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Microstructure of welded and thermal-aged low activation steel F82H IEA heat

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Abstract

F82H(8Cr–2WVTa steel) IEA heat was used to prepare tungsten-inert-gas (TIG) and electron-beam (EB) weld joints, followed by heat treatment at 720°C for 1 h. Hardening in the weld metal and softening in the heat-affected zone (HAZ) were detected in TIG weld joints. In EB weld joints, hardening in the weld metal was more clearly observed but HAZ softening was hardly observed. Hardness of TIG weld metal was reduced after 550°C thermal-aging, but softening of the base metal was only observed after 650°C thermal-aging. $M_{23}C_6$ phase was the major precipitate in aged base metal and weld joints. The amount of precipitates in aged weld metal was lower than that of normalized and tempered base metal. W-rich Laves phase was also detected in aged weld metal, HAZ and base metal. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

Ferritic steels with higher thermal conductivity and better void swelling resistance than austenitic stainless steels offer an attractive solution for fusion reactor structural applications. Replacement of elements to avoid long life radioactive isotopes has been applied to these alloys, resulting in several reduced-activation ferritic and/or martensitic steels. F82H, a 0.1C–8Cr–2W–0.2V–0.04Ta steel to be used in a normalized and tempered condition, has been thus developed for the fusion application in Japan [1,2]. F82H is among the alloys of the IEA round robin tests [3] on reduced-activation ferritic/martensitic (RAF/M) steels for fusion structural applications, and a new heat of F82H is now being tested by several organizations [4–6].

Welding is an inevitable procedure for the fabrication of fusion reactor core components and welded F82H plates have been distributed for the above IEA round robin tests. The microstructures of both the weld metal and the heat-affected zone (HAZ) are different from that of the base metal. Furthermore, the chemical composition of the weld metal is usually modified to obtain better properties in tungsten-inert-gas (TIG) welding [7]. In this paper, TIG and Electron-beam (EB) weld joints were fabricated with the IEA heat of F82H. Differences in both types of weld joints were examined with hardness tests. Microstructural changes in the TIG weld joints and the base metal after thermal aging are also reported.

2. Experimental

The chemical composition of the plates of F82H IEA heat is shown in Table 1. Hot rolled plates 25 mm thick were normalized by holding at 1040°C for 40 min, followed by tempering at 750°C for 60 min. The microstructure consists of lath martensite and major precipitates of $M_{23}C_6$ with 200 nm size dispersed in grains and at the grain boundary [8].

TIG weld joints were prepared using an oscillating arc method with the electrode swinging, which enabled one path to complete one layer. Ten to twenty paths were required to fill the narrow gap groove with a 15 mm width. The welding speed was 80 mm/min and the welding position was flat. The chemical composition of filler wire is given in Table 1. Plates with an I-groove

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Table 1
Chemical compositions of used F82H plates and TIG weld wire

	C	Si	Mn	P	S	Cr	W	V
Base metal	0.09	0.07	0.1	0.003	0.001	7.84	1.98	0.19
TIG wire	0.08	0.10	0.49	0.004	0.004	7.38	2.04	0.22
	Ta	Nb	Ni	Mo	Cu	Al	B	N
Base metal	0.04	0.0002	0.02	0.003	0.01	0.001	0.0002	0.007
TIG wire	0.026	<0.005	0.01	<0.005	0.01	<0.002	<0.0002	0.0064

were EB-welded without filler metal. A welding speed of 300 mm/min was achieved with an electron beam of 200 mA and 90 kV. The welding position of EB-welding was also flat. Post-welding heat treatment (PWHT) was performed on both TIG and EB weld joints at 720°C for 1 h to improve the mechanical properties. Further details of the welds have been reported in elsewhere [9]. Base metal plates 15 mm thick from the same heat as the welded plates were thermal-aged at 500–650°C up to 10 000 h. TIG weld joints were also thermal-aged at 550°C up to 10 000 h.

Vickers hardness tests were performed both on TIG and EB weld joints, and on aged base metal and TIG weld joints. The test weight was 100 N for base metal and 10 N for weld joints. Transmission electron microscopy (TEM) specimens were taken from the upper 1/4 depth of the weld metal and HAZ of aged TIG weld joints. HAZ specimens were taken from the area heated above A_{c3} during welding. A Hitachi HF-2000 with a field emission gun (FEG) was operated at 200 kV for microstructural observation and an attached energy dispersive X-ray spectrometer (EDS), Voyager 2000 was used for the in-foil analysis of precipitate compositions.

3. Results and discussion

3.1. Hardness test

Hardness of F82H IEA heat base metal in the normalized and tempered condition is around 220 Hv measured with a test weight of 100 N. Hardness changes of the base metal due to aging at 500–600°C up to 10 000 h are small. On the other hand, the hardness decreased down to 195 Hv after 1000 h aging at 650°C. The hardness measured after 10 000 h aging at 650°C was 175 Hv. Cross-sections of TIG and EB weld joints after PWHT are shown in Fig. 1(a) and (b), and typical results of hardness tests on these cross-sections are shown in Fig. 1(c) and (d), respectively. Hardening at weld metal and the adjacent region in HAZ is detected in the TIG weld joint. Softening is also detected in HAZ just outside of the above region. In EB weld joints, hardening was more clearly observed but softening was hardly observed. The hardness of TIG weld metal shown in Fig. 1 is about 260 Hv and decreased to 230 Hv after 550°C aging for 3000 h. But longer aging for 10 000 h at 550°C resulted in little difference in the hardness from that of 3000-h aging.

Welding heat affects the weld joints both in hardening and softening. F82H is quench-hardenable so that the cooling of weld metal and surrounding HAZ from the austenite region easily makes a fully martensitic structure, which is harder than the base metal. In the rest of the HAZ where the temperature was below A_{c3} during welding, the welding heat just anneals the existing martensite. Hardened HAZ regions can be clearly distinguished from the rest of the HAZ in Fig. 1(a) and (b). Slower welding rate (80 mm/min) and wider weld metal (10 mm) make the cooling of TIG weld joints slower than that of EB weld joints, of which the welding rate and weld metal width are 300 mm/min and 3–5 mm, respectively. Furthermore, hardness data measured in the upper 1/4 of the thickness of the TIG weld joint reflect heat cycles due to successive layers, while the EB weld was made in one path. Slower cooling and repeated heat cycles of TIG weld joint result in less hardening in weld metal than in the EB weld joint and obvious HAZ softening. Both TIG and EB weld joints were subjected to PWHT at 720°C, which is somewhat lower than the standard tempering temperature, 750°C. This PWHT has not removed the effect of weld hardening.

3.2. TEM analysis

Fig. 2 shows the TEM micrographs of aged TIG weld metal and HAZ. Fig. 3 shows the EDS data obtained from precipitates in 3000-h aged weld metal. The chemical composition of the matrix corresponds to 8 Cr and 2 W. EDS data show two typical compositions of precipitates; one is around 8 Cr and 60 W and the other is around 55 Cr and 18 W. Data between these values are affected by the matrix signal or are due to excitation of both types of precipitates at once. EDS measurements for 3000-h aged HAZ and 10 000-h aged weld metal and HAZ showed similar compositions. These results suggest no significant change in chemical compositions of precipitates due to 550°C aging. According to previous reports on F82H [2,10], Cr-rich precipitates are $M_{23}C_6$ and W-rich precipitates are Laves phase. In the 3000-h

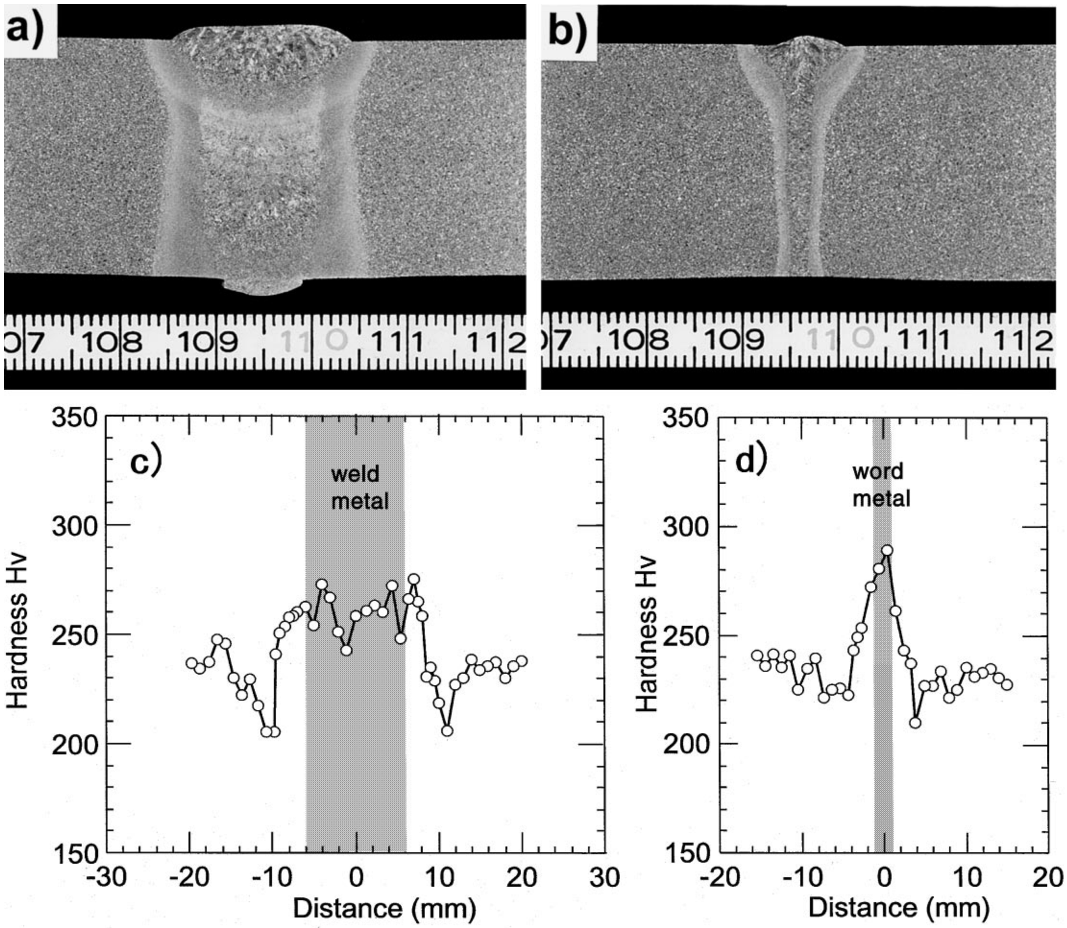

Fig. 1. Cross-sections of TIG (a) and EB (b) welded F82H plates and hardness distributions on TIG weld joint (c) and EB weld joint (d). Hardness data were obtained at upper 1/4 depth of the plates and beads.

aged weld metal specimen, $M_{23}C_6$ particles up to 300 nm were observed in grains or at the grain boundary. Laves phase precipitates were observed as small rods. The maximum length and width were about 100 and 30 nm, respectively. Images suggested Laves precipitates contained characteristic faults. Streaks in the diffraction patterns were also observed. In the 10 000-h aged weld metal specimen, the shape and the maximum size of $M_{23}C_6$ and Laves phase precipitates are similar to those of the 3000-h aged weld metal, and the number of $M_{23}C_6$ precipitates with the smaller size (about 100 nm) increased. The total amount of precipitate is, however, still lower than that of typical F82H base metal after standard normalized and tempered condition. In aged HAZ specimens, the maximum size of $M_{23}C_6$ precipitates was about 200 nm. Smaller ones (about 50–100 nm) were frequently observed at the lath boundaries and in lath grains. The number densities of $M_{23}C_6$ precipitates in 3000 and 10 000-h aged HAZ specimens were almost the same. Laves phase precipitates were mostly observed at prior austenite boundaries, where $M_{23}C_6$ precipitates were also observed. The maximum length and width of Laves phase rod is about 300 and 30 nm, respectively. Some Laves phase precipitates were observed associated with $M_{23}C_6$ precipitates, as shown in Fig. 4.

Precipitates in the aged weld metal were fewer than those in normalized and tempered base metal, even after PWHT and 550°C aging for 10 000 h. It is suggested that the amount of precipitate in the weld metal just after PWHT would be even less than that in the quench-hardened HAZ. It should be noted that the weld metal and the quench-hardened HAZ in a TIG weld joint show the same level of hardness in Fig. 1(c), although they have different levels of precipitates.

Precipitation behavior and a TTP diagram of the present heat of F82H base metal have been analyzed at 500–650°C for up to 10 000 h by chemical analysis and X-ray diffraction of extraction residue [11,12]. The TTP

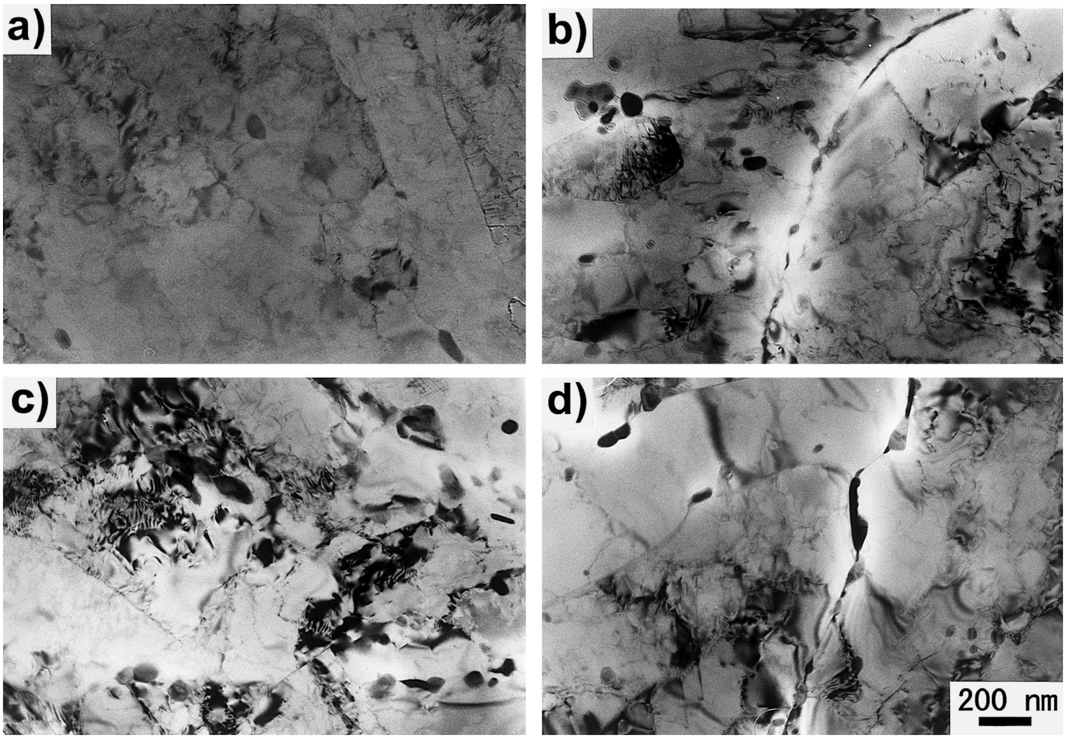

Fig. 2. TEM micrographs of TIG weld joints after 550°C aging. Aging time is 3000 h for (a) and (b), and 10 000 h for (c) and (d). (a) and (c) are weld metal and (b) and (d) are HAZ.

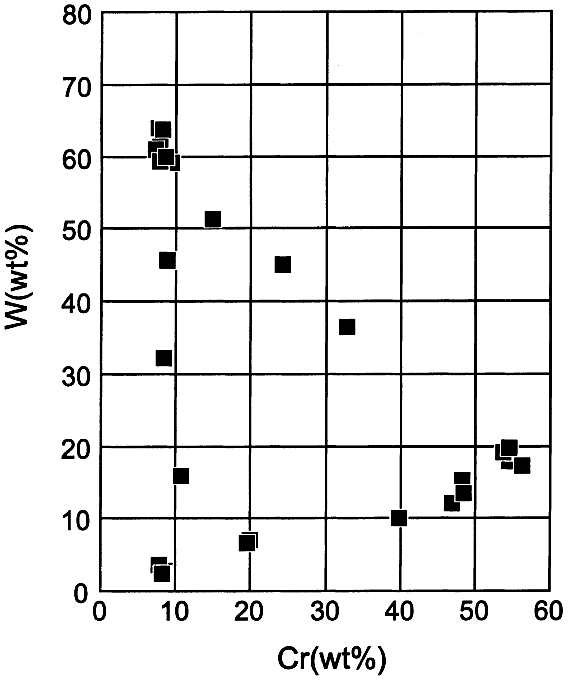

Fig. 3. In-foil analysis data of precipitates obtained for 3000-h aged TIG weld metal. Two points near 8Cr–2W represent matrix data and others are for precipitates.

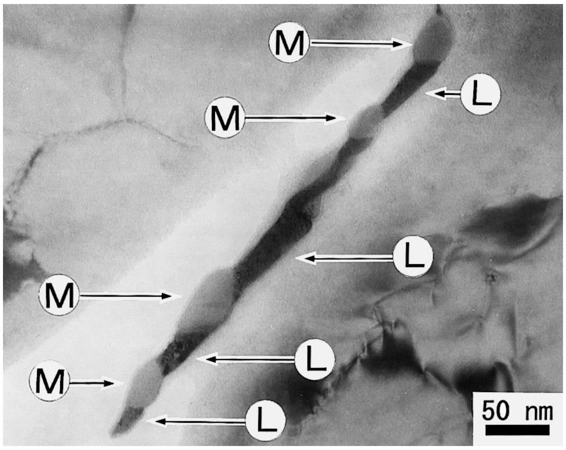

Fig. 4. Precipitates observed in a prior austenite boundary of 10 000-h aged HAZ. Laves phase precipitates are marked with 'L' and $M_{23}C_6$ precipitates with 'M'.

diagram determined [12] is similar to that reported for the previous heat [2]. These TTP diagrams show that Laves phase precipitation during 550°C aging requires more than 6000 h, while Laves phase precipitation is detected in the TIG weld metal and HAZ after PWHT and 550°C aging for 3000 h in the present work. PWHT temperature, 720°C, is above the C-curve of the Laves precipitation in F82H. The TTP diagram shows that it takes 2500 h for Laves precipitation even at the nose temperature (about 650°C). Accelerated precipitation of Laves phase due to welding heat cycle would be less likely. Ta addition to F82H is one of the major modifications, and it is reported that Ta retards Laves precipitation [2]. Lower Ta content in the filler wire may have something to do with the early precipitation of Laves phase in the weld metal. It should be, however, noted that present detection of fine Laves phase precipitates was enabled by the in-foil analysis using FEG–TEM, while TTP diagrams of base metal were determined by the analysis of extraction residue. Present TEM examination has detected fine Laves particles in weld metal and HAZ aged at 550°C for 3000 h. Their growth after extended aging time up to 10 000 h is still small.

4. Summary

TIG and EB weld joints were prepared from F82H IEA heat, followed by PWHT. These weld joints were thermal-aged with base metal. The main results are:

1. Hardening at weld metal and surrounding HAZ were detected in both weld joints. Comparison of the hardness distribution in TIG and EB weld joints is well understood by the slower cooling in the TIG weld joint. PWHT at 720°C has not removed these differences completely. Hardness of the TIG weld metal was reduced after 550°C thermal-aging, but softening of the base metal was observed only after 650°C.
2. TIG weld metal after 720°C PWHT and 550°C aging for 3000 h contained a much smaller amount of precipitates than that observed in the normalized and tempered base metal. $M_{23}C_6$ and Laves phase were observed in weld metal and HAZ after aging at 550°C. Laves phase precipitates in aged HAZ were mostly observed at prior austenite boundaries with $M_{23}C_6$ precipitates. Laves phase precipitates in 3000-h aged weld metal were very fine. Their growth after extended aging time up to 10 000 h is still small.

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