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Evaluation of weld crack susceptibility for neutron irradiated stainless steels

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Abstract

In order to clarify the mechanisms of weld cracking, especially for heat affected zone cracking in heavily neutron irradiated stainless steels and to establish a measure to evaluate crack susceptibility, a mini-sized Varestraint (variable restraint) test machine for hot laboratory operation was designed and fabricated. This unique PIE facility was successfully applied in the hot laboratory of IMR Oarai Branch of Tohoku University. The maximum restraint applied was 4% at the surface of the specimen. Specimen surface morphology and specimen microstructures were inspected by video microscope, SEM and TEM. Under the 2% surface restraint condition, clear formation of heat affected zone (HAZ) crack was observed for the case of neutron irradiation to produce 0.5 appm He and of 2.4 kJ heat input by TIG.

1. Introduction

In fusion reactor application, properties of welds and welded joints are the key factors which limit the service conditions including their end-of-life. Where, an availability of reliable repair welding techniques is strongly required in order to improve cost of electricity. One of the most difficult and the unique characteristic, of which the repair welding has to overcome is the radiation damaged microstructure including nuclear transformed gaseous atoms, such as helium atoms form the (n, α) [1] and hydrogen from the (n, p) reaction.

There have been many attempts to investigate weldability of heavily neutron damaged materials for establishing criteria of repair welding applicability [2–5], but hitherto clear and quantitative definition of weldability for neutron damaged specimens were not presented. The objective of this work is to clarify the mechanisms of weld cracking, especially for heat affected zone cracking in heavily neutron irradiated stainless steels and to establish a measure to evaluate crack susceptibility. For this purpose, a mini-sized Varestraint (variable restraint) test machine for hot laboratory operation was designed and fabricated.

2. Experimental procedure

2.1. Specimen

The specimens used were plates of SUS 304. The chemical composition of SUS 304 is shown in Table 1. The plates were cut out from the plates with 20 mm in thickness. The plate thickness was reduced to 2 mm by a milling machine. The size of the plate tested was $100 \times 25 \times 2$ mm. The specimens used were neutron irradiated in Japan Materials Test Reactor (JMTR) of Naka Establishment, JAERI to the three neutron fluences. Table 2 shows neutron fluence and He contents of the specimens neutron irradiated.

2.2. Varestraint test [6]

To evaluate the weld crack susceptibility, the Varestraint test is introduced. The Varestraint test was originally designed by Savage and Lundin [7], as the means to evaluate the weld crack susceptibility, for example weld metal crack, heat affected zone (HAZ) crack and etc.

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Table 1
The composition of SUS304 (mass%)

C	Si	Mn	P	S	Cr	Ni	N	Al	Co
0.05	0.6	1.03	0.002	0.004	18.3	8	0.06	0.01	0.02

Table 2
Neutron fluence for specimens

Specimen ID	The fast neutron fluence ($E > 1$ MeV)	The thermal neutron fluence ($E < 1$ MeV)	The concentration of He
A-1	1.5×10^{21} n/m^2	140×10^{21} n/m^2	0.13 appm
A-2	20×10^{21} n/m^2	400×10^{21} n/m^2	0.50 appm
A-3	100×10^{21} n/m^2	1200×10^{21} n/m^2	1.5 appm

Fig. 1 shows the principle of the Varestraint test. To start the test, a specimen is placed to the Varestraint test machine. The welding method applied here is TIG welding. The bead-on plate by TIG welding was done for about 35 mm and followed by a rapid bend of the specimen and a simultaneous arc stop. The restraint strain was controlled by the curvature of the bending die. The precise surface strain of the specimen was also measured by strain gauges. The nominal surface stain (ε) given by the Varestraint test is as follows:

$$\varepsilon(\%) = \{(t/2)/(R + t/2)\} \times 100 \fallingdotseq (t/2R) \times 100$$

where t is the specimen thickness, R the radius of curvature of bending die.

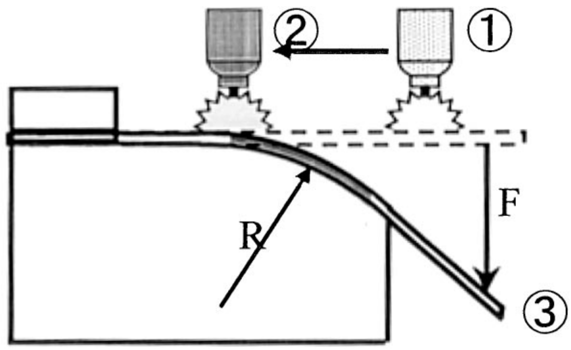

Fig. 1. The process of Varestraint test.

2.3. Development of the mini-sized Varestraint test machine

The specific feature of the mini-sized Varestraint test machine (Fig. 2), newly developed, was to be used for neutron irradiated specimens with induced radioactivity. Therefore, the following features have been considered in designing the machine.

1. Operative in radiation environment utilizing radioactive specimens.
2. Easy for operation in glovebox or hotcell where indirect specimen handling processes, such as magic hand handling etc., are to be applied.
3. Applicable to small or mini-sized specimens which requires modification of bending die shape.

These require system miniaturization, remote operation capability, easy specimen setting and maintainability to the machine. The most difficult part was to simplify the mechanism of quick specimen bending procedure where pneumatic system was used.

To control the whole test procedure, sequential control by simple relay circuits were designed and used.

Fig. 3 shows the appearance of the mini-sized Varestraint test machine where by changing the bending die degree of restraint was controlled.

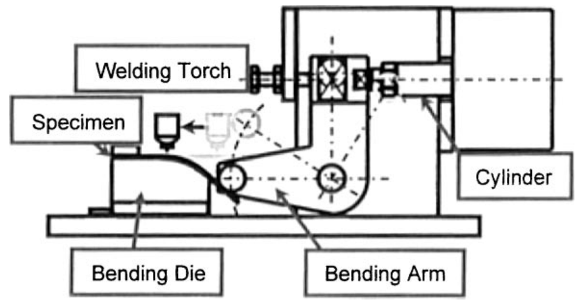

Fig. 2. The design of the mini-sized Varestraint test machine.

3. Results

At the beginning of this experiment, Varestraint tests for unirradiated specimens were carried out. For the case of unirradiated specimens, HAZ cracks were not observed even after polish with fairly a large surface strain as large as 4%. as shown in Fig. 4.

Even for the case of irradiated specimens, HAZ cracks were hardly observed, by video-microscopic observation with the magnification of $\times$ 175. By the precise observation of the surface of specimens Varestraint

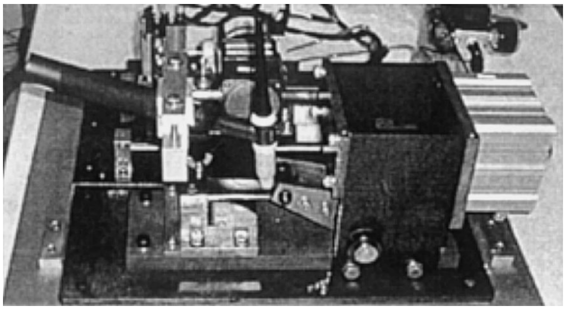

Fig. 3. The mini-sized Varestraint test machine (side view).

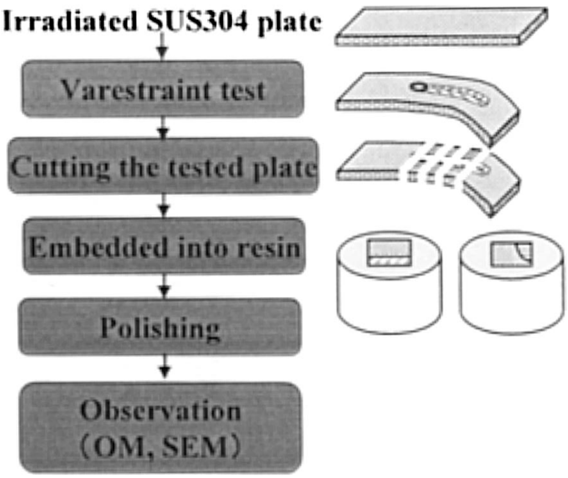

Fig. 4. The flowchart of the crack measurement.

tested by SEM, as shown in Fig. 5 for an example, many HAZ cracks nearby weld metal could be detected with no crack in weld metal.

The weld cracks exist not only on the surface but also in the sub-surface regions. Fig. 6 is the cross section of the specimen Varestraint tested. There are HAZ cracks nearby the weld metal. Because the inner part of the specimen was less strained than that at the surface, the majority of the cracks observed were located nearby the surface.

Fig. 7 is the optical micrograph of the polished surface of the specimen Varestraint tested in order to observe the surface cracks more precisely. There are many small cracks nearby the weld metal. Some of them would be a part of large crack connected beneath the surface.

Fig. 8 shows the effect of weld heat input value on the distribution of HAZ cracks. The larger the heat input, the more HAZ cracks were introduced with the tendency to be reduced the crack density with decreasing surface temperature when specimen was bent. When the heat input was reduced to 0.7 kJ/cm, no crack was observed.

Fig. 9 shows the effects of neutron fluence, those are displacement damage effect and He transmutation effect,

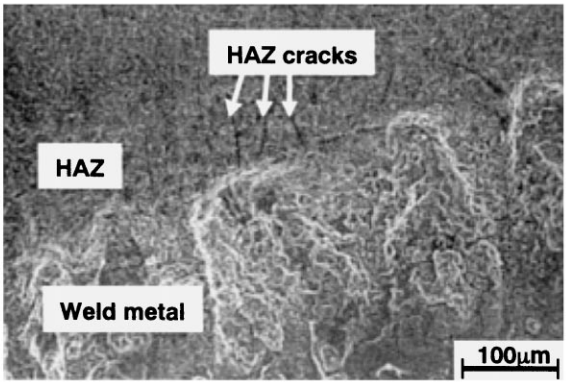

Fig. 5. The surface of the specimen (SEM) heat input: 1.8 kJ/cm, surface strain: 2%, fast neutron fluence: 100×10^{21} n/m^2 He content: 1.5 appm.

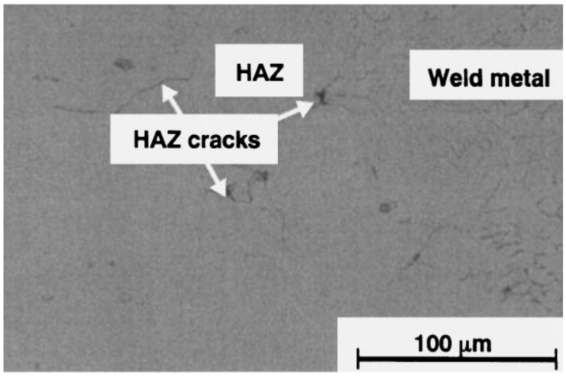

Fig. 6. Optical micrograph of the specimen cross-section heat input: 1.8 kJ/cm, surface strain: 2%, fast neutron fluence: 100×10^{21} n/m^2, He content: 1.5 appm.

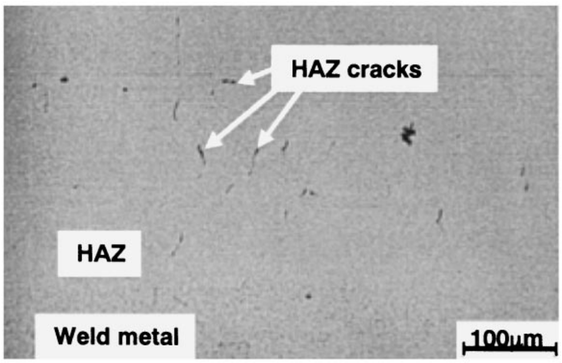

Fig. 7. The polished surface of the specimen (OM) heat input: 1.8 kJ/cm, surface strain: 2%, fast neutron fluence: 100×10^{21} n/m^2, He content: 1.5 appm.

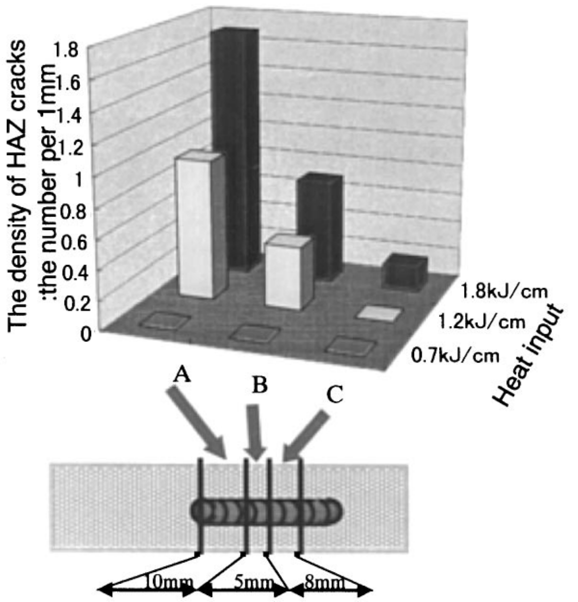

Fig. 8. The distribution of HAZ cracks (heat input) surface strain: 2%, fast neutron fluence: 100×10^{21} n/m^2, He content: 1.5 appm.

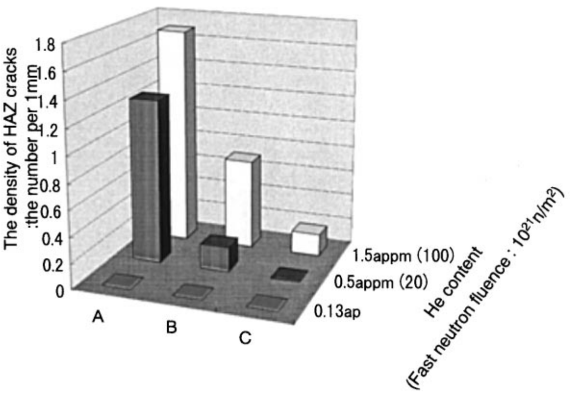

Fig. 9. The distribution of HAZ cracks (neutron fluence) heat input: 1.8 kJ/cm, surface strain: 2%.

simultaneously, on the distribution of HAZ cracks. High He contents and high displacement damage makes many cracks. And for the case of 0.13 appm He contents, there is no crack observed.

4. Discussion

About the effect of neutron fluence, two effects are simultaneously involved those are displacement damage and transmutation damage where the former produces radiation embrittlement. Because the cracks were HAZ cracks attached to the fusion line, it may be appropriate to estimate the effect of radiation hardening is not the most important factor. This is indirectly supported by the heat-input dependence on crack density and crack distribution.

HAZ cracks observed, as shown in Figs. 6 and 7, were grain boundary cracks. This is not directly related with the He transmutation effect phenomenologically. However, as reported in many papers [8,9], a large amount of He caused grain boundary cracks by welding and the results obtained in the present work might be the similar case, although the amount of He was very low comparing with the previous reports. According to the present study, 0.5 appm He contents will become a problem when restraint strain becomes larger than 2% and not for the case of 0.13 appm. But a crack susceptibility is the functions of welding condition and is difficult to define by only one factor. Thus, the knowledge at present may suggest the possibility that the lower He contents than 0.13 appm becomes a problem for introducing HAZ cracking by welding under, somehow, severe conditions. This is the important remaining issue to be defined in the future.

5. Conclusions

1. To evaluate the weld crack susceptibility for neutron irradiated stainless steels, a mini-sized Varestraint (variable restraint) test machine for hot laboratory operation was designed and fabricated. It was operated in- and out- of hot cell at Oarai Branch, IMR, Tohoku University, using TIG welding method.
2. For the case of unirradiated specimens, HAZ cracks were hardly observed even after polishing.
3. For the case of neutron fluence of 2.0×10^{22} n/m^2, no visible HAZ crack was observed by optical microscope without surface polishing after 2% restraint.
4. Under severe conditions, those are higher heat input, larger restraint and higher He contents (high neutron fluence), many HAZ cracks were observed. The crack susceptibility maps, as the functions of heat input value, restraint value and neutron fluence, are to be provided from the existing database, in the near future.

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