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Re-weldability tests of irradiated 316L(N) stainless steel using laser welding technique

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Abstract

SS316L(N)-IG is the candidate material for the in-vessel and ex-vessel components of fusion reactors such as ITER (International Thermonuclear Experimental Reactor). This paper describes a study on 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. The laser welding process is used for re-welding of the water cooling branch pipeline repairs. It is clarified that re-welding of SS316L(N)-IG irradiated up to about 0.2 dpa (3.3 appm He) can be carried out without a serious deterioration of tensile properties due to helium accumulation. Therefore, repair of the ITER blanket cooling pipes can be performed by the laser welding process.

1. Introduction

One of the most important requirements for the water cooling branch pipelines in ITER is repairability of different types of defects by welding. Those components that 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 be operated for the lifetime of the reactor.

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]. The estimated helium production at the in situ welding joints of the ITER blanket cooling pipes are 3.3 appm He for the neutron fluence of about 0.2 dpa. 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 the heating of stressed regions in the welds accompanied the re-welding [5,6].

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

2. Experimental

2.1. Materials

About SS316L(N)-IG, SS means stainless steel, and IG means ITER Grade. The chemical composition of SS316L(N)-IG is shown in Table 1. In this study, two types (plate type: L35 mm × W15 mm × 3 mm and tube type: OD48 mm × ID42 mm) of specimens were prepared.

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Table 1
The chemical composition of SS316L(N)-IG (wt%)

	C	Mn	Si	P	S	Cr	Ni	Mo	Nb	Cu	Co	N	B (ppm)
Standard	0.015 – 0.03	1.6 – 2.0	– 0.5	– 0.025	0.005 – 0.010	17.0 – 18.0	12.0 – 12.5	2.3 – 2.7	– 0.15	– 0.3	– 0.25	0.06 – 0.08	– 20
Actual	0.029	1.64	0.44	0.012	0.009	17.48	12.11	2.56	0.067	0.07	0.02	0.067	3

2.2. Irradiation conditions

These specimens were irradiated for one cycle operation (25%) at the beryllium reflector of the first layer in the JMTR (Japan Materials Test Reactor). Neutron fluence was determined by fluence monitors (Fe wire), and the maximum value was 2.0×10^{20} n/cm^2 ($E > 1$ MeV), corresponding to a displacement dose of approximately 0.20 dpa. The helium generation was calculated by MCNP code and was about 2.5 appm. The thermal neutron fluence was presumed to be 4.2×10^{20} n/cm^2 (maximum value) and actual neutron fluence which was determined by fluence monitors (Al–Co wire) was a maximum of 3.8×10^{20} n/cm^2 ($E < 0.68$ eV).

After the irradiation test, the helium content in the plate specimen was measured. It was 3.3 appm and this was almost the same as the result of calculation. Irradiation temperature of the specimens was calculated by the ABAQUS code and it was 150–200 °C.

2.3. Welding procedure

YAG laser welding was carried out in a hot cell by remote operation. The YAG laser welding apparatus is shown in Fig. 1. Three types of specimens were employed for laser welding (un-irradiated/un-irradiated (Type A), irradiated/un-irradiated (Type B), and irradiated/irradiated (Type C)) specimens were prepared without filler metal. The power and welding speed of laser welding were selected using the Type A specimens and final confirmation of laser welding conditions was performed by Type C specimens. Results of the final confirmation test of laser welding conditions are shown in Fig. 2. Cracking did not occur in the heat affected zone (HAZ) and in the zone between the melted material and the HAZ. For un-irradiated/irradiated joints of tube, some helium bubbles were observed by SEM observation at near the welding joint position (Fig. 3). But, they were very small, so it was considered that they had no effect on tensile properties. Finally, laser power was 1 kW, welding speed was 0.5 m/min, and welding heat input was calculated as 1.2 kJ/cm. About the restriction method of specimen, plate specimen was just set to welding jig, then there is almost no force to set on welding and tube specimen was fixed by spring jig for setting each axis of tube on straight. The force to fix tube specimens was about 20 kgf.

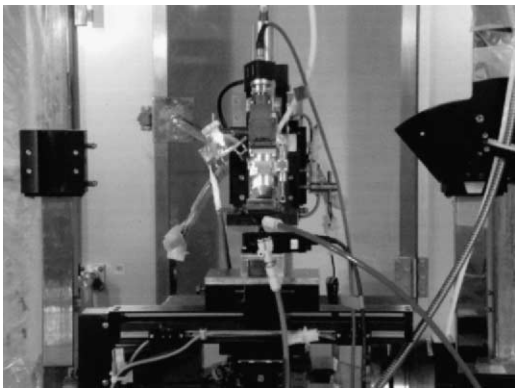

Fig. 1. YAG laser welding apparatus.

2.4. Testing procedures

Tensile tests were carried out on the irradiated and un-irradiated base materials, and three combinations of weldments. The tests were performed in air at two temperatures, 20 °C and irradiation temperature (200 °C) and tensile test of un-irradiated specimens without welding were performed at 20, 150 and 300 °C. The cross-head speed was 0.5 mm/min (strain rate was 2%/min). Total elongation was measured on enlarged images of the tested specimens. The fracture surfaces after tensile tests were observed with a scanning electron microscope (SEM). The microstructures of the weldments were examined by preparing a metallographic section transverse to the welded direction so that welding conditions could be evaluated. The sections were electrochemically etched by HNO_3 after polishing. Hardness was measured with a Knoop indenter using a Vickers microhardness tester. The structures of the weldments were examined with an optical microscope using a metallographic section transverse to the welded direction.

3. Results and discussion

3.1. Mechanical properties

Dimensions of tensile specimens and results of tensile tests are shown in Fig. 4. The results of tensile

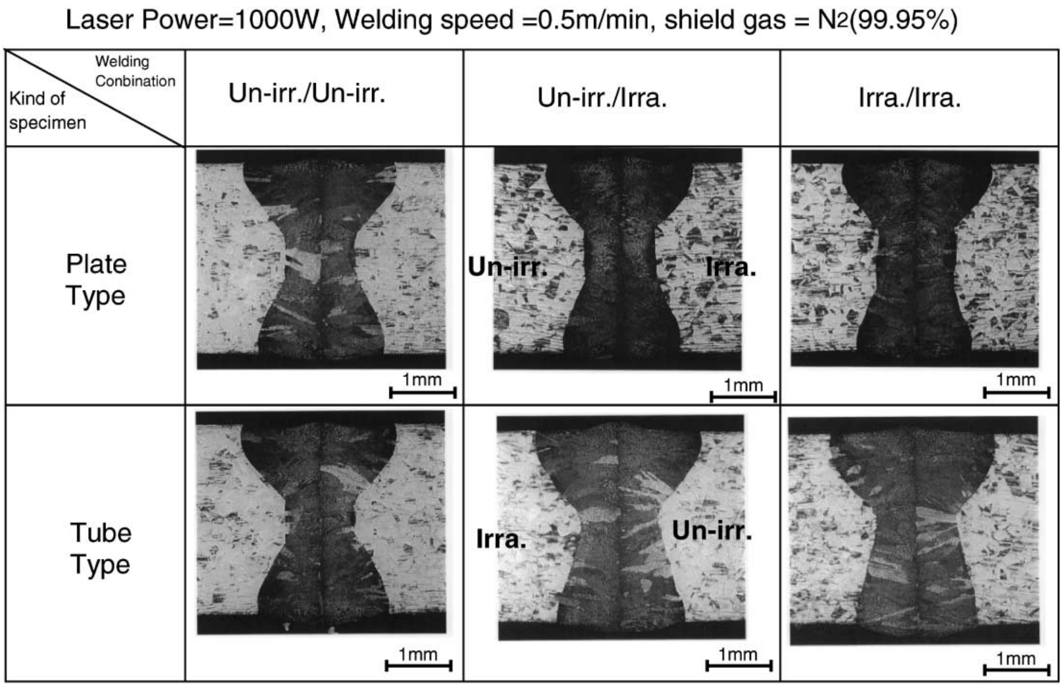

Fig. 2. The result of final confirmation test of laser welding condition.

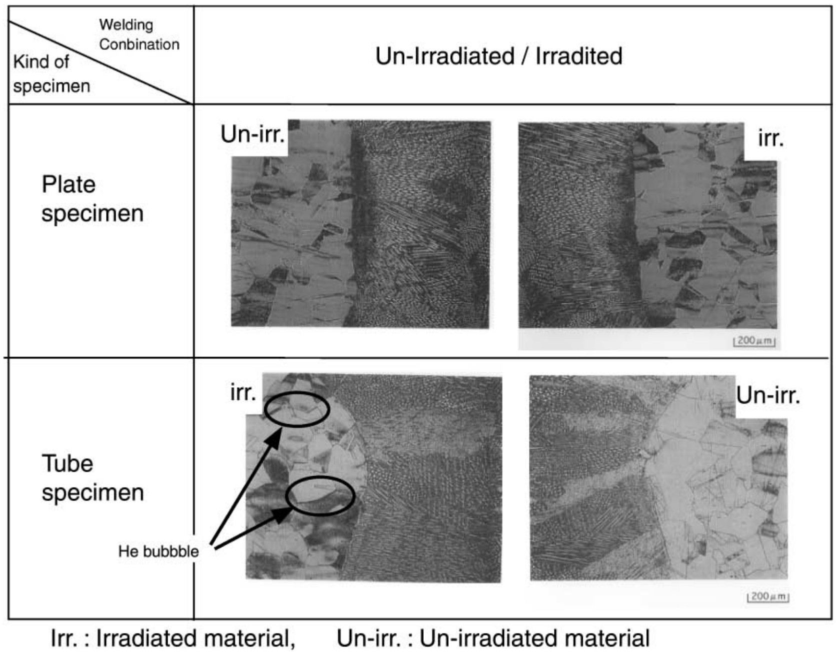

Fig. 3. Helium bubbles in near the welding joint position.

test clarified that tensile strength of all weld joints was similar to un-irradiated materials. For Type A specimens, they broke at the un-irradiated material, not welding position. For Type B specimens, they broke at the un-irradiated base material or HAZ at room temperature. On the other hand, at 200 °C, the specimens

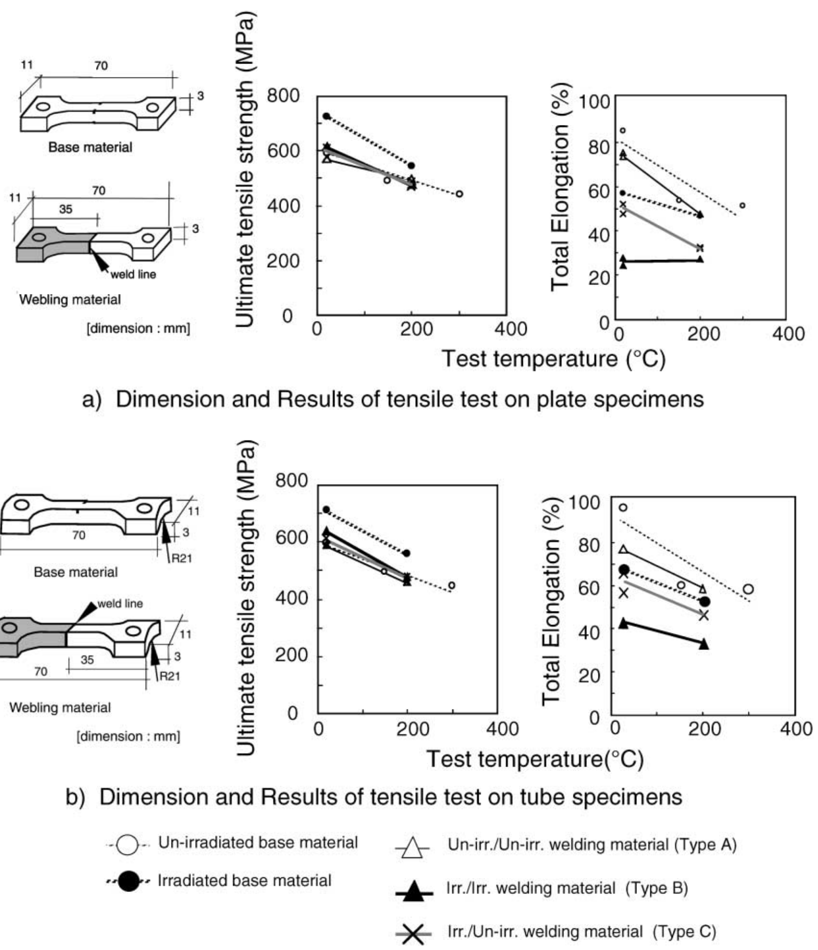

Fig. 4. Dimension of tensile specimen and result of tensile test.

broke at the HAZ of the irradiated material or un-irradiated base material. For Type C specimen, all of them broke at HAZ. The ductility of Type B (this was actual combination of un-irradiated/irradiated material at water cooling branch piping on fusion reactor repair) was almost similar to that of irradiated material (irradiation damage was about 0.2 dpa) without welding. However, it was cleared that ductility reduction by irradiation was larger than that by welding, and it was considered that ductility reduction by welding would be constant at same heat input but that by irradiation damage would be increase as the level of irradiation damage higher. Then, it is considered that ductility reduction depended on the irradiation damage rather than welding because welding condition for repair of water cooling branch piping will not change widely.

Fracture surfaces of tensile specimens by SEM observations are shown in Fig. 5. A few intergranular cracks were observed in the rupture surface of irradiated/irradiated welding specimens. The other rupture surfaces were similar and it was considered that it had transgranular fracture by dimple in fracture surface.

The hardness distributions for Types A, B, C specimens are shown in Fig. 6. The hardness of un-irradiated material was lower than that of irradiated material. The hardness of the HAZ on Type B specimen was slightly higher than that of un-irradiated material.

From these results, tensile strength of all weld joints was almost similar to that of un-irradiated materials. The points of breakage for Types A, B, C specimens were the low hardness point, the weld metal was not broken selectively. The rupture surfaces of the three types were almost transgranular fracture. Therefore welding by YAG laser did not affect the mechanical properties of un-irradiated/irradiated and irradiated/irradiated welding materials.

3.2. Observation of weld joint

After welding, Dye penetration tests for Types A, B, C specimens were carried out. Cracks were not observed

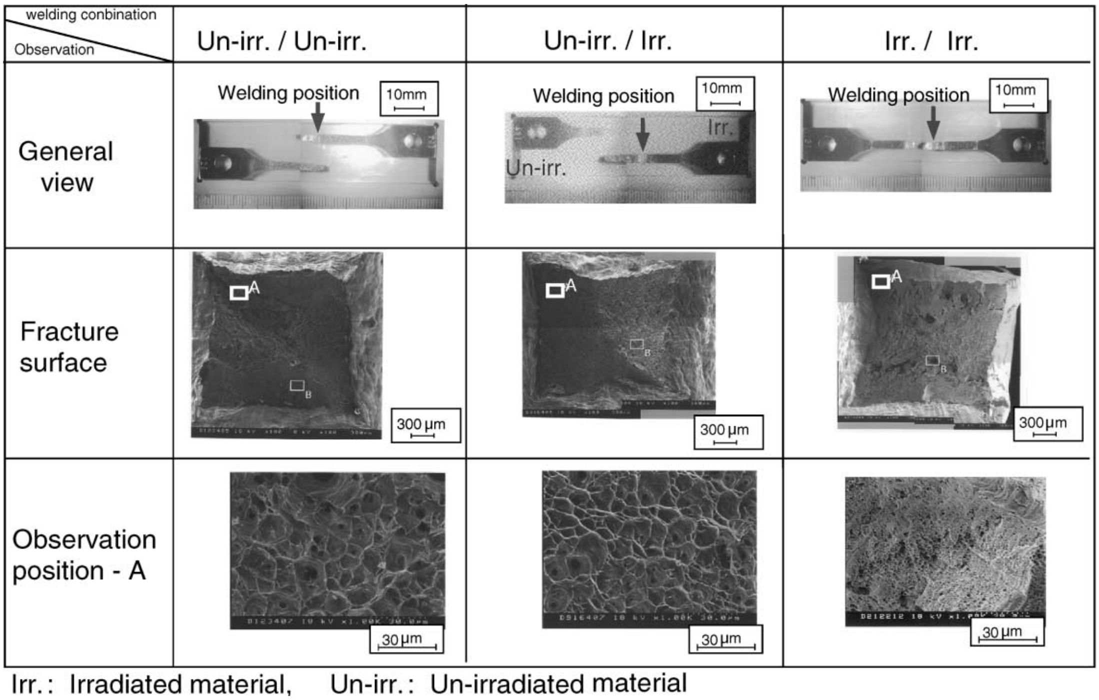

Fig. 5. The fracture surface of each specimens after tensile test.

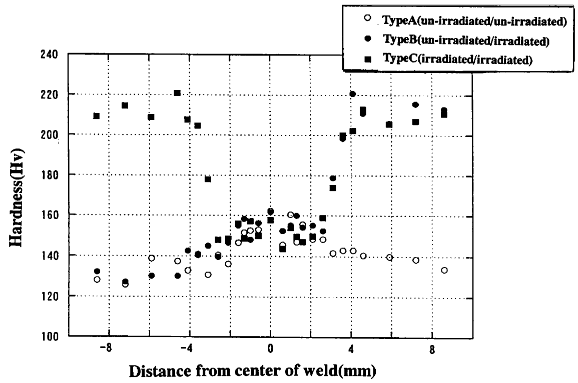

Fig. 6. Hardness distribution for Types A, B, C.

in any specimens. As reference, for TIG welding (about 3 appm helium content, about 3 kJ/cm heat input), no cracks were observed [7]. Therefore the present results are reasonable.

The results of TEM observation of the weldments are observation points shown in Fig. 7. TEM observations were done for Types A and B specimens and clarified that there were few helium bubbles to affect mechanical properties in both specimens.

In this investigation, the amount of helium generation by irradiation was small, and the results of metallographic observation showed that there were no helium bubbles that affected mechanical properties. Then, it was concluded that helium bubbles produced by welding did not affect to mechanical properties.

4. Conclusion

The results of tensile test results clarified that tensile strength of all weld joints was similar to the un-irradiated material without welding. The points of rupture were low hardness points the weld metal was not broken selectively. The ductility of material deteriorated by welding. However, it was considered that the ductility of irradiated/un-irradiated weld joints was almost similar to that of irradiated material without welding at irradiation damage was about 0.2 dpa. In the case that the irradiation damage increases, the ductility reduction would be depended on irradiation damage. Then, ductility reduction by laser welding would be not so important to the design of fusion reactor.

The rupture surfaces were almost all transgranular fracture. Therefore welding by YAG laser did not affect mechanical properties of un-irradiated/irradiated and irradiated/irradiated materials directly.

It is clarified that re-welding of SS316L(N)-IG irradiated up to about 0.2 dpa (3.3 appm He) could be carried out without a serious deterioration influence on

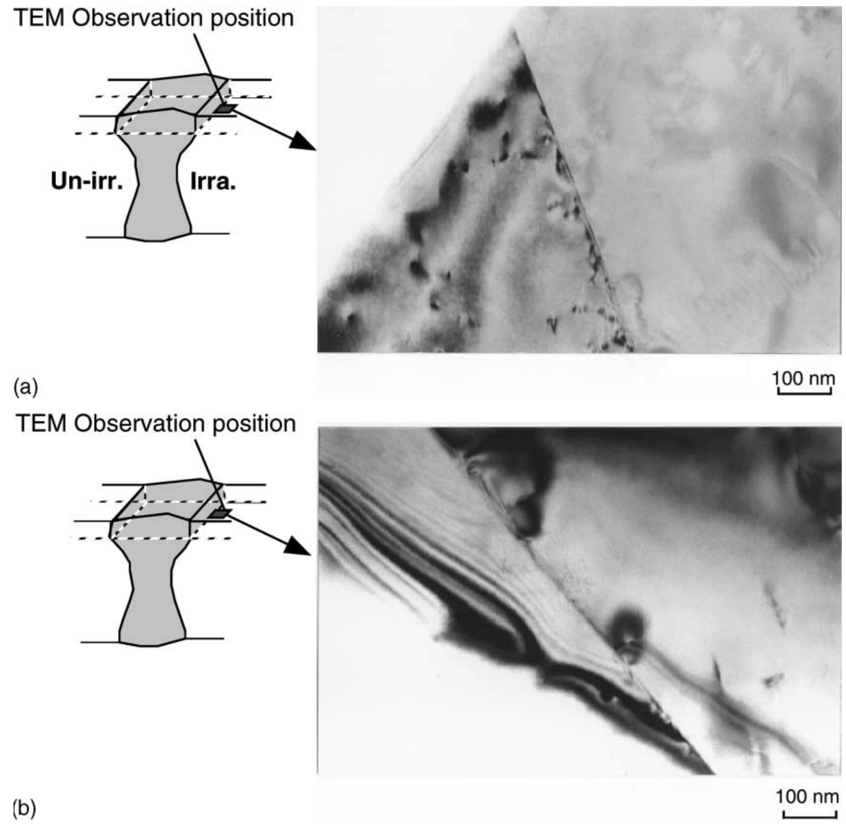

Fig. 7. The results of TEM observation to weldments. (a) Irradiated material/un-irradiated material (Type B). (b) Un-irradiated material/un-irradiated material (Type A).

tensile properties due to helium accumulation. Therefore, the re-welding of the ITER blanket cooling pipes can be performed without any degradation of material properties.

References

[1] H.R. Brager, J.L. Straalsund, J. Nucl. Mater. 46 (1973) 134.
[2] H. Ullmaier, Radiat. Eff. 78 (1983) 1.
[3] J.v.d. Driesch, P. Jung, High Temp. High Pressures 12 (1980) 635.
[4] J. Laakmann, P. Jung, W. Uelhoff, Acta Metall. 35 (1987) 2063.
[5] H.T. Lin, M.L. Grossbeck, B.A. Chin, Metall. Trans. A 21A (1990) 2585.
[6] C.A. Wang, H.T. Lin, M.L. Grossbeck, B.A. Chin, Metall. Trans. A 21A (1990) 2585.
[7] K. Asano et al., 19th International Symposium, ASTM STP 1366.