. With such short tempering time, it is expected that the temperature to reach the full hardness would be still higher. Indeed, the distance between the lowest hardness point and fully hardened point in HAZ was about 3 mm in this weld [4]. As the specimen of quenched HAZ in the present work was sampled only at 0.5 mm inside the transformation line, quench hardening was not sufficient to obtain an enough dislocation density, and thus not sufficient to obtain enough swelling resistance.

4. Summary

TIG weld joints and base metal specimens of F82H IEA heat were ion irradiated. The main results are:

1. The Ac1 temperature determined in the present work is 820 °C.
2. High dislocation densities due to lower tempering condition or cold working suppresses the growth of cavities in the base metal irradiated with Fe and He ions.
3. Triple-beam irradiation including hydrogen injection makes the swelling larger but the suppression of cavity growth by cold work was effective.
4. Degradation of swelling resistance in the TIG weld joint was detected. Tempered HAZ which was heated close to Ac1 showed much larger cavities than those of the base metal.

References

[1] M. Tamura, H. Hayakawa, M. Tanimura, A. Hishinuma, T. Kondo, J. Nucl. Mater. 141–143 (1986) 1067.
[2] M. Tamura, H. Hayakawa, A. Yoshitake, A. Hishinuma, T. Kondo, J. Nucl. Mater. 155–157 (1988) 620.
[3] A. Hishinuma, A. Kohyama, R.L. Kule, D.S. Gelles, W. Dietz, K. Ehrlich, J. Nucl. Mater. 258–263 (1998) 193.
[4] T. Sawai, K. Shiba, A. Hishinuma, J. Nucl. Mater. 283–287 (2000) 657.
[5] E. Wakai, N. Hashimoto, Y. Miwa, J.P. Robertson, R.L. Klue, K. Shiba, S. Jitsukawa, J. Nucl. Mater. 283–287 (2000) 799.
[6] E. Wakai, T. Sawai, T. Tomita, K. Furuya, A. Naito, S. Yamashita, S. Ohnuki, S. Yamamoto, H. Naramoto, S. Jitsukawa, these Proceedings.
[7] K. Shiba et al., JAERI-Tech 97-038 (1997) (in Japanese).