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# Mechanical properties of weldments using irradiated stainless steel welded by the laser method for ITER blanket replacement

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**Abstract**

In the case of a blanket module replacement in the ITER, cooling water pipe will be joined to irradiated pipe by the laser welding method. On the cooling water piping of the ITER blanket, various loads (the vibration of coolant flow, plasma disruption or deadweight of blanket) will be applied to the joint. Therefore, an evaluation of the mechanical properties of weldments using irradiated material is necessary for replacement of the cooling water piping of the ITER blanket. In this study, the bending strength of weldments on irradiated material using the laser welding method was evaluated. This study made clear that the bending strength of weldments using irradiated material with 3.3 appm He by the laser welding method was similar to that of weldments of un-irradiated material to un-irradiated material. On the weldments using irradiated material, small bubbles were observed at the grain boundaries in heat-affected zone because the coagulation of helium generated in irradiated material was accelerated by heat input from laser welding. However, small bubbles did not have a bad influence on the bending strength up to at least 300 °C.


## 1. Introduction

For replacement of the blanket of the International Thermonuclear Experimental Reactor (ITER), the cooling water pipe of the blanket must be joined to irradiated cooling water pipe by the laser welding method. As for the joining technology of irradiated material, a tungsten inert gas (TIG) welding method and a laser welding method were investigated [1–3]. In welding irradiated material, the helium present in irradiated material affects the validity of the laser welding method and mechanical properties of weldments. At the cooling pipe of the ITER blanket, various loads (the vibration of cooling water flow, plasma disruption and so on) would be present at the joint during the operation of

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ITER. Therefore, the estimation of mechanical properties of weldments is an important consideration. For the study of laser welding using irradiated material, the laser welding method was found effective to weld irradiated material without defects and the tensile strength of weldments was about the same as that of un-irradiated material [4]. However, there are few studies of bending properties using irradiated ITER candidate material.

In this study, weldments using irradiated material and un-irradiated material were fabricated by the laser welding method, and the bending properties of weldments using irradiated material were evaluated.

## 2. Experiment

### 2.1. Material

In this study, SS316LN-IG was used as the stainless steel because this is a candidate material for ITER cooling pipe. The chemical composition of SS316LN-IG is shown in Table 1. For the preparation of irradiated material, irradiation was performed at the JMTR (Japan Materials Test Reactor) of JAERI (Japan Atomic Energy Research Institute). The fast neutron fluence was determined by fluence monitors (Fe wire), and its maximum value was about $1.6 \times 10^{24}$ n/m$^2$ ($E > 1$ MeV), corresponding to a displacement dose of approximately 0.2 dpa (displacement per atom). The thermal neutron fluence was determined by fluence monitors (Al–Co wire), and its maximum value was about $4.0 \times 10^{20}$ n/cm$^2$ ($E < 0.68$ eV). The irradiation temperature of the specimens was calculated by the ABAQUS code, and it was about 200 °C. After the neutron irradiation, the helium content in the irradiated materials was measured by melting the actual irradiated material, and it was found to be 3.3 appm.

Table 1
The chemical composition of SS316LN-IG

| Elements | Content | Unit |
|---|---|---|
| Fe | Balance | |
| C | 0.029 | |
| Mn | 1.64 | |
| Si | 0.44 | |
| P | 0.012 | |
| S | 0.009 | |
| Cr | 17.48 | wt% |
| Ni | 12.11 | |
| Mo | 2.56 | |
| Nb | 0.067 | |
| Cu | 0.07 | |
| Co | 0.02 | |
| N | 0.067 | |
| B | 3 | ppm |

### 2.2. Fabrication of specimens

In this study, three types specimens made from weldments and two types of specimens of base material were prepared. As the three types of weldment specimens, Type-A was a combination of an un-irradiated material and an un-irradiated material, Type-B was the combination of an irradiated material and an un-irradiated material, and Type-C was the combination of an irradiated material and an irradiated material. For the two types of specimens of base material, un-irradiated base material specimens and irradiated base material specimens were prepared as reference for the weldments. Weldments were fabricated by a YAG laser welding machine (LAY-659F, Toshiba Co.) without filler metal. As the welding parameters for the laser welding were as follows: laser power was 1 kW (pulse laser), welding speed was 0.5 m/min and the welding heat input was about 1.2 kJ/cm. During welding, materials were supported with no load at the butt position to prevent residual stresses from the heat input was of the welding process. Liquid dye penetration testing at room temperature 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 that all weldment specimens were intact without cracks. Figures of the bending specimens are shown in Fig. 1.

### 2.3. Test procedure

Three-point bending tests were performed using the procedure shown in Fig. 2. The loading speed was 0.5 mm/min. In this study, face bend tests and root bend tests were performed on each of the weldments for evaluation of the influence of the directions of the bending load and the heat input.

Bending strength was calculated by the following equation:

$$S = \frac{3P_{\mathrm{y}}L}{2wt^2} \tag{1}$$

$S$: bending strength (kN/mm$^2$);
$P_{\mathrm{y}}$: maximum load (kN);
$L$: distance of support point (=20 mm);
$w$: width of specimen (=4 mm);
$t$: thickness of specimen (=3 mm).

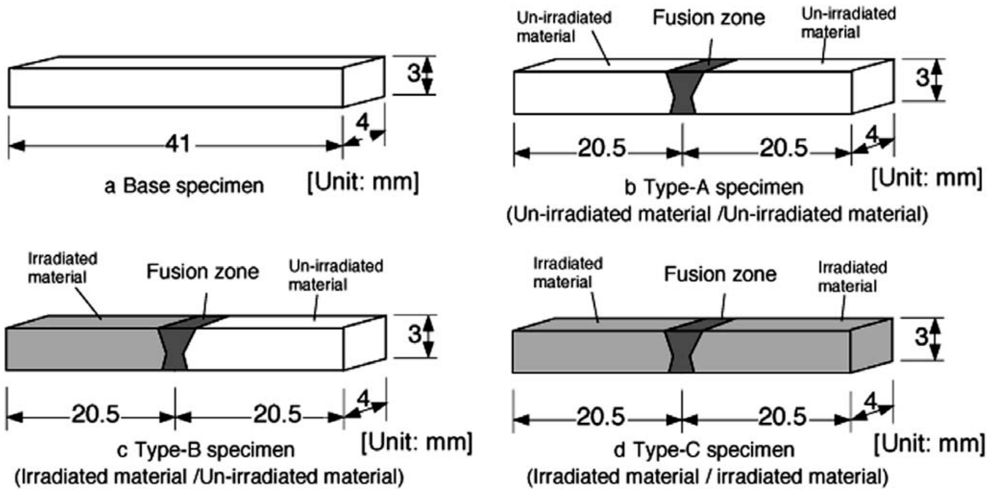


Fig. 1. The figures of bending specimens.

The maximum load on the specimens without fracture is considered to be the load shown by the intersection point of the SS curve and the straight line generated by moving the elastic curve by a distance of 0.2% *L*. This is based on the bending test procedure in the Japanese Industrial Standard. For the example where a specimen does not fracture, the maximum bending load is shown in Fig. 3.

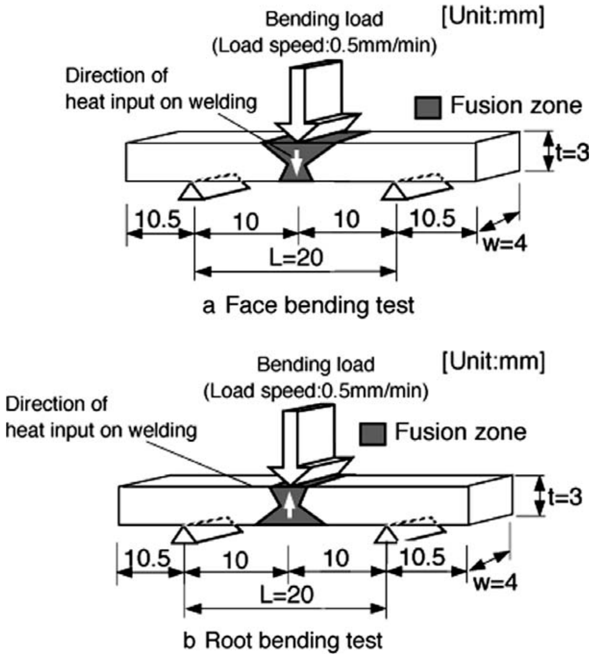


Fig. 2. The procedure of bending test.

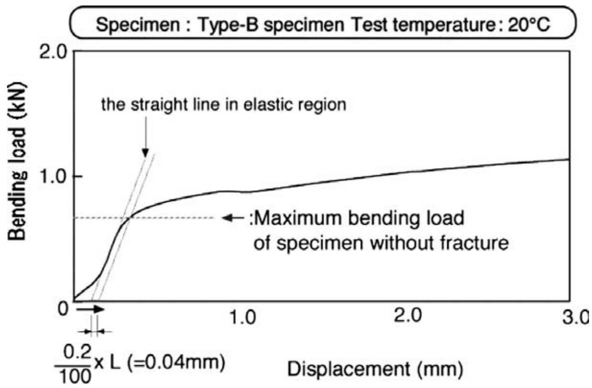


Fig. 3. Bending specimens after bending test.

## 3. Results and discussion

Bending specimens following testing are shown in Fig. 4. Not all specimens fractured, not all specimens exhibited cracks. Generally, the welding crack is generated by heat input at fusion zone when irradiated material with helium welded. However, the welding crack generation depends on the relationship between the helium content and it was reported that it was reported that a welding crack would be not generated at an irradiated material with high helium content when the heat input was low on TIG welding [5]. It is considered that the condition of heat input (1.2 kJ/cm) in this study was low to generate the welding crack at irradiated material with 3.3 appm He.

Additionally, the angles of bending in all specimens were same. The bending strengths of all

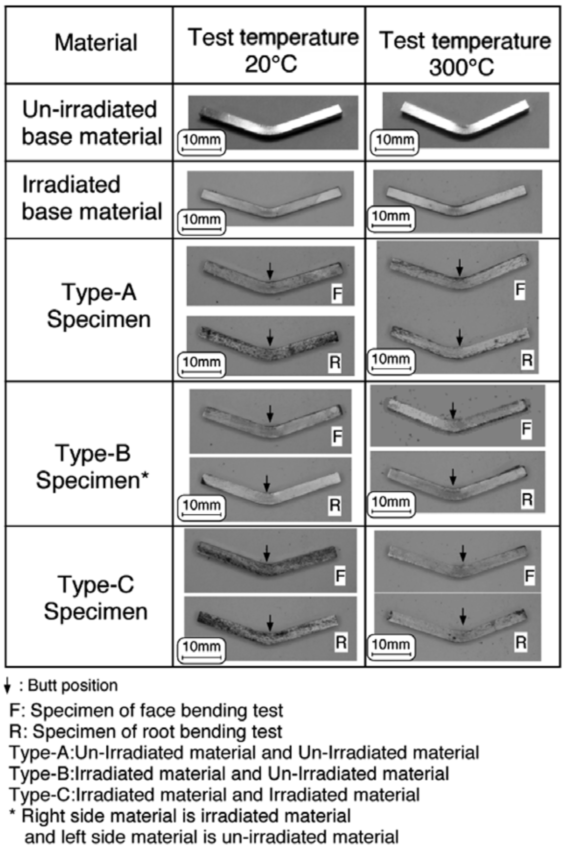


Fig. 4. The curve of bending load and displacement on bending test.

specimens are shown in Fig. 5. The bending of all specimens was largely confined to the fusion zone. Therefore, bending properties of weldments depended on those of the fusion zone. The results of bending tests showed that the bending properties of weldments using irradiated material were almost the same as the bending properties of weldments of un-irradiated material and un-irradiated material up to 300 °C. Therefore, it is believed that the difference between irradiated material and un-irradiated material did not influence the bending properties of weldments using these materials because dislocations in irradiated material disappeared from the fusion zone by the melting process of laser welding.

A metallographic image from the fusion zone of a weldment using irradiated material is shown in Fig. 6. In the irradiated material used for this study, the amount of helium generated by the neutron irradiation was 3.3 appm. The migration of helium atoms accelerated by the heat input of the welding process and the migration of helium formed small bubbles of ~1 μm diameter at the grain boundaries in the HAZ of Types-B and -C specimens. However, small bubbles did not influence the bending properties of weldments using irradiated material up to 300 °C since the bending strengths of Types-B and -C specimens were almost same as those of Type-A specimens.

The bending strength of weldments tested by the face bending method was similar to those tested by the root bending method. Therefore, it is believed that the bending strength of weldments was not influenced by the direction of the bending load.

From the comparison between the weldments specimens and the base material, the temperature-dependence of bending strength of weldments was different from that of base material specimens. This resulted because the bending remained within the fusion zone. In this study, the thickness of material for welding was small, and the cooling rate of the fusion zone was rapid. It is believed that the fusion zone was quenched in this case.

This study made clear that the temperature-dependence of the bending strength of a laser weldments using irradiated material with 3.3 appm He

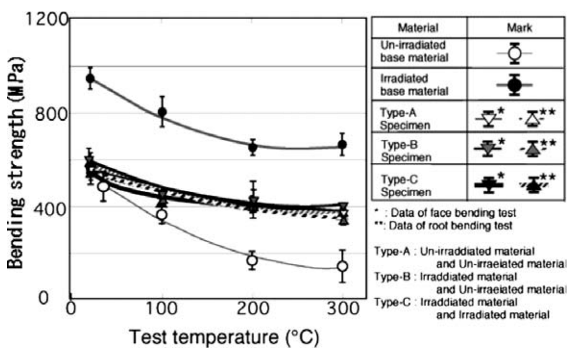


Fig. 5. Bending properties of weldments and base material.

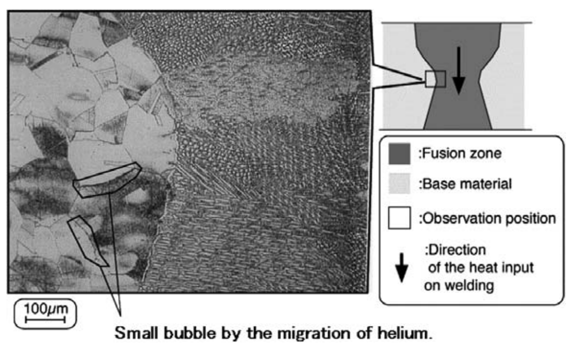


Fig. 6. Metal graphical observation of weldments.

was similar to that of the bending strength weldments of un-irradiated material and un-irradiated material.

Additionally, This study shows the application of the laser welding method for the replacement of ITER blanket because the threshold of the helium amount in an irradiated material is set to 1 appm in the replacement of the ITER blanket [6].

## 4. Conclusion

This study demonstrated that the difference between irradiated material and un-irradiated material did not influence the bending properties of weldments. This is believed to result because the dislocations generated by neutron irradiation in irradiated material disappeared from the fusion zone by the melting process of laser welding. In addition, helium in irradiated material did not influence the bending properties of weldments up to 300 °C, when the irradiated material with 3.3 appm He was welded by the laser welding method (welding speed: 0.5 m/min, heat input: 1.2 kJ/cm) in this study.

Therefore, it is concluded that bending properties of weldments using irradiated material will be estimated by the weldments of un-irradiated material and un-irradiated material.

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