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Journal of Nuclear Materials 373 (2008) 212–216

journal of nuclear materials

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Effect of re-irradiation by neutrons on mechanical properties of un-irradiated/irradiated SS316LN weldments

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Received 19 February 2007; accepted 21 May 2007

Abstract

Stainless steel of type SS316LN-IG (ITER Grade) is used for the branch pipeline connecting of the module coolant system and for other structures of ITER. One of the most important requirements for the branch pipeline connection is to recover various defects by welding. In the present study, characteristics of irradiated weldments were evaluated. SS316LN-IG specimens irradiated to helium contents of 3 and 10 appm He were prepared by the first neutron irradiation. Thereafter, the SS316LN-IG specimens with three different combinations of un-irradiation and irradiation were welded by a tungsten inert-gas (TIG) welding method. These weldments were re-irradiated at 150 °C up to a fast neutron fluence of about 7.5×10^{24} n/m^2 ($E > 1$ MeV). Tensile tests of the weldments and the base material were carried out at 20 and 150 °C after the re-irradiation. The results of the comparison before and after the re-irradiation showed that tensile properties of all weldment specimens with the different combinations were almost the same as those of the base materials.

1. Introduction

Austenitic stainless steel of type SS316LN-IG (IG means ITER grade) is a candidate material for structural materials for ITER (International Thermonuclear Experimental Reactor) [1]. Rewelding of irradiated materials has a large impact on the design and the maintenance scheme of in-vessel components of ITER [2].

Recently, joining technology of irradiated structural materials has been developed using the methods of tungsten inert-gas (TIG) welding [3,4], laser welding [5–7] and electron beam (EB) welding [8]. Helium atoms are one of the most prominent transmutation products to be generated in austenitic stainless steels because of a considerably large cross-section of Ni for (n, α) reaction by high-energy neutrons in a fusion reactor [9].

For neutron irradiation of stainless steels, it is thermodynamically favorable for entrapped helium to precipitate as bubbles at relatively low temperatures below about 400 °C. Formation of bubbles at grain boundaries could ultimately lead to drastic changes of macroscopic properties, including severe embrittlement at elevated temperatures. At high temperatures (above ∼600 °C), these bubbles will grow under the influence of stress and temperature [9–11]. Welding processes produce internal stresses and temperature rise.

In the present study, un-irradiated and irradiated SS316LN-IG weldments were irradiated in the Japan Materials Testing Reactor (JMTR), and the effects of re-irradiation of neutrons on mechanical properties of the weldments were evaluated.

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0022-3115/$ - see front matter
doi:10.1016/j.jnucmat.2007.05.046

2. Experimental

A flow chart of the re-weldability test and the re-irradiation test in this study is given in Fig. 1. Two kinds of SS316LN-IG specimens were used. One was SS316LN-IG (JA: Japan) of the Japanese Industrial Standard (JIS) grade, which was fabricated by the Japan Steel Works, LTD. The other was SS316LN-IG (EU: European Union), which was fabricated by an EU company. Chemical compositions and mechanical properties of SS316LN-IG(JA) and SS316LN-IG(EU) are shown in Table 1 [12]. These specimens were irradiated in JMTR (as the first neutron irradiation test) for preparation of irradiated materials for weldments. Dimensions of samples for the first neutron irradiation are shown in Fig. 2. The fast neutron and thermal neutron fluences were about 2.0×10^{24} and 5.0×10^{24} n/m^2, respectively. The irradiation temperature was about 150 °C. The detail irradiation conditions in the first irradiation were already described in Ref. [12].

A TIG welding procedure with remote operation was adapted for preparation of weldment specimens in the JMTR hot cell. Procedures of the TIG welding were also described in Ref. [12]. The TIG welding with different heat inputs was carried out on both sides of the SS316LN-IG samples.

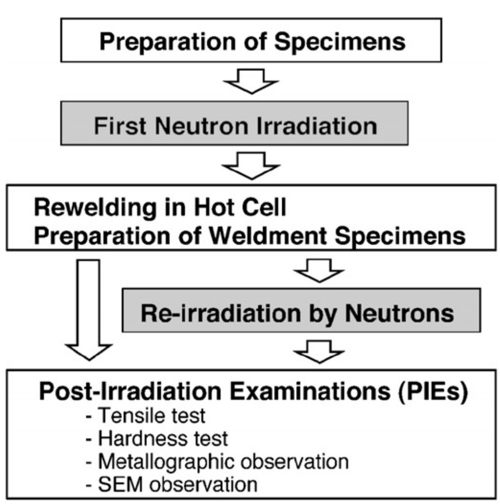

Fig. 1. Flow chart of re-weldability test and re-irradiation test.

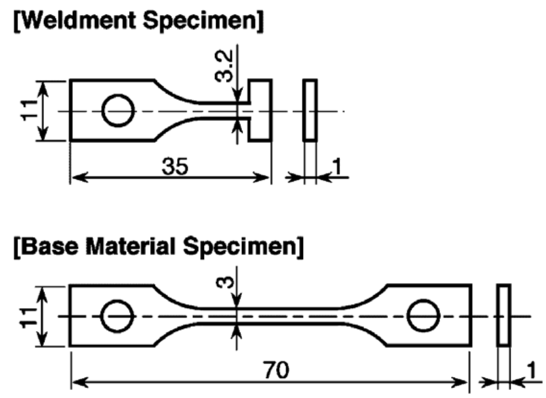

Fig. 2. Dimensions of SS316LN samples for the first neutron irradiation.

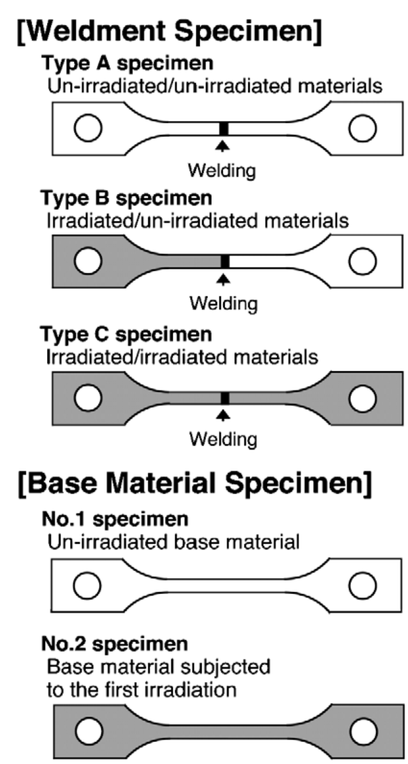

Fig. 3. Configuration of irradiation specimens for the re-irradiation.

Three kinds of weldment and base material specimens (see Fig. 3) were irradiated in JMTR for the re-irradiation of neutrons. Irradiation temperatures were calculated by

Table 1
Chemical compositions and mechanical properties of SS316LN-IG [12]

	Ultimate tensile strength (UTS) (MPa, 20 °C)			0.2% Yield strength (0.2%YS) (MPa, 20 °C)			Total elongation (TEL) (%, 20 °C)		
Mechanical properties									
SS316LN-IG(JA)	583			269			46		
SS316LN-IG(EU)	590			300			54		
Chemical composition (wt% except for B)									
	Cr	Ni	Fe	Mo	Mn	C	Co	N	B (ppm)
SS316LN-IG(JA)	17.45	12.24	Bal.	2.66	1.64	0.023	0.02	0.075	3.4
SS316LN-IG(EU)	17.15	12.19	Bal.	2.38	1.75	0.020	0.079	0.077	11.8

the GENGTC code [13], and the temperature at the center of tensile specimens was about 150 °C from the calculation. The neutron fluence was measured by fluence monitors, and the maximum value of the fast neutron fluence (>1 MeV) was 7.5×10^{24} n/m^2, which corresponds to a displacement damage of 1.0 dpa. The concentration of helium, which was generated by (n, α) reaction of boron, in the irradiated material was calculated by a Monte-Carlo code (MCNP) [14]. It is estimated that all the boron which had remained in the material after the first irradiation was burned up in the re-irradiation.

After the re-irradiation, tensile tests were performed in air at two temperatures, room temperature (about 20 °C) and 150 °C (the irradiation temperature). A crosshead speed of 0.1 mm/min was used below the 0.2% yield strength (0.2%YS) and 1 mm/min above this strength. The 0.2%YS, ultimate tensile strength (UTS) and total elongation (TEL) were measured in these tensile tests.

3. Results and discussion

3.1. Preparation of weldment specimens

A photograph of weldment specimens in metallographic observation is given in Fig. 4. This figure shows that no cracking occurred in the heat affected zone (HAZ) nor in the fusion zone. Fig. 5 shows the result of weldability in this study. A relationship between helium content in irradiated stainless steel (SS304 and SS316L) and weld heat input in a TIG welding method was reported by Asano et al. [15,16]. The weldability for SS316LN-IG using the TIG welding method in the present study is consistent with the reference data.

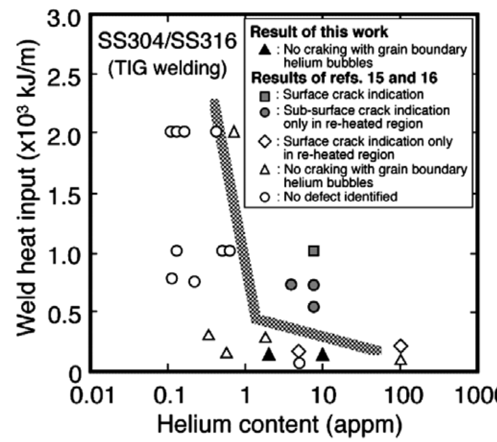

Fig. 5. Dependence of the character of weld-induced defects on helium content and weld heat input.

3.2. Mechanical properties

Typical stress–strain curves of weldment specimens of SS316LN-IG(JA) before and after the re-irradiation are shown in Fig. 6. Results of the tensile tests of the weldment specimens are summarized in Fig. 7. Tensile properties of the irradiated base materials (SS316LN-IG(JA) and SS316LN-IG(EU)) were obtained and are shown in Table 2. In these tensile tests, all types of the weldment specimens fractured in the base material after the re-irradiation.

The ultimate tensile strength (UTS) of all type specimens (Type-A, Type-B and Type-C) using SS316LN-IG(JA) and SS316LN-IG(EU) were about 730 and 740 MPa, respectively, at 20 °C. These values agree with those of the base material specimens which were irradiated in the re-irradia-

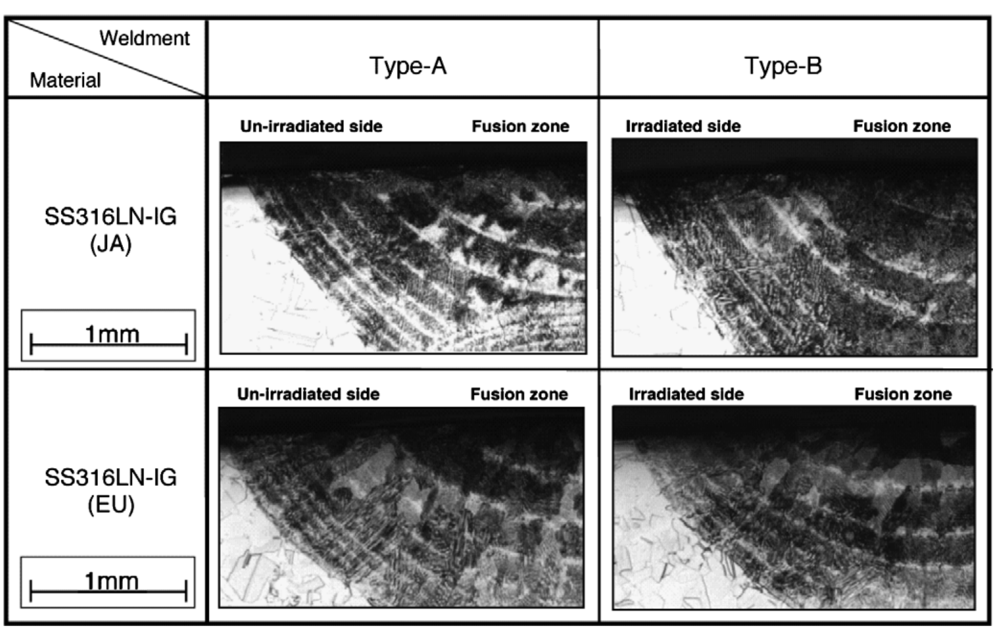

Fig. 4. Metallographical observation near the butt position of weldment specimens.

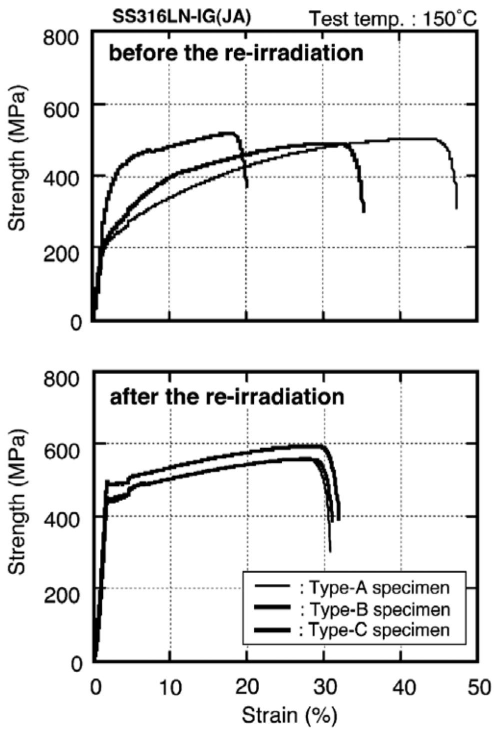

Fig. 6. Tensile strain–stress curves of SS316LN-IG(JA) at 150 °C before and after the re-irradiation.

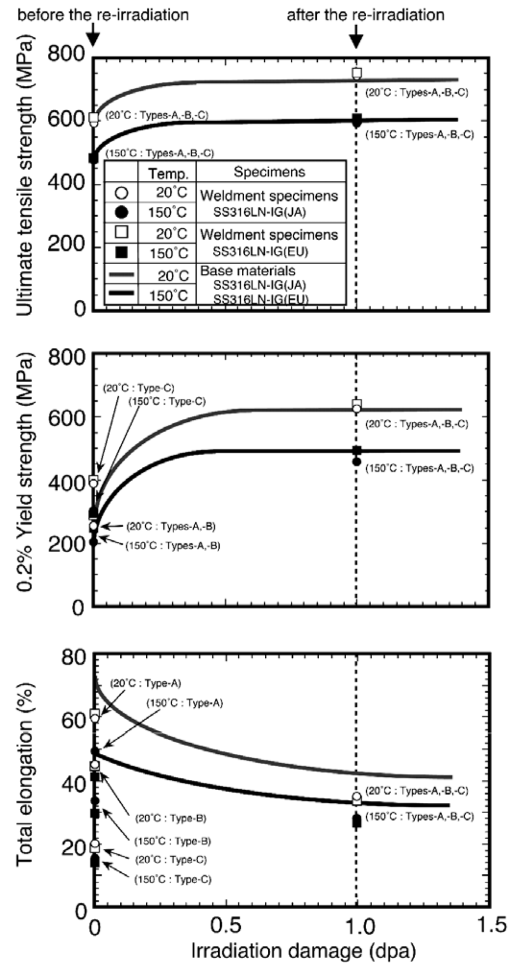

Fig. 7. Results of tensile tests of weldment specimens before and after the re-irradiation.

tion test, within a difference of 5%. The UTS values of all types of specimens using SS316LN-IG(JA) and SS316LN-IG(EU) were about 565 and 590 MPa, respectively, at 150 °C. These values also agreed with those of the base material specimens within a difference of 5%. The 0.2%YS values of all weldment specimens were almost the same as those of the base material specimens. It is considered that irradiation defects created in the first irradiation were recovered by the fusion process of the TIG welding, and that irradiation defects were re-created during the re-irradiation.

The total elongation (TEL) was different for weldment specimens (Type-A, Type-B, Type-C) before the re-irradiation. However, the TEL of these specimens was almost the same after the re-irradiation. The TEL of Type-A and Type-B specimens decreased by the re-irradiation. The main elongated part of Type-A and Type-B specimens was the un-irradiated part in the weldment specimens before the re-irradiation. This part became brittle and the TEL of Type-A and Type-B specimens was decreased by the re-irradiation. On the other hand, the TEL of Type-C specimens was increased by the re-irradiation.

It is believed that TEL of Type-C specimens before the second irradiation depended on the strength of the fusion

Table 2
Results of tensile tests of SS316LN-IG base materials before and after the re-irradiation

Material	Specimen	Temperature (°C)	Before re-irradiation			After re-irradiation		
			UTS (MPa)	0.2%YS (MPa)	TEL (%)	UTS (MPa)	0.2%YS (MPa)	TEL (%)
SS316LN-IG(JA)	No. 1	20	590	247	73.0	753	605	44.6
		150	480	180	48.3	590	461	37.2
	No. 2	20	707	554	53.0	737	606	41.7
		150	585	456	41.3	595	482	35.2
SS316LN-IG(EU)	No. 1	20	599	292	73.0	738	617	44.1
		150	485	234	48.3	597	498	35.0
	No. 2	20	726	601	48.3	745	631	42.9
		150	586	479	37.4	612	510	33.9

UTS: ultimate tensile strength, 0.2%YS: 0.2% yield strength, TEL: total elongation.

zone metal. All parts of the Type-C specimen changed into irradiated material after the re-irradiation, and the Type-C specimen was elongated not only in the fusion zone but also in the base material. Thus, the increase in the TEL of the Type-C specimen was caused by the increase in the size of the effective gage section for the re-irradiation specimens.

The TEL of weldment specimens was lower than that of the base material. The fusion zone in the weldment specimens was hardened by the residual stress formed during quenching in the welding process, and this part was hardly elongated compared with the part of the base material. Tensile properties of the weldment specimen were almost the same as those of the base materials irradiated to 1.0 dpa, except for total elongation. Further, tensile tests of weldment specimens irradiated to more than 0.3 dpa are necessary to clarify the mechanical properties of weldment specimens.

4. Conclusions

The base material specimens and the three types of weldment specimens (see Fig. 3) were irradiated in JMTR up to a fast neutron fluence of about 1.0 dpa at about 150 °C, and the effect of the re-irradiation on tensile properties of the weldment specimens was examined.

The weldment specimens fractured in the part of the base materials, and the tensile properties of all weldment specimens were almost the same as those of the base material specimens after the re-irradiation test. The combination of the different patterns of un-irradiated and irradiated weldments did not influence the tensile strength. The results of the comparison before and after the re-irradiation showed within the present experiment range that the neutron irradiation effect on the tensile properties (UTL, 0.2%YS and TEL values) of the weldment specimens of SS316LN-IG(JA) and (EU) was almost the same, and that the effect was also the same as that of the base materials irradiated to about 1.0 dpa.

Acknowledgement

The authors wish to thank Dr K. Yamada of Kawasaki Plant Systems, Ltd. (a former member of JAEA), for his help in post-irradiation examination (PIE) and discussion on PIE results. The authors also wish to thank Dr K. Hayashi of JAEA for his helpful advice in preparing the present paper.

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