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Neutron irradiation effect on the mechanical properties of type 316L SS welded joints

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Abstract

In the International Thermonuclear Experimental Reactor design activity, the vacuum vessel (VV) is designed as a double walled structure so that some parts are not qualified by the conventional design standards. JAERI has executed the preparation activity of the new design standards and obtained the technical data to support them. In this study, neutron irradiation effects on the mechanical properties of 316L SS welded joints were investigated. The tensile and Charpy-impact specimens were irradiated at 473 K. The results of post irradiation experiments indicate that sufficient ductility is still maintained for tungsten inert gas (TIG) and electron beam (EB) welded joints; whereas, the impact properties of metal inert gas (MAG) weld metal are extremely poor. Consequently, the soundness of the 316L SS base metal and its TIG and EB welded joints are retained after 0.2–0.5 dpa neutron irradiation. However, it is rather difficult to adopt MAG welding for the fabrication of the VV.

1. Introduction

In the design activity for International Thermonuclear Experimental Reactor (ITER), the vacuum vessel (VV) is one of the most important components from the view point of safety design [1,2]. The VV is designed as a double walled structure so that some parts are not qualified by the conventional design standards. JAERI has executed the preparation activity for the new design standards [3] and obtained the technical data to support them. The irradiation data on the mechanical properties of 316L or 316LN base metal at low temperature (<523 K) and low dose (<1 dpa) are reported in the literature [4–12]. These data show that low temperature irradiation causes considerable irradiation hardening at low doses. For welded joints, a few data have been reported [6,13–15]. The irradiation effects on weld metals (WMs) or heat-affected zone (HAZ) of welded joints are not fully understood. Therefore it is required to obtain irradiation data on welded joints at low temperature.

In this study, neutron irradiation tests were performed at the Japan Material Testing Reactor (JMTR) to investigate neutron irradiation effects on the mechanical properties of 316L SS welded joints. The irradiated specimens were cut from the welded joints made by the candidate welding processes for the fabrication of the ITER VV.

2. Experimental

2.1. Materials and welded joints

Type 316L SS plates 40 mm thick were used in this study. The plates were solution-annealed at 1400 K, followed by water quenching. Butt-joint welds of the plates were made by tungsten inert gas (TIG) welding

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Table 1
Chemical composition of 316L stainless steel and welding rod (wt%)

Welding	Fe	Ni	Cr	Mo	Mn	C	Si	P	S
Base metal	Bal.	12.07	17.16	2.14	1.07	0.011	0.51	0.021	0.001
TIG welding rod	Bal.	12.31	19.42	2.28	1.95	0.017	0.43	0.027	0.002
MAG welding rod	Bal.	11.99	19.01	2.17	1.52	0.03	0.5	0.022	0.012

and T-joints were made by electron beam (EB) and metal active gas (MAG) welding. These welded joints were selected as representative examples of the candidate welding processes for the fabrication of the ITER VV. The chemical composition of the 316L SS base metal and its welding rods are listed in Table 1. The tensile and Charpy V-notch (CVN) specimens were machined from the plates and the welded joints. The tensile specimen had a gauge section of 3 mm diameter and 30 mm length. The CVN specimen was 5 mm in width, 10 mm in height and 55 mm in length. The V-notch depth was 2 mm. Tensile specimens and the V-notch of the Charpy-impact specimens of base metal were oriented parallel and orthogonal to the rolling direction (RD). Two types of tensile specimens were machined from the welded joints. The WM specimens were taken from only the WM. The welded joint (Joint) specimens were taken perpendicular to the welding direction so that the base metal, the HAZ and the WM were all in the gage length. The V-notch of the impact specimens was located in the HAZ and in the WM.

2.2. Irradiation and post-irradiation experiments

The neutron irradiation tests were performed at JMTR. The irradiation temperature was 453–473 K. The fast neutron fluence, determined by fluence monitors, was in the range $1.2–3.4 \times 10^{22}$ N/m^2 ($E > 1$ MeV). The values correspond to damage level of 0.2–0.5 dpa. The helium production in 316L SS was calculated to be about 0.1–0.3 appm. The post-irradiation experiments were performed at the Hot Laboratory of JMTR. Tensile tests were carried out in air at room temperature and 473 K. The crosshead speed was 0.5 mm/min. Charpy-impact tests were done in air at room temperature. The fracture surface after tensile and impact tests was observed by scanning electron microscopy (SEM). The fracture surface of the unirradiated Charpy specimen for the MAG–WM was observed using an electron microprobe analyzer (EPMA).

3. Results and discussion

3.1. Tensile properties

The results of tensile tests on the base metal are summarized in Table 2 and the stress–displacement curves are shown in Fig. 1. The results indicate that the 0.2–0.5 dpa irradiation caused considerable irradiation hardening and degradation of ductility. It seems there were no differences in the results compared to the RD. The appearance of a yield point is a typical phenomenon for low temperature (−573 K) irradiation of austenitic steel [5]. The yield strength (YS) increased with dose level. Fig. 2 shows the dpa dependence of the YS with literature values. It has been reported that the YS increase is proportional to dpa to the one-forth power [4,16] and saturates at about 1–3 dpa. For our conditions, no saturation was observed. The trends of the YS increase and the YS values in this study agree with literature values. As shown in Table 2, the uniform elongation (UE) decreases by approximately one-half after irradiation and the UE values ranged between 20% and 30%. For low temperature (−500 K) and low dose irradiation, the UE values remain high [5,8–12]. The reduction of area (RA) values were also reduced. These results indicate degradation of ductility. However, the RA values ranged between 70% and 80%, which were only 10–15% lower than those of the unirradiated base metal.

The results of tensile tests on the WM are summarized in Table 3. The results indicate that irradiation to 0.22 dpa causes an increase in the YS. However, the increase in the YS is not seen after further irradiation. The YS values of TIG and EB–WM agree with those of the 5–7 dpa irradiated specimens [14,15] and the work-hardening after the yield point is very small. Probably, the YS increase has already reached saturation. It has been reported that ductility of a welded joint is to be evaluated by RA [14]. The RA values of TIG and EB–WM ranged between 70% and 90%, which were comparable to those of the irradiated base metal. The RA values of the irradiated MAG–WM ranged between 40% and 60%. They were lower than those of the other WM.

The joint specimens of TIG and MAG welds fractured at the base metal or WM. All of the EB joint specimens fractured at the WM. It seems there were no differences in the tensile strength (UTS) corresponding to the fracture location. The RA values of the specimens fractured at the base metal were slightly higher than those of specimens fractured at the WM. Regardless of the fracture location, all of the joint specimens fractured in a ductile manner. Weld joint efficiency (η) for the UTS of the base metal is defined by following:

Table 2
Results of tensile tests on 316L SS base metal

Direction to RD	Irradiation temperature (K)	Test temperature (K)	dpa	Strength (MPa)		Elongation (%)		RA (%)
				Yield	Tensile	Uniform	Total	
Parallel		RT	Unirradiated	237	568	63.7	74.6	86.0
	473	RT	0.16	547	703	30.7	38.2	76.0
	453	RT	0.27	614	720	32.2	41.8	80.5
	473	RT	0.44	627	732	30.1	43.4	78.4
	473	RT	0.50	613	730	30.5	44.8	76.5
	473	RT	0.50	604	726	28.7	42.8	80.3
		473	Unirradiated	169	432	33.2	41.0	87.5
	473	473	0.50	474	575	22.4	28.0	77.8
	473	473	0.50	451	562	22.4	27.9	77.5
Orthogonal		RT	Unirradiated	234	563	59.4	67.2	87.0
	473	RT	0.16	539	705	33.7	40.9	76.2
	453	RT	0.27	608	718	31.9	44.0	74.3
	473	RT	0.44	625	727	29.7	43.5	76.8
	473	RT	0.49	611	732	29.5	40.4	72.9
	473	RT	0.49	600	727	30.7	41.3	74.9
		473	Unirradiated	169	441	35.7	42.7	87.0
	473	473	0.49	456	569	22.8	28.7	77.5
	473	473	0.49	457	570	20.8	27.1	77.2

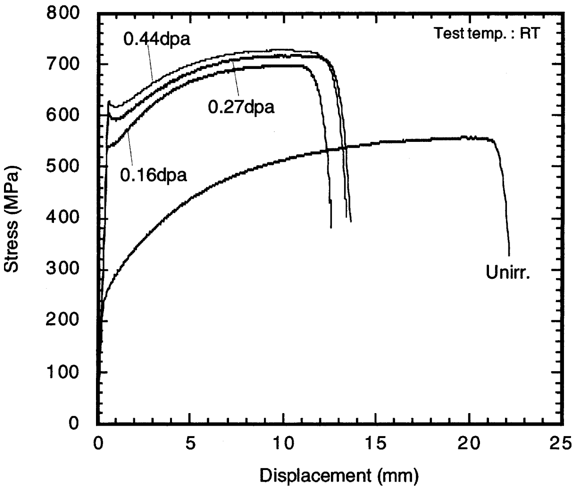


Fig. 1. Stress–displacement curves of unirradiated and irradiated 316L SS base metal.

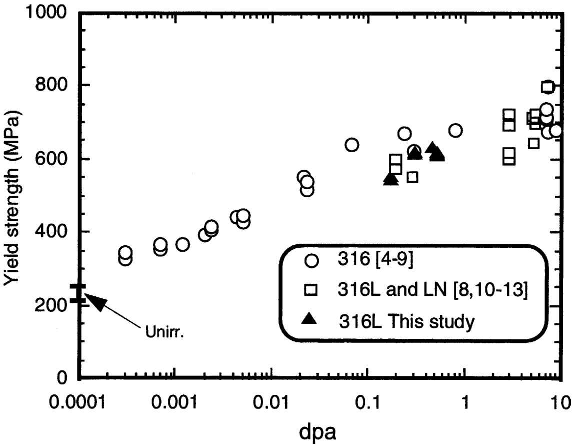


Fig. 2. The dpa dependence of YS of 316 series stainless steels ($T_{\mathrm{irr.}} \leqq 573$ K, $T_{\mathrm{test}} \leqq 373$ K, and $T_{\mathrm{test}} \leqq T_{\mathrm{irr.}}$).

$$\eta = (\text{UTS of the irradiated welded joint}) \\ /(\text{UTS of the unirradiated base metal}).$$

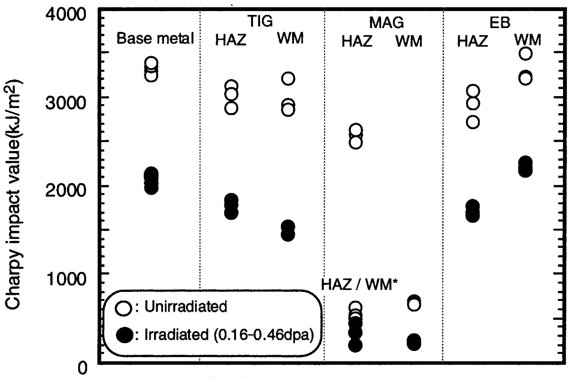
The η of the TIG, MAG and EB-joint increased to 1.2–1.3 after irradiation.

3.2. Charpy-impact tests

Fig. 3 shows the results of Charpy-impact tests of the base metal and the welded joints. No dpa dependence of the impact values can be observed in these conditions. For the base metal, the irradiation hardening caused about a 40% reduction in impact values. However, values of about 2000 kJ/m^2 are sufficiently large for structural applications. There was little difference in the results compared to the RD. For TIG–WM, TIG–HAZ and EB–HAZ specimens, impact values were reduced by 40–50%. No intergranular fracture was observed for HAZ specimens. Impact values of EB–WM were reduced by 30% and the values were slightly higher than those of the

Table 3
Results of tensile tests on 316L SS welded joints

	Irradiation temperature (K)	Test temperature (K)	dpa	Strength (MPa)		Elongation (%)		RA (%)
				Yield	Tensile	Uniform	Total	
TIG/WM		RT	Unirradiated	456	551	19.8	27.1	80.0
	473	RT	0.22	725	725	8.5	14.2	75.0
	473	RT	0.29	736	736	12.2	18.1	77.3
	473	RT	0.45	691	691	8.3	13.8	69.1
	473	RT	0.47	720	726	14.1	21.4	66.6
	473	RT	0.47	731	731	9.8	15.2	71.7
		473	Unirradiated	395	453	10.3	15.9	79.5
	473	473	0.47	567	579	8.2	13.5	85.4
	473	473	0.47	579	593	8.4	13.0	71.7
MAG/WM		RT	Unirradiated	379	515	27.9	30.9	55.0
	473	RT	0.22	627	646	19.0	22.8	47.5
	473	RT	0.29	641	659	18.6	23.4	48.2
	473	RT	0.45	663	694	8.6	12.1	54.3
	473	RT	0.49	695	703	18.8	24.2	46.8
	473	RT	0.49	680	689	21.3	26.4	57.4
		473	Unirradiated	321	413	23.8	26.9	53.0
	473	473	0.49	529	551	12.9	16.4	42.6
	473	473	0.49	537	554	15.8	18.6	52.4
EB/WM		RT	Unirradiated	361	552	35.5	42.7	86.0
	453	RT	0.21	662	687	22.3	30.8	79.9
	473	RT	0.33	644	678	20.4	28.3	84.5
	473	RT	0.41	649	687	19.3	25.6	83.6
	473	RT	0.41	637	684	21.9	28.6	82.0
	473	RT	0.43	655	688	20.9	29.8	79.0
		473	Unirradiated	292	423	22.2	29.5	82.0
	473	473	0.41	503	539	15.2	20.9	87.5
	473	473	0.41	489	538	15.8	21.9	85.3



*HAZ / WM : V-notch position were too close to WM.

Fig. 3. The Charpy-impact value of unirradiated and irradiated 316L SS base metal and WMs.

base metal. The base metal, TIG and EB specimens also fractured in a ductile manner.

On the other hand, MAG–WM exhibited extremely low impact values and lateral expansion, like a brittle material. From SEM observations of the fracture surface for the MAG specimen, there were a number of fine non-metallic inclusions in the bottom of small dimples. From the results of EPMA observations of unirradiated specimens, it was found that the inclusions contain titanium, aluminum, silicon and oxygen. In general, some fine oxide ceramics particles, like titanium dioxide, alumina and silica, are added to the MAG welding rod as a flux. The particles may have been left in the WM.

4. Conclusions

The results obtained from this study are as follows:

1. Neutron irradiation up to 0.5 dpa at 473 K caused considerable irradiation hardening and degradation of ductility for base metal and welded joints. However, all specimens except MAG–WM showed sufficiently large RA and impact values. The specimens fractured in a ductile manner.
2. The dpa dependences of the YS increase and the YS values of the base metal have almost the same trend as that in the literature.
3. The RA values of MAG–WM specimens were slightly lower than those of other materials. The extremely

low impact values of MAG–WM were attributed to non-metallic inclusions added as a flux.

4. It seems that the soundness of the base metal of 316L SS and its TIG and EB welded joints are retained after 0.2–0.5 dpa neutron irradiation. However, it seems rather difficult to adopt MAG welding for the fabrication of the VV.

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