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Re-weldability of neutron irradiated Type 304 and 316L stainless steels

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Abstract

Weldability of irradiated stainless steel (SS) has been studied to develop the technical guideline regarding the repair-welding of reactor internals. Type 304 and 316L SSs were irradiated at ambient temperature in the US Advanced Test Reactor. The multi-pass bead-on-plate TIG (GTA) and YAG laser welding with heat input levels less than 1 MJ/m were performed on specimens containing helium up to 18 appm. In this paper, results of cross-sectional micrograph observations of the heat affected zone were considered in light of helium bubble properties. The tendency for weld crack formation of irradiated Type 316L SS was compared with that of irradiated Type 304 SS.

1. Introduction

The life extension of fusion and fission reactors needs the repairs of irradiation-degraded components. Welding is one of the practical countermeasure candidates for repairing and replacing such components.

Welding techniques on irradiated materials have been extensively studied in the last decade, and studies have pointed out that welding was not always successful in neutron-irradiated SSs [1]. Weld cracks of irradiated SSs generally occurred in the weld HAZ [2]. The cracks were intergranular in nature, which was attributed to nucleation along grain boundaries, coalescence and growth of helium bubbles from the thermal cycle and thermal stress during welding [3,4].

In this work, the weldability of neutron irradiated Type 304 and 316L SSs is studied by multi-pass TIG and YAG laser welding to clarify the welding conditions which can obtain the sound welding. Also, weldability of irradiated Type 316L SS was compared with that of irradiated Type 304 SS.

2. Experimental procedure

2.1. Test specimens

Specimens were made from solution annealed Type 304 SS (Fe–0.06 wt% C–0.71 wt% Si–1.06 wt% Mn–0.020 wt% P–0.001 wt% S–8.44 wt% Ni–18.23 wt% Cr–0.04 wt% Co–2 wtppmB) and Type 316L SS (Fe–0.015 wt% C–0.52 wt% Si–0.96 wt% Mn–0.020 wt% P–0.004 wt% S–12.39 wt% Ni–16.23 wt% Cr–2.12 wt% Mo–0.02 wt% Co–3 wtppmB). Specimens were $60\times100\times10$ mm plate and used for bead-on-plate type welding test.

They were irradiated up to 1.9×10^{25} n/m^2 ($E > 1$ MeV) and 3.5×10^{25} n/m^2 ($E < 0.414$ eV) at ambient temperature (below 473 K) in the Advanced Test Reactor (ATR), INEEL [5]. The helium concentrations of specimens were measured by mass spectrograph measurements after the irradiation.

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2.2. Bead-on-plate welding

Welding tests were carried out in a hot laboratory by TIG and YAG laser welding techniques, which supplied a Type 308L SS and a Type 316L SS filler wire for Type 304 SS and 316L SS specimens, respectively. Several heat input conditions were employed from 0.1 to 1 MJ/m in order to find the optimum welding conditions for irradiated SSs. Bead-on-plate welding with multi-pass was performed. Three layers, 9 passes and 4 layers, 22 passes were performed by TIG and YAG laser welding, respectively. This multi-pass welding introduced multiple heat cycles to the specimens. Particular care was given to constraint of the specimens during welding in order to avoid their distortion. Heat input was a nominal value which disregarded the heat absorption efficiency, and heat input by YAG laser was defined as follows:

$$H = P/V, \tag{1}$$

where H is heat input (MJ/m), P is average laser power (kW), and V is travel speed (mm/s).

After welding, cross-sectional micrograph observations were carried out for each specimen by using an optical microscope. The region along the weld fusion line was carefully observed by ×100 and ×400 magnifications. The as-polished micrograph was used to see if there were any defects or not. The metallurgical structure was observed after 10% oxalic acid etching to identify the location of defects. The observed results were categorized into the following three cases:

Case 1: no cracking;
Case 2: no cracking but continuous point traces along the grain boundary which suggested helium bubble formation;
Case 3: line shape defect along the grain boundary, which were considered as the cracking caused by helium bubble formation and growth.

3. Examination results

3.1. TIG welding

Observation results of cross-sectional micrograph of the multi-pass bead-on-plate welding by TIG for Type 304 and Type 316L SSs are shown in Fig. 1. For Type 304 SS, continuous point traces were only observed in the specimen with 0.4 MJ/m heat input at 3.4 appm helium. However, it was possible to obtain no cracking results by reducing the heat input to 0.2 MJ/m. By comparing results of Type 304 and Type 316L SSs, it seems that Type 316L SS is more sensitive than Type 304 SS for its weld cracking susceptibility. There were cracks in all test points for Type 316L SS.

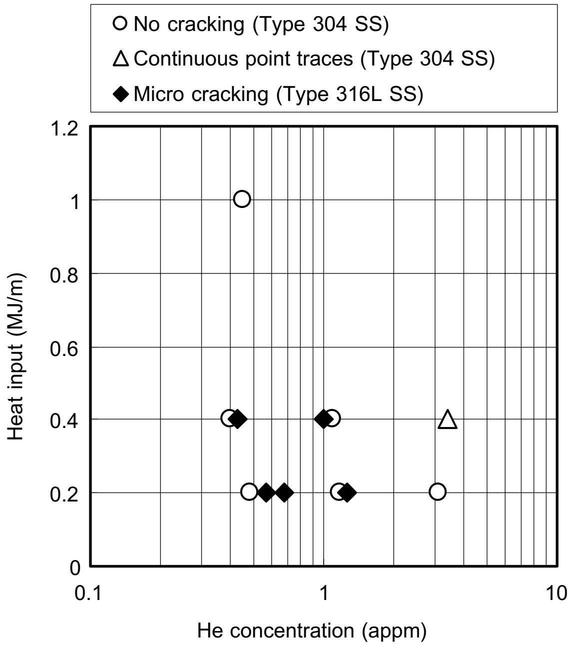

Fig. 1. TIG bead-on-plate welding test results for irradiated Type 304 and 316L SSs. Heat input is a nominal value which disregards the heat absorption efficiency.

Typical cross-sectional micrographs are shown in Fig. 2. Although there was not any crack along the grain boundary for Type 304 SS specimen, there were some microcracks for Type 316L SS specimen nevertheless the welding condition and the helium concentration were same in these two cases. By counting the length of observed crack in Type 316L SS, cracks whose length were lower than 50 μm occupied 90% of the total. The grain size of Type 316L SS specimen was around 50–100 μm as seen in Fig. 2, therefore, crack length was mainly equivalent or smaller than the grain size.

3.2. Laser welding

Observation results of cross-sectional micrograph of the multi-pass bead-on-plate welding by YAG laser for Type 304 and 316L SSs are shown in Fig. 3.

Continuous point traces were observed for Type 304 specimen with 0.2 MJ/m heat input at 6.5 appm helium. For other welding conditions, defects were not observed up to 18 appm helium.

Although test results of YAG laser welding for Type 316L SS were limited, focus was put on the specimen which contains 1 appm helium level because no condition which showed no cracks was found in the case of multi-pass TIG welding. Fig. 4 shows comparison of cross-sectional micrographs of Type 316L SS welded by TIG and YAG laser with 0.2 MJ/m heat input.

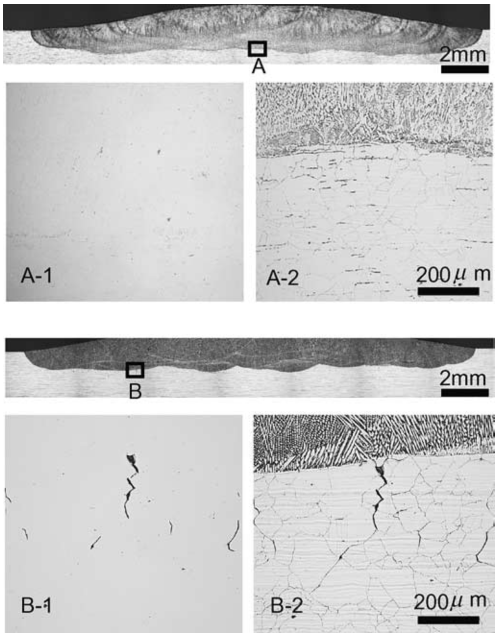

Fig. 2. Comparison of cross-sectional micrographs of the 0.4 MJ/m multi-pass TIG welded Type 304 and 316L specimens. A-1 and A-2 are cross-sections of Type 304 specimen containing 1.1 appm He. B-1 and B-2 are cross-sections of Type 316L specimen containing 1.0 appm He. A-1 and B-1 show as polished surface, A-2 and B-2 show etched surface.

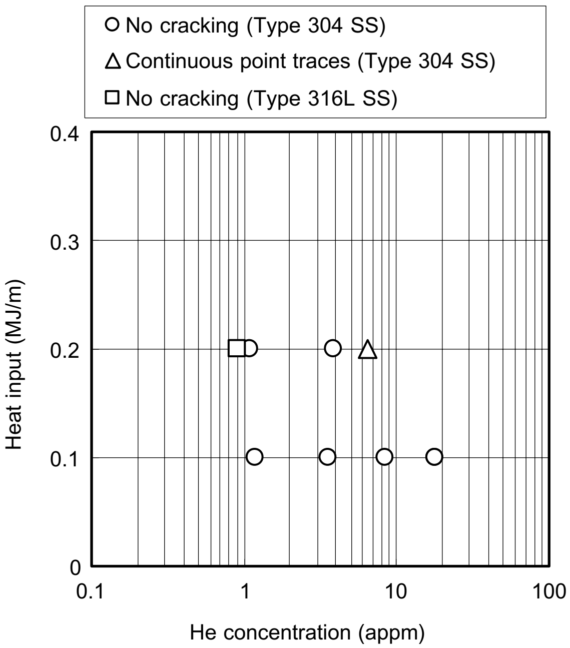

Fig. 3. YAG laser bead-on-plate welding test results for irradiated Type 304 and 316L SSs. Heat input is a nominal value which disregards the heat absorption efficiency.

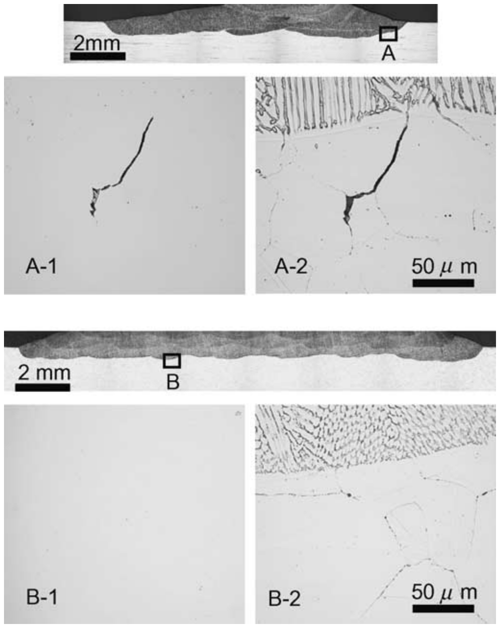

Fig. 4. Comparison of cross-sectional micrographs of the 0.2 MJ/m multi-pass welded Type 316L specimens by TIG and YAG laser welding. A-1 and A-2 are cross-sections of TIG welded Type 316L specimen containing 1.0 appm He. B-1 and B-2 are cross-sections of YAG laser welded Type 316L specimen containing 0.91 appm He. A-1 and B-1 show as polished surface, A-2 and B-2 show etched surface.

Although there was microcracking in Type 316L SS specimen welded by TIG, no defects were found in Type 316L SS specimen welded by YAG laser. Therefore, for Type 316L SS, cracking susceptibility by YAG laser welding was mitigated as compared with that by TIG welding at equivalent helium concentration. According to the difference in the heat absorption efficiency between TIG and YAG laser welding, effective heat input of YAG laser welding was considered to be lower than that of TIG welding even if the nominal values were the same.

4. Discussion

Fig. 5 shows comparison of the test results for irradiated Type 304 SS by TIG welding on plate type specimens between this study and reported studies [6,7]. The weld heat input conditions examined in this study were lower than those of reported studies. The weld cracking susceptibility of Type 304 SS became sensitive as helium concentration and weld heat input increased. Also, sound welding was possible if the heat input was low enough. The welding pass number of this study was different from those of reported studies. For helium concentration level 3–4 appm, reported one pass welding

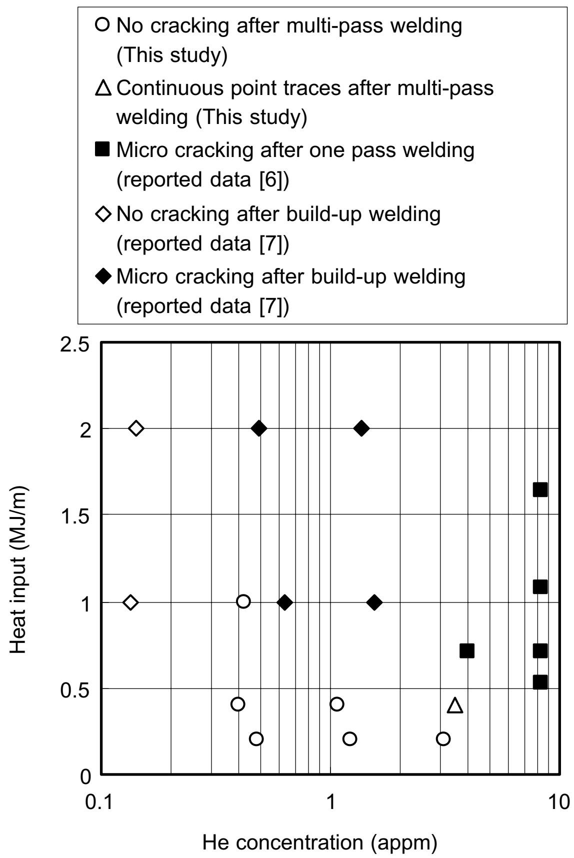

Fig. 5. Test results comparison between this study and reported study for welding on Type 304 SS by TIG welding.

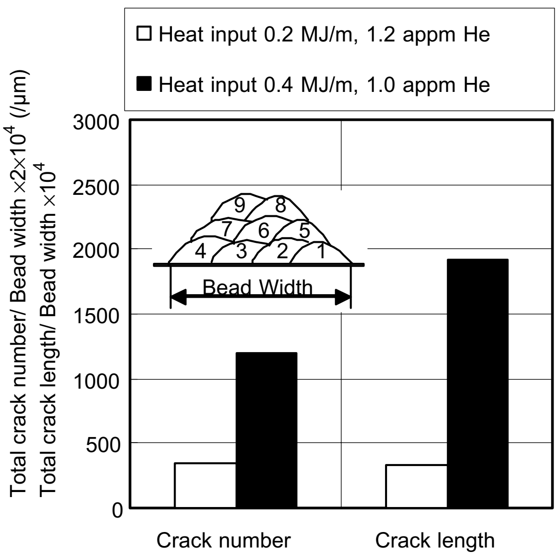

Fig. 6. Comparison between the crack magnitude and the welding conditions. Results were from multi-pass bead-on-plate TIG welding on Type 316L SS specimens.

result with 0.7 MJ/m heat input showed cracking, however, there was no cracking in multi-pass welding with 0.2 MJ/m heat input of this study. The weld cracking susceptibility is considered to become high as pass number increases [8,9]. Therefore, contribution of heat input reduction to obtaining the sound weld was seemed to be larger than that of pass number in this case.

In consideration of difference of material, irradiated Type 316L SS had higher cracking susceptibility than Type 304 SS at equivalent helium concentration as shown in Fig. 1. Reported welding examinations on Type 316L SS containing helium have been limited, and helium induced cracking along the grain boundary was confirmed only by a helium-doped specimen by tritium trick method [3]. In order to confirm the cause of the weld cracking on neutron irradiated Type 316L SS, the form of a crack on Type 316L SS was investigated in more detail.

Fig. 6 shows the relationship between the crack magnitude and the weld heat input. The number and length of cracks were measured using the as-polished surface micrograph. One continuous line was counted as one crack. Observed crack number and length were standardized by the bead width to evaluate cracks per lateral HAZ size. The standardized crack number and length decreased as the weld heat input decreased. It seemed that cracking susceptibility was mitigated by the weld heat input reduction. This tendency is consistent with that of the weld cracking of irradiated Type 304 SS [6,7]. Nucleation, coalescence and growth of helium bubbles can occur only if the weld duration has high enough temperature and tensile stress [10,11]. If the heat input was higher, the duration in which helium bubble formation and growth was possible became longer.

Fig. 7 shows the relationship between the distance from the fusion line to the crack and the fraction of cracks to the total in Type 316L SS welded with 0.4 MJ/m heat input at 1.0 appm helium. The distance from the fusion line to the nearest crack tip was measured for every crack. And, the fraction of observed cracks in each range was evaluated. The following were found from Fig. 7:

(1) The fraction of cracks decreased as distance from fusion line became longer.
(2) Cracks were concentrated at 0–150 μm from the fusion line.

It was thought that the maximum temperature reached during welding was lower as distance from the fusion line became far. Not only the maximum temperature, but also the duration in which helium bubble

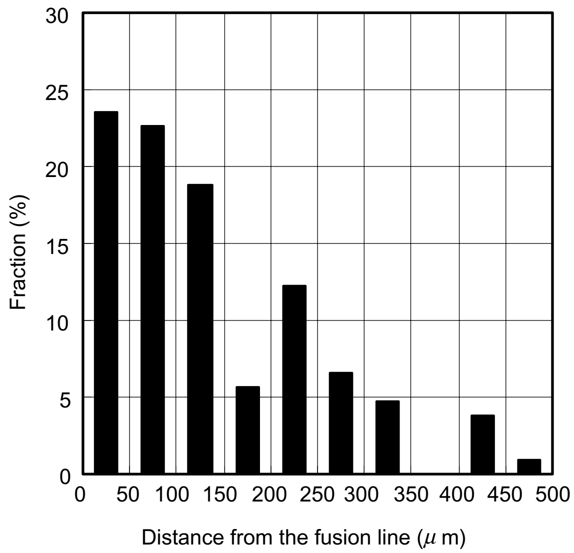

Fig. 7. Relationship between the distance from the fusion line to a crack and the fraction of cracks of 0.4 MJ/m multi-pass TIG welded Type 316L SS specimen containing 1.0 appm He.

formation and growth was possible might become shorter as distance from the fusion line became longer. Therefore, the helium bubble formation and growth were restricted as the distance from the fusion line became longer.

The observed crack nature of neutron irradiated Type 316L SS was along the grain boundary, and these were located in the weld HAZ as shown in Fig. 2. This kind of cracks was not observed in the welding test by using the un-irradiated Type 316L SS specimen with the same welding condition as those for irradiated specimens. Furthermore, analyses for test results of irradiated Type 316L SS discussed above showed the same tendency as that of the weld crack on irradiated Type 304 SS. Therefore, it was considered that the helium bubble formation at grain boundary due to weld heat input caused cracking in the weld HAZ of irradiated Type 316L SS the same as in Type 304 SS [6,7].

5. Summary

Welding tests were conducted for neutron-irradiated stainless steels. Findings were as follows:

1. Neither visible cracks nor traces of helium bubbles were found in the multi-pass bead-on-plate TIG welding test for Type 304 SS specimens containing up to 3 appm helium.
2. In the case of YAG laser welding, neither visible cracks nor traces of helium bubbles were found in the multi-pass bead-on-plate welding test for Type 304 SS specimens containing up to 18 appm helium.
3. The weld cracking susceptibility of irradiated Type 316L SS seemed to be higher than that of Type 304 SS. However, crack-free multi-pass welding was achievable for Type 316L SS containing 1.0 appm helium by 0.2 MJ/m multi-pass YAG laser welding.
4. Helium bubble formation and growth process was considered to cause the weld cracking of irradiated Type 316L SS as well as Type 304 SS. The detailed reason for the difference of the weld crack susceptibility between Type 316L and Type 304 SSs should be studied in future.

Acknowledgements

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