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The effect of neutron irradiation on mechanical properties of YAG laser weldments using previously irradiated material

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Abstract

The objective of this study is to make clear the effect of neutron irradiation on mechanical properties of laser weldments using irradiated material. This estimation is necessary for the application to joining coolant piping of the ITER blanket. Irradiation testing was performed at Japan Material Testing Reactor (JMTR). On the irradiation condition for weldments using irradiated material, fast neutron fluence was $1.4 \times 10^{24}\,n/m^2$, which corresponds to a displacement damage rate of 0.26 displacement per atom (dpa) and irradiation temperature 200 °C. The results of this study show that tensile properties of all weldments changed into that of base material by the effect of neutron irradiation. The results of hardness tests show that irradiation hardening at an irradiation damage dose of 0.3 dpa is almost same as that at irradiation damage 0.6 dpa. It is concluded that irradiated weldments using irradiated material were moved toward irradiated base material on tensile and hardness properties up to 0.6 dpa. On the other hand, tensile properties of base material were changed by the effect of neutron irradiation up to about 0.3 dpa, and with much less change from 0.3 dpa to 0.6 dpa. It is inferred that the effect of neutron irradiation of SS316LN-IG almost saturated up to 0.3 dpa.

1. Introduction

In a fusion reactor such as the International Thermonuclear Experimental Reactor (ITER), a blanket surrounds the plasma and protects the vessel material from high levels of nuclear radiation [1,2]. On the maintenance of the blanket, the used blanket is removed after cutting coolant piping of the blanket. After that, a new blanket is set and the coolant piping of the blanket is joined to the irradiated coolant piping by the YAG laser weld method [3]. Therefore, the coolant piping of blanket has a joint between irradiated material and un-irradiated material, and an estimation of the effect of neutron irradiation on the weldment using irradiated material is required for the estimation of the coolant piping integrity.

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Recently, joining technology with irradiated structural materials has been investigated using tungsten inert gas (TIG) welding [4–6], laser welding [6,7], and it is well known that the generation of helium degrades the properties of materials [8,9].

In this study, Irradiated material was prepared by the first irradiation test in Japan Material Testing Reactor (JMTR) and weldment specimens were fabricated by laser welding method using irradiated materials or un-irradiated materials. After the fabrication of weldment specimens, a part of weldment specimens was used for the estimation of mechanical properties and the other specimens were irradiated at second irradiation test. After that, the effect of neutron irradiation on mechanical properties of weldments using irradiated material by second irradiation test was estimated.

2. Experiment

The event sequence of this study is shown in Fig. 1. The irradiation test for the preparation of irradiated material was carried out and this test named 'the first stage irradiation test'. After the welding performance, the next irradiation test was carried out and this test named 'the second stage irradiation test'. The mechanical properties of the weldment specimens were evaluated before and after the second stage irradiation test.

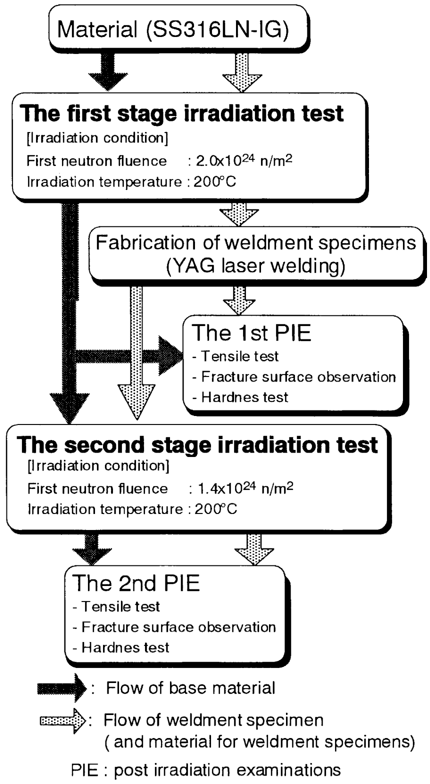

Fig. 1. Event sequence of this study.

2.1. Material and the first stage irradiation test

Type 316LN-IG stainless steel (SS316LN-IG) was used for this study. IG means that it is ITER Grade. The SS316LN-IG was fabricated by the Japan Steel Work, Ltd. The chemical composition of SS316LN-IG is shown in Table 1. The first stage irradiation test had been performed previously at JMTR. On this irradiation test, the maximum value of fast neutron fluence (>1 MeV) was $2.0 \times 10^{24}\,n/m^2$ which correspond to a maximum value of displacement damage rate of 0.32 displacement per atom (dpa), and irradiation temperature was about 200 °C. Helium content in irradiated material was measured by melting of the actual irradiated material and it was 3.3 appm.

2.2. Fabrication of weldment specimens

Three kinds of weldment specimens were fabricated in these following combinations: un-irradiated and un-irradiated materials (Type-A), un-irradiated and irradiated materials (Type-B), irradiated and irradiated materials (Type-C). Additionally, specimens of un-irradiated and irradiated base materials were also prepared for references. The dimensions of weldment specimens and base material for the second stage irradiation test are shown in Fig. 2, respectively.

All weldment specimens were fabricated by Yttrium Aluminum Garnet (YAG) laser weld methods in a hot cell by remote operation. As the processing procedure for laser welding, laser power was 1 kW (pulse laser), welding speed was 0.5 m/min and heat input was 1.2 kJ/cm. At the process of welding, materials were supported without load at the butt position to prevent the residual stress by the welding. The liquid penetration test at room temperature with dyeing penetration liquid was performed in order to confirm the macro integrity of weldment specimens and the penetration period and development period were both 15 min. It was confirmed

Table 1
Chemical composition of stainless steel SS316LN-IG (wt%)

Fe	C	Mn	Si	P	S	Cr	Ni	Mo	Nb	Cu	Co	N	B[a]
Balance	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

[a] Unit is 'ppm'.

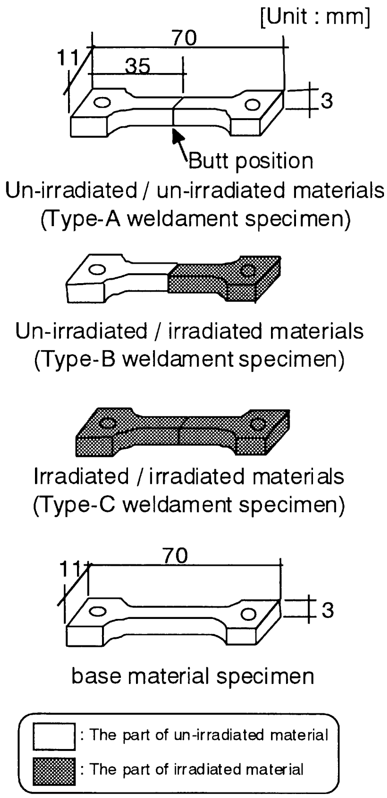

Fig. 2. Dimension of tensile specimens.

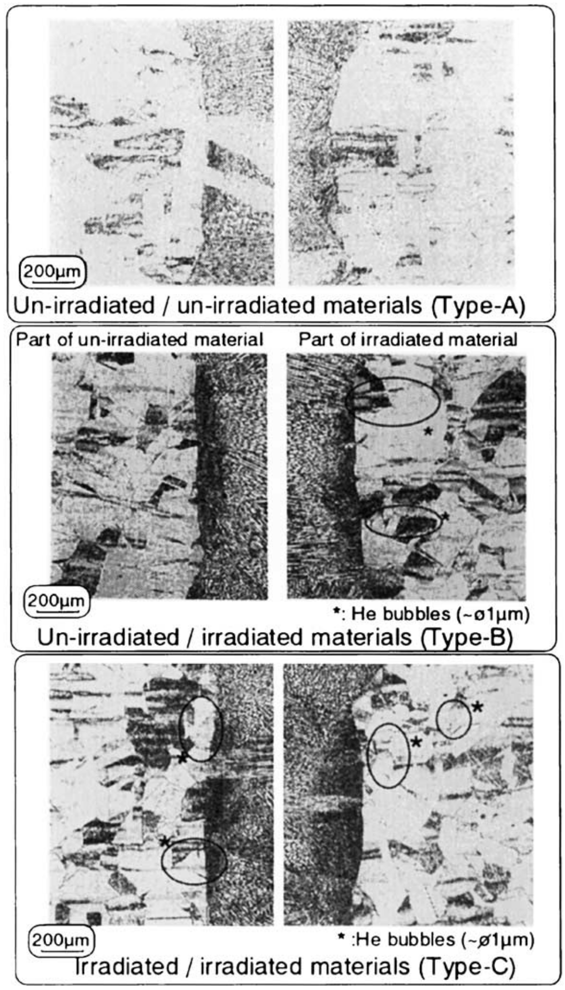

Fig. 3. Metallographical observation near the butt position of weldment specimens.

that all weldment specimens were intact without crack. Observation by a scanning electron microscopy (SEM) was performed in order to confirm the micro integrity of weldment specimens. Photographs of weldment specimens by SEM observation are shown in Fig. 3. Some bubbles (~1 μm diameter) were observed for confirmation the microintegrity of weldments the heat-affected zone (HAZ) for the irradiated material. It is inferred that the migration of helium by the heat input on the welding process formed small babbles at the grain boundary.

2.3. The second stage irradiation test

Two kinds of base material specimens and three kinds of weldment specimens were irradiated at the second stage irradiation test in the JMTR. Fast and thermal neutron fluences were evaluated by the calculation with Monte-Carlo (MCNP) code and the measurement with the fluence monitors. Maximum values of fast and thermal neutron fluences by fluence monitor were $1.4 \times 10^{24}\,\mathrm{n/m^2}$ and $4.3 \times 10^{24}\,\mathrm{n/m^2}$, respectively. Maximum value of irradiation damage in the second stage irradiation test was corresponding to a displacement dose of 0.26 dpa.

Helium content in the irradiated material was generated by the (n, α) reaction of boron, and it is estimated that all the boron in the irradiated material have been burned up in the first stage irradiation test already by the calculation of MCNP code. Therefore, the helium content of the irradiated materials part did not change in the second stage irradiation test and it was about 3.3 appm.

The irradiation temperature of the second stage irradiation test was calculated by the ABAQUS code to be about 200 °C.

3. Post irradiation examination

Tensile testing was performed in air at two temperatures, room temperature (25 °C) and the temperature of irradiation (200 °C). A crosshead speed of 0.5 mm/min was used, and it corresponds to a strain rate of about 2.2%/min. The fracture surfaces after tensile test were examined by SEM. Hardness testing was performed by vickers microhardness tester with a knoop indenter. Weight and loading period of hardness test were 200 g and 30 s, respectively.

4. Results and discussion

4.1. Effect of the second stage irradiation test on tensile properties

Results of tensile testing are shown in Table 2. Before the second stage irradiation test, the ultimate tensile strength (UTS) of all types of weldment (Type-A, Type-B and Type-C) materials was almost the same as that of un-irradiated base material because the effect of neutron irradiation near butt position of weldment specimens disappeared by the heat effect on laser welding [10]. On the other hand, 0.2% yield stress (0.2%YS) and total elongation (TEL) were different by the type of specimen. After the second stage irradiation test, 0.2%YS and UTS of all types of specimens were changed to be similar and it was that of irradiated base material. TEL was different for the different materials types, but the difference by which each type of specimen

Table 2
Effect of neutron irradiation of the second stage irradiation test on tensile properties

Material	Test temperature (°C)	0.2YS (MPa)			UTS (MPa)			TEL (%)		
		Before second irradiation	After second irradiation	*R*	Before second irradiation	After second irradiation	*R*	Before second irradiation	After second irradiation	*R*
Un-irradiated base	20	247.4	523.7	2.1	586.7	693.7	1.2	85.3	55.4	0.6
	200	200.8	425.9	2.1	456.9	564.2	1.2	66.5	42.5	0.6
Irradiated base	20	560.5	589.5	1.1	715.5	731.7	1.0	58.4	47.2	0.8
	200	438.5	392.2	0.9	549.0	505.6	0.9	46.3	39.4	0.9
Un-irradiated/un-irradiated	20	298.0	543.0	1.8	583.7	705.2	1.2	72.5	42.2	0.6
	200	222.0	383.9	1.7	476.5	514.7	1.1	49.8	37.7	0.8
Un-irradiated/irradiated	20	320.3	553.3	1.7	595.0	708.1	1.2	52.2	37.5	0.7
	200	239.3	384.2	1.6	472.7	518.4	1.1	35.0	32.7	0.9
Irradiated/irradiated	20	443.7	592.8	1.3	615.7	722.3	1.2	30.2	36.4	1.2
	200	375.5	402.6	1.1	478.5	512.2	1.1	28.5	32.6	1.1

Second irradiation: The second stage irradiation test.
R: Ratio of effect by re-irradiation (after second irradiation/before second irradiation).
Un-irradiated/un-irradiated: Weldment of un-irradiated/un-irradiated material (Type-A)
Un-irradiated/irradiated: Weldment of un-irradiated/irradiated material (Type-B).
Irradiated/irradiated: Weldment of irradiated/irradiated material (Type-C).

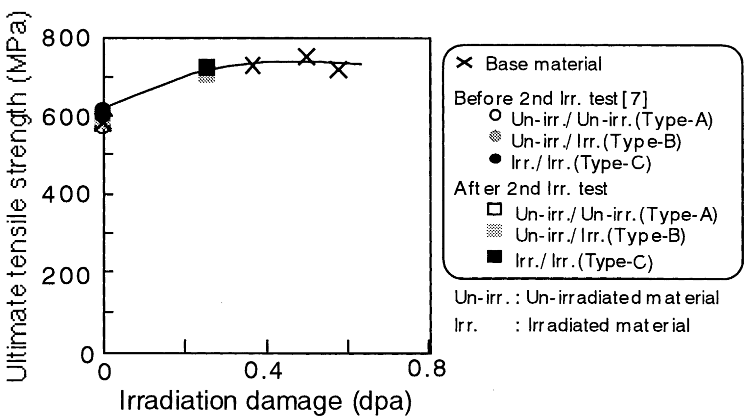

Fig. 4. Ultimate tensile strength of base material and weldment by irradiation damage.

was changed was small following the second stage irradiation test. It is believed that irradiation defects were animated by the fusion process of laser welding, but its were re-created by the second stage irradiation test.

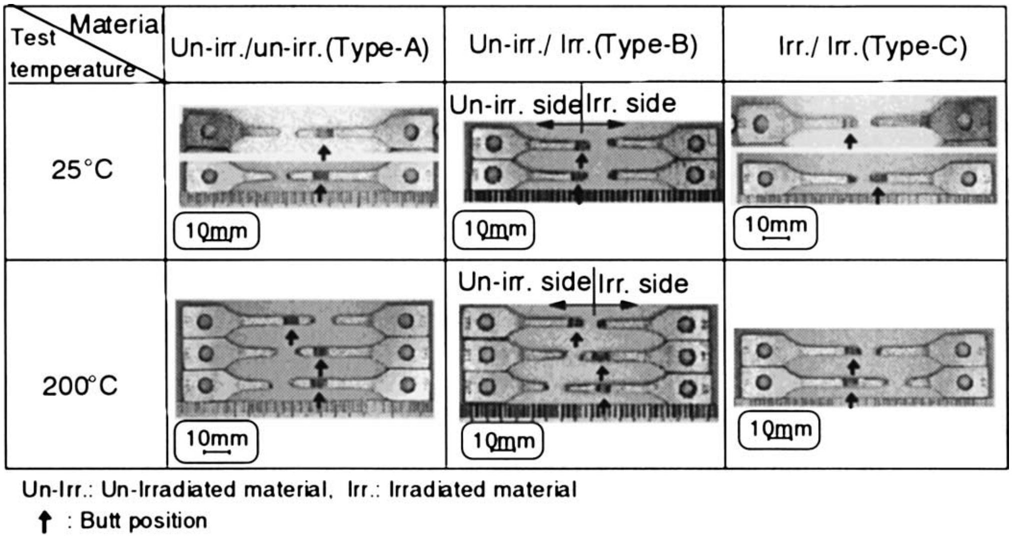

Fig. 5. Fracture position of tensile specimens.

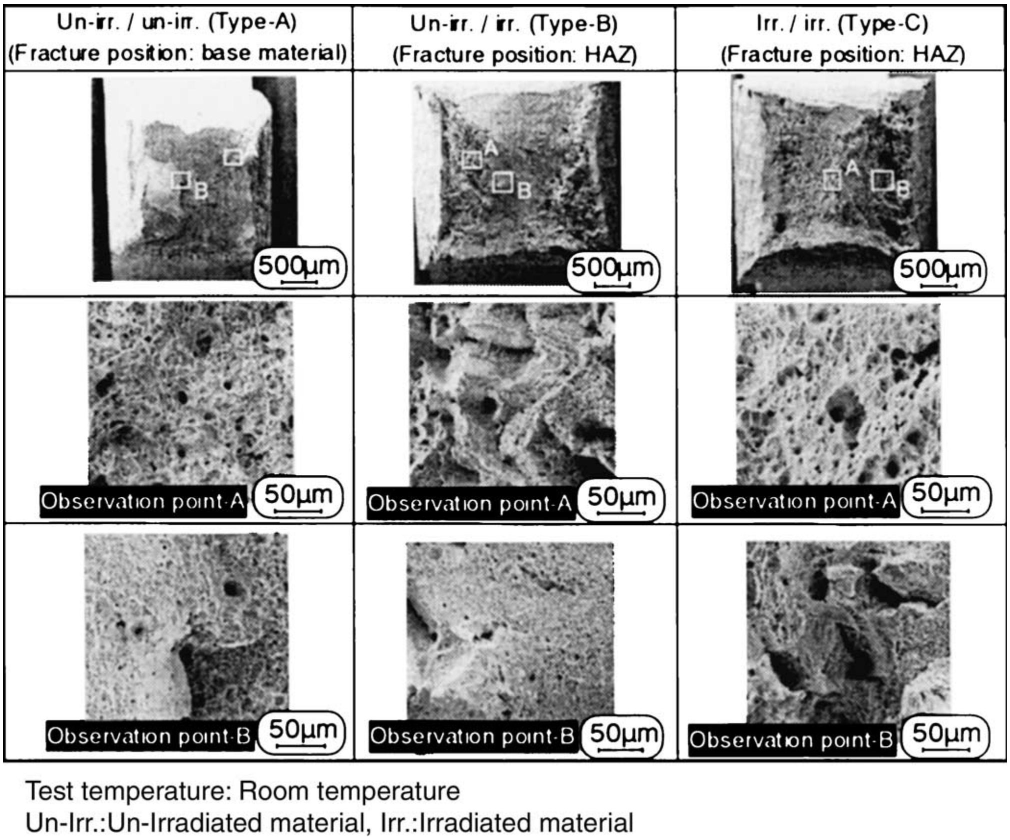

Fig. 6. SEM observation on fracture surface of tensile specimen.

Therefore, the un-irradiated parts of Type-A and Type-B were changed into irradiated parts in the second stage irradiation test, and all weldment specimens became combinations of irradiated and irradiated materials.

Table 2 shows that 0.2%YS of un-irradiated base material became 2.3 times and UTS of un-irradiated base material became 1.2 times by the embrittlement due to the effect of neutron irradiation at the second stage irradiation test. On the other hand, 0.2YS and UTS of the irradiated base material hardly changed by the effect of neutron irradiation at the second stage irradiation test. The change in UTS of base material and weldment specimen at room temperature with the irradiation damage is shown in Fig. 4. About the weldment specimens, irradiation damage is regarded to irradiation damage of fracture position because tensile properties of material depend on the part of fracture position. This figure shows that UTS changes by irradiation damage in proportion up to 0.3 dpa, but UTS changed hardly over 0.3 dpa. It is inferred that the embrittlement by the effect of neutron irradiation was almost saturated at the first stage irradiation test and that value of irradiation damage was about 0.3 dpa. Weldment specimens fractured at the part of un-irradiated material or HAZ at room temperature. Therefore, the irradiation damage of weldment before the second stage irradiation test was 0 dpa and the irradiation damage of weldment after the second stage irradiation test was 0.26 dpa. It is confirmed that UTS of weldments after the second stage irradiation test was accord to that of base material in this figure.

4.2. Effect of the second stage irradiation test on the fracture mechanism

Photographs of weldment specimens after tensile testing are shown in Fig. 5. All of Type-A weldment specimens fractured at base material. However, Type-B and Type-C weldment specimens fractured at base material and HAZ. The fracture position in HAZ located in irradiated material. For the confirmation of the reason that fracture at HAZ occurred only irradiated material, photographs of fracture surfaces of weldment specimens after the tensile test at room temperature are shown in Fig. 6. It is clear that ductile fracture occurred in the Type-A weldment specimen that broke at the base material. On the other hand, intergranular fracture occurred in the Type-B and Type-C weldment specimen that broke in HAZ. It is inferred that the small babbles at the grain boundary influenced to the fracture mechanism because the helium bubbles were observed in HAZ in irradiated material and the fracture at the HAZ occurred in this part exclusively. And, it is inferred that tensile properties were not influenced by helium bubble because the tensile properties of the weldments that fractured at HAZ was almost the same as those of the specimen that fractured at base material.

4.3. Effect of the second stage irradiation test on hardness properties

The results of hardness test are shown in Fig. 7. Before the second stage irradiation test, embrittlement of irradiated material occurred by the effect of neutron irradiation in the first stage irradiation test. The irradiated material near the butt position was melted in welding process and the irradiation defects in this part

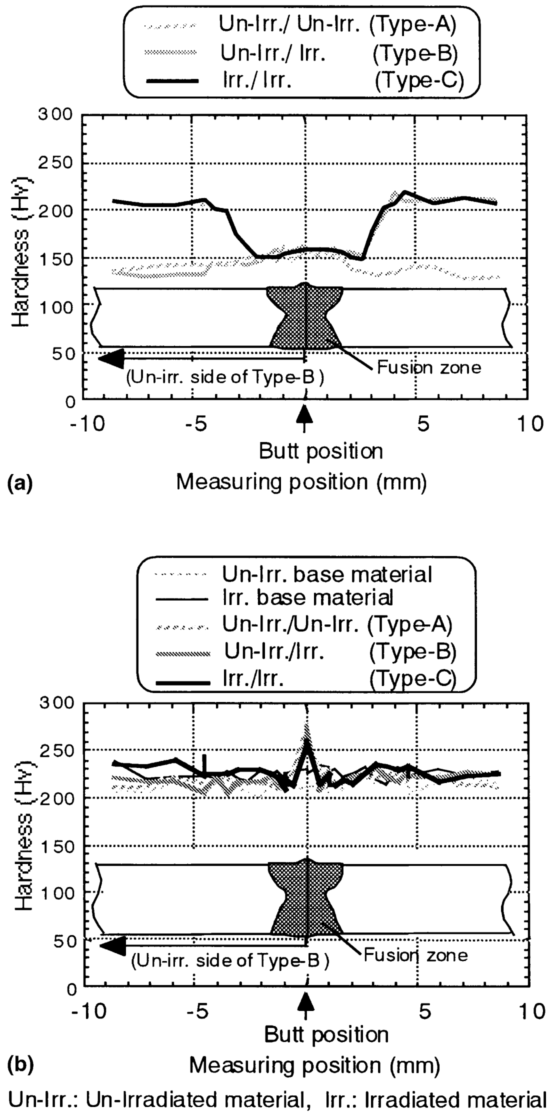

Fig. 7. Results of hardness tests. (a) Hardness test before the second stage irradiation test and (b) hardness test after the second stage irradiation test.

vanished. Therefore, the hardness of the fusion zone was lower than that of the irradiated base material. However, the hardness of fusion zone was little higher than that of un-irradiated base material. It is inferred that this cause was the effect of quench at the fusion zone of weldments.

Hardness of fusion zone and base material became 1.8 times and 1.5 times by the neutron irradiation of the second stage irradiation test. Additionally, the irradiation damage of the fusion zone of all types weldment specimens was 0.3 dpa because the melting in the welding process erased irradiation damage and new irradiation defect generated by the second stage irradiation test. It is inferred that the cause of such a difference is the decoration and stabilization of the dislocation loops with interstitial impurities precipitated from solid solution [11]. On the other hand, the hardness of all part in the irradiated material was almost the same. The irradiation damage of un-irradiated material in Type-A or Type-B weldment specimens created by the second stage irradiation test and it was about 0.3 dpa. On the other hand, irradiated material in Type-B or Type-C weldment specimens was irradiated on the first stage irradiation test already and the irradiation damage of irradiated material was about 0.3 dpa. Therefore, the total irradiation damage of irradiated material increased by the second stage irradiation test and it changed into about 0.6 dpa. Therefore, the hardness of base material hardly changed between 0.3 dpa and 0.6 dpa of irradiation damage and this trend was also confirmed in tensile properties.

5. Conclusion

This study clarified the effect of neutron irradiation on mechanical properties of weldments using irradiated material. Tensile properties and hardness were changed by the effect of neutron irradiation up to 0.3 dpa and the change on these properties was hardly observed between 0.3 dpa and 0.6 dpa. Therefore, the effect of neutron irradiation is saturated at about 0.3 dpa on the base material and weldments of SS316LN-IG. On the other hand, the tensile properties of weldments changed into that of irradiated base material by the effect of neutron irradiation. The combination pattern of un-irradiated material and irradiated material does not influence the tensile properties of weldments after neutron irradiation.

On the weldments using irradiated material with 3.3 appmHe, the helium in the irradiated material influenced the fracture mechanism of weldments using irradiated material. However, the tensile properties of weldments were not influenced by helium because the tensile properties of weldments that broke at HAZ were almost the same as that of weldments that broke at base material.

This estimation shows that it regarded irradiated weldments using irradiated material as irradiated base material on tensile properties and hardness up to irradiation damage 0.6 dpa and the effect of neutron irradiation was not observed between 0.3 dpa and 0.6 dpa on tensile and hardness properties of SS316LN-IG.

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