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Re-weldability tests of irradiated austenitic stainless steel by a TIG welding method

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Abstract

Austenitic stainless steel (SS) is widely used for the in-vessel and ex-vessel components of fusion reactors. In particular, SS316L(N)-IG (IG-ITER Grade) is used for the vacuum vessel (VV), pipe lines, blanket modules, branch pipe lines connecting the module coolant system with the manifold and for the other structures of ITER. One of the most important requirements for the VV and the water cooling branch pipelines is the possibility to repair different defects by welding. Those components which may require re-welding should be studied carefully. The SS re-weldability issue has a large impact on the design of in-vessel components, in particular, the design and efficiency of radiation shielding by the modules. Moreover, re-welded components should operate for the lifetime of the reactor. This paper deals with the study of re-weldability of un-irradiated and/or irradiated SS316L(N)-IG and the effect of helium generation on the mechanical properties of the weld joint. Tungsten inert gas (TIG) welding was used for re-welding of the SS.

1. Introduction

Austenitic stainless steel (SS) (SS316L(N)-IG) is used widely as a structural material in international thermonuclear experimental reactor (ITER). When SS316L(N)-IG is irradiated by neutrons, helium accumulates in the steel due to the high cross-section of the (n,α) nuclear reaction [1,2]. Helium is essentially insoluble in metals [3,4]. The presence of helium in the irradiated steel results in defect formation (bubbles, pores, cracks, etc.) because heating of stressed regions in the welds accompanies the re-welding [5,6].

In this study, un-irradiated and/or irradiated SS316L(N)-IG welds were fabricated by the tungsten inert gas (TIG) welding method, and the effect of helium generation on mechanical properties of the weld joint was evaluated.

2. Experimental

The flow chart of the re-weldability test is shown in Fig. 1. Specimens irradiated in the Japan materials testing reactor (JMTR) were welded by the TIG welding method. After welding, the specimens were machined and tensile tests of the weldments performed.

2.1. Materials

Two SS316L(N)-IG grades with different boron contents were used in this study. The SS316L(N)-IG(JA) was fabricated by the Japan steel works and SS316L(N)-IG(EU) was fabricated by Creusot–Loire Industrie. The chemical composition and mechanical properties of the steels are shown in Table 1. Two kinds of specimens were prepared and the dimension of these specimens is given in a previous paper [7].

2.2. Irradiation conditions

Neutron irradiation of the specimens for re-welding was carried out in the JMTR. The fast-neutron fluence ($E > 1$ MeV), as determined by fluence monitors

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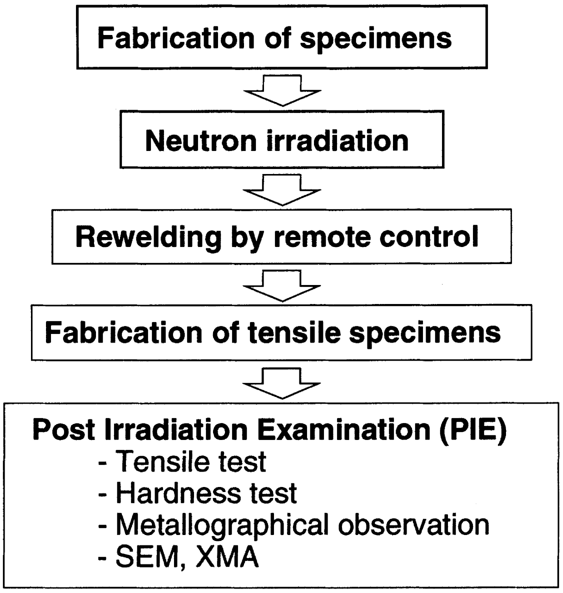

Fig. 1. Flow chart of re-weldability test.

(Fe wire) inserted in the irradiation capsules, was about 2.0×10^{20} n/cm^2, corresponding to a dose of approximately 0.3 dpa. The thermal neutron fluence, as determined by fluence monitors (Al–Co wire), was $\sim5.0\times10^{20}$ n/cm^2 ($E<0.68$ eV). The irradiation temperature of the specimens for re-welding was about 150°C, which was calculated by the GENGTC code.

2.3. Welding procedure

TIG welding procedures was adapted for remote operation. The butt-welding was carried out on both sides of the specimens and three combinations of weldments, un-irradiated/un-irradiated (Type A), irradiated/un-irradiated (Type B) and irradiated/irradiated (Type C), were prepared. No filler metal was applied. The welding current was selected using the irradiated/un-irradiated and irradiated/irradiated specimens and welding heat input was calculated between 1 and 2 kJ/cm. The manufactured welds were machined remotely to prepare the specimens for tensile tests.

2.4. Testing procedures

Tensile tests were carried out on the three combinations of weldments. The tests were performed in air at 20°C and 150°C. The fracture surfaces after tensile testing were observed by a scanning electron microscope (SEM). Hardness tests were carried out on the three combinations of weldments in air at room temperature. Hardness was measured with a Knoop indenter using a Vickers microhardness tester. The structures of the weldments were examined by optical microscopy using a metallographic section transverse to the weld direction.

3. Results and discussion

3.1. Estimation of helium generation

Calculated values of helium generation in the steels 316L(N)-IG(JA) and 316L(N)-IG(EU), due to the (n,α) reactions is shown in Table 2. This calculation was

Table 2
Calculated values of helium generation

	Amount of He generation (appm)	
	SS316L(N)-IG(JA)	SS316L(N)-IG(EU)
Fe(n,α)	6.7×10^{-2}	6.7×10^{-2}
Ni(n,α)	8.5×10^{-2}	8.5×10^{-2}
Cr(n,α)	9.7×10^{-3}	9.6×10^{-3}
Mn(n,α)	7.8×10^{-4}	8.3×10^{-4}
^{58}Ni(n,γ)^{59}Ni(n,α)	2.2×10^{-1}	2.2×10^{-1}
^{10}B(n,α)	3.0	10
Total He generation (appm)	3.4	11

Table 1
Chemical compositions and mechanical properties of SS316L(N)-IG(JA) and SS316L(N)-IG(EU)

	Tensile strength (MPa, 20°C)			Yield strength (MPa, 20°C)			Elongation (%, 20°C)		
Mechanical properties									
316L(N)-IG(JA)	583			269			46		
316L(N)-IG(EU)	590			300			54		
Chemical composition (*wt% except for* B)									
	Cr	Ni	Fe	Mo	Mn	C	Co	N	B (ppm)
316L(N)-IG(JA)	17.45	12.24	Bal.	2.66	1.64	0.023	0.02	0.075	3.4
316L(N)-IG(EU)	17.15	12.19	Bal.	2.38	1.75	0.020	0.079	0.077	11.8

performed on the basis of the neutron spectrum of the JMTR [8]. From this result, it can be concluded that the amount of helium generation by the $^{58}Ni(n,\gamma)$ $^{59}Ni(n,\alpha)^{56}Fe$ reaction was smaller than that by the $^{10}B(n,\alpha)^{7}Li$ reaction for one duty cycle of the JMTR, and the total amount of helium generation in SS316L(N)-IG(JA) and SS316L(N)-IG(EU) were about 3.4 and 11 appm, respectively.

3.2. Mechanical properties

Tensile test results are summarized in Table 3. Tensile test results of the irradiated and un-irradiated base metals are also carried out as a reference test, and the results are also shown in Table 3.

The tensile strength of weldments of both type A and type B was about 600 MPa at 20°C and the strength was

Table 3
Tensile test results

Material	Specimen	Test temperatures (°C)	Tensile strength (MPa)	Fracture point
SS316L(N)-IG(JA)	Base metal	20	590	–
	(Un-irradiated)	150	480	–
	Base metal	20	707	–
	(Irradiated)	150	585	–
	Type A[a]	20	605	Un-irradiated base metal
		150	504	Un-irradiated base metal
	Type B[b]	20	625	Un-irradiated base metal
		150	496	Un-irradiated base metal
	Type C[c]	20	642	HAZ
		150	519	HAZ
SS316L(N)-IG(EU)	Base metal	20	599	–
	(Un-irradiated)	150	485	–
	Base metal	20	726	–
	(Irradiated)	150	586	–
	Type A	20	602	Un-irradiated base metal
		150	498	Un-irradiated base metal
	Type B	20	610	Un-irradiated base metal
		150	498	Un-irradiated base metal
	Type C	20	640	HAZ
		150	533	HAZ

[a] Three combinations of weldments: Type A: un-irradiated/un-irradiated.
[b] Type B: irradiatted/un-irradiated.
[c] Type C: irradiated/irradiated.

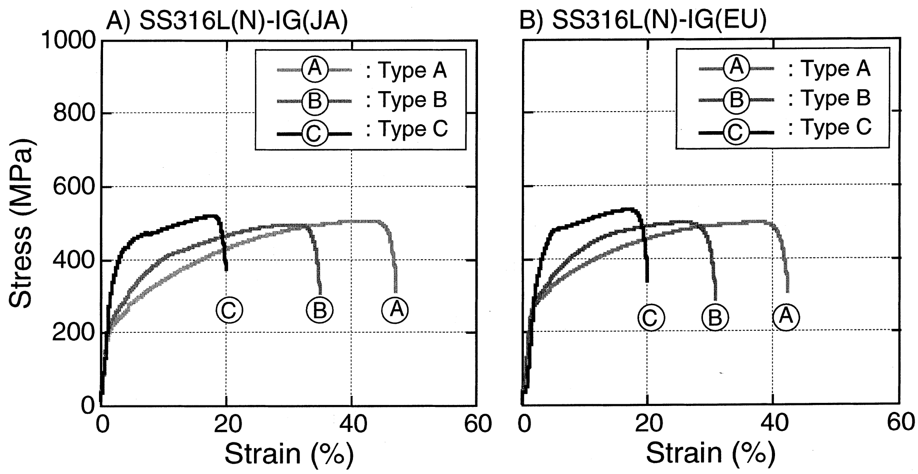

Fig. 2. Tensile stress–strain curves of SS316L(N)-IG(JA) and SS316L(N)-IG(EU) at 150°C.

almost the same as the un-irradiated base metal. Welds of both type A and type B were fractured in the un-irradiated base metal. Strain–stress curves of SS316L(N)-IG(JA) and SS316L(N)-IG(EU) welds at 150°C are shown in Fig. 2. The tensile strength of type A and type B was about 500 MPa at 150°C and the strength was similar to that of the un-irradiated base metal. Again, the weldments of both type A and type B were fractured in the un-irradiated base metal. SEM observations of fracture surfaces of the welds after the tensile test are shown in Fig. 3. The main fracture mode of these specimens was ductile.

The hardness distributions for welds of type C are shown in Fig. 4. The hardness of weld metal was lower than that of irradiated base metal. The tensile strength of type C welding was about 640 and 520 MPa at 20°C and 150°C, respectively. These strengths were smaller than that of the irradiated base metal at each tempera-

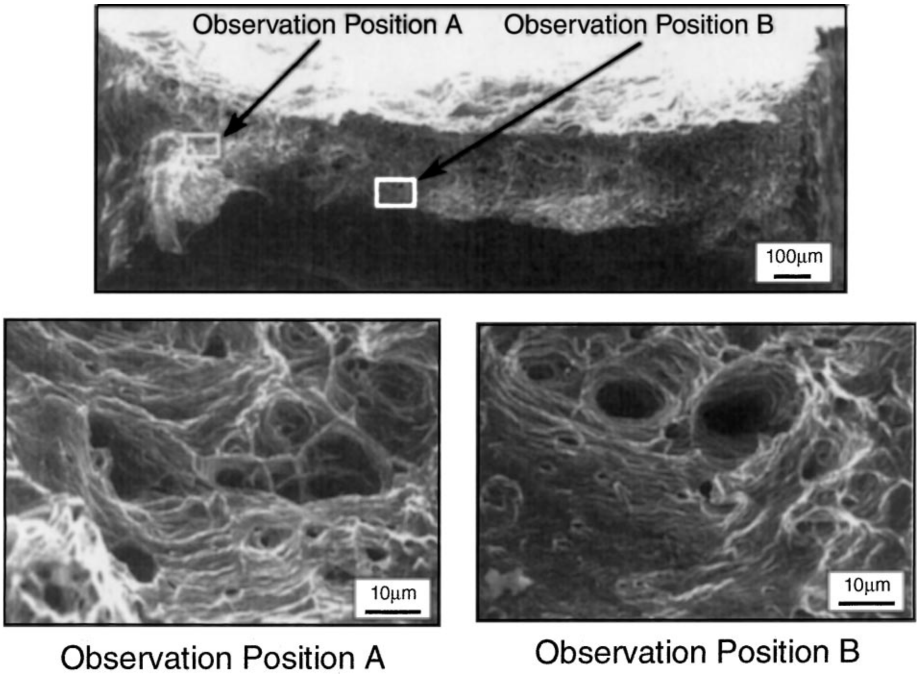

Fig. 3. SEM micrographs of fracture surfaces of irradiated/un-irradiated weldment (SS316L(N)-IG(JA)) after tensile testing at 150°C fractured in un-irradiated base material.

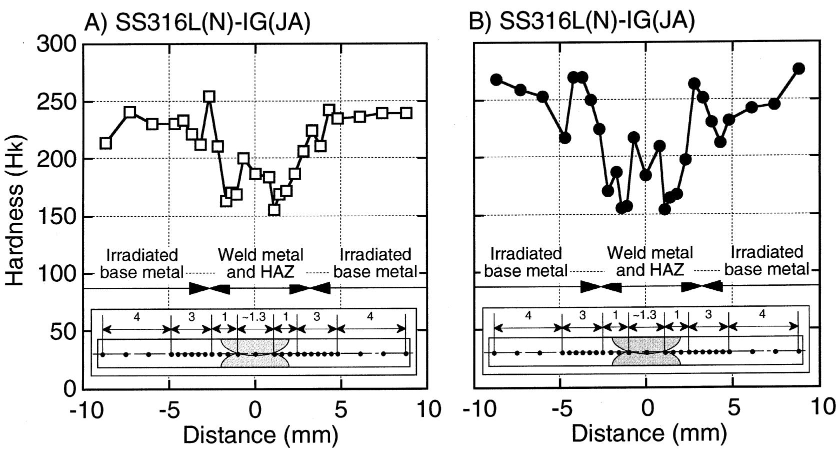

Fig. 4. Hardness distributions for weldments of irradated/irradiated SS316L(N)-IG(JA) and SS316L(N)-IG(EU) with a sketch showing the measuring points.

ture, and the type C fractured at the weld metal or heat affect zone (HAZ). The fracture location correlates with the low hardness region of the welds.

Lin et al. [5] reported that intergranular cracking occurred even in specimens containing 2.5 appm He by the tritium trick technique. Asano et al. [9] showed the reduction of tensile strength in welded SS304 tube containing 5 appm He. In this study, no cracking occurred in the welds of type C and the welds had almost the same tensile strength as un-irradiated base metal. It seems that the higher irradiation temperature, heat sinking by the jig and constraint of the welding specimens have an effect on crack growth and strength reduction in weldments.

4. Conclusion

In the re-weldability tests of SS316L(N)-IG(JA) and SS316L(N)-IG(EU), the tensile strength of irradiated/un-irradiated welds (type B) was approximately equal to that of the un-irradiated base metal and the main fracture mode was ductile. It was shown that re-welding between irradiated and un-irradiated SS316LN-IG (type B) can be successfully carried out up to about 10 appm He. The weldments of irradiated/irradiated welds (type C) were fractured at the weld metal or in the HAZ. Fracture always took place in the softest (not hardened due to irradiation) part of the welds. In the future, the re-welding specimens made of SS316LN-IG will be irradiated in JMTR to a fast-neutron fluence of 0.8–1.0 dpa at about 150°C.

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