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Weldability of helium-containing stainless steels using a YAG laser

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Abstract

Bead-on-plate welding experiments using a 400 W YAG laser were conducted on SUS304 stainless steels implanted with helium ions of 0.5, 5 and 50 appm uniformly to a depth of 0.25 mm. High heat input welding at 20 kJ/cm caused surface grain boundary cracking in the heat-affected zone at 50 appm He. Cross-sectional observations after etching in oxalic acid solution revealed that bubble growth at grain boundaries in the heat-affected zone was enhanced at higher heat input and at higher helium concentrations. Bubble growth was negligible for the laser welding condition of 1 kJ/cm even at 50 appm He. The results suggest that YAG laser welding is a promising welding technique for stainless steels containing high amounts of helium.

1. Introduction

Replacement and repair techniques for degraded structural components is one of the important technical issues for fusion reactor development from the viewpoint of reactor maintenance. Such procedures are likely to require various welding techniques for joining irradiated materials. The reactor components exposed to high energy neutrons contain large amounts of helium produced by nuclear transmutation reactions. Helium is known to have a large effect on weldability and properties of welded joints [1–8]. Weld metal cracking, heat-affected zone (HAZ) cracking and underbead cracking have been reported in helium-containing stainless steels. Although the full process of weld cracking is well understood, helium is considered to affect weldability by weakening grain boundaries through rapid growth of bubbles under the influence of high temperature and thermal stresses. A low penetration gas metal arc (GMA) weld overlay [2] and stress-modified welding [3] have been proposed for the improvement of weldability compared to that obtainable with conventional gas tungsten arc (GTA) welding.

The objective of the present study is to investigate the effect of helium concentration and heat input on weldability using an yttrium aluminum garnet (YAG) laser and to demonstrate the applicability of the YAG laser welding technique to stainless steels containing high amounts of helium. The YAG laser welding technique is considered to be beneficial for welding of helium-containing materials because of its low heat input and rapid cooling rate compared to GTA welding and also because of the availability of remote maintenance procedures using optical systems.

2. Experimental procedures

The material used was SUS304 stainless steels, solution-annealed for 0.5 h at 1323 K. The chemical composition is as follows: 0.05 C, 0.41 Si, 0.86 Mn, 0.025 P, 0.004 S, 8.27 Ni, and 18.25 Cr in weight percent. The material was cut into platelet specimens of 40 mm diameter and 10 mm thickness and the specimen surface was finished with #600 paper. The specimens were implanted with 36 MeV helium ions using a cyclotron at

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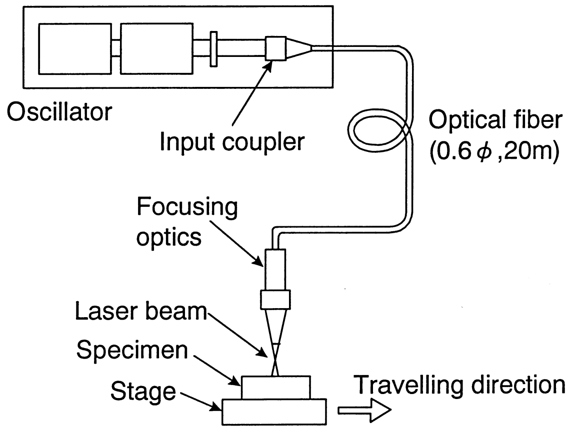

Fig. 1. Schematic diagram of the equipment and specimen.

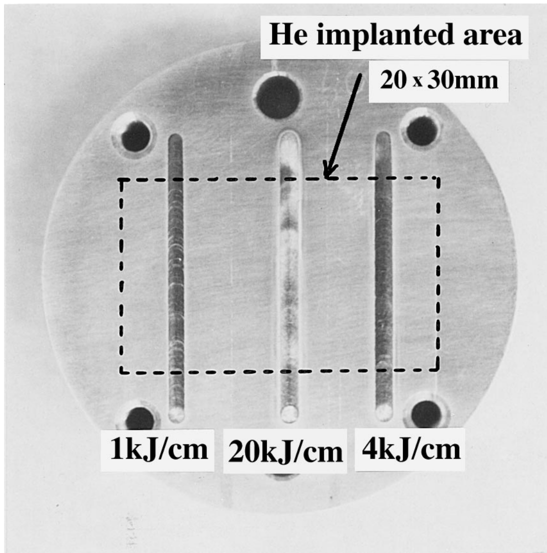

Fig. 2. Surface appearance of a 50 appm He specimen after welding.

Tohoku University. The implanted area was limited to 30×20 mm^2 by the same size window placed on the specimen surface for the scanned beam. A beam energy degrader was applied to obtain uniform implanted helium distribution from the surface to a depth of 0.25 mm. The calculated helium concentration was 0.5, 5 and 50 atomic parts per million (appm). The specimen surface temperature was monitored during implantation and kept below 423 K.

After implantation, bead-on-plate welding experiments were conducted with a 400 W continuous wave laser beam from a 600 W YAG laser oscillator. Fig. 1 shows a schematic diagram of the equipment. The laser beam from the oscillator was irradiated on the specimen surface through an input coupler, 20 m optical fiber and focusing optics. Argon shielding gas was used during welding. The laser beam diameter on the specimen surface was 1.6 mm. The specimen surface was slightly polished before welding to keep reflection efficiency of the surface constant for the laser beam. On each specimen, three weld beads were formed across the helium-implanted area at welding speeds of 0.2, 1 and 4 mm/s. The specimens, fixed on the heat sink block made of stainless steel, were moved relative to the focusing optics. The welding at 0.2, 1 and 4 mm/s corresponds to nominal heat inputs of 20 kJ/cm which is typical of high heat input GTA welding, 4 kJ/cm which is typical of low heat input GTA welding, and 1 kJ/cm which is typical of laser welding, respectively.

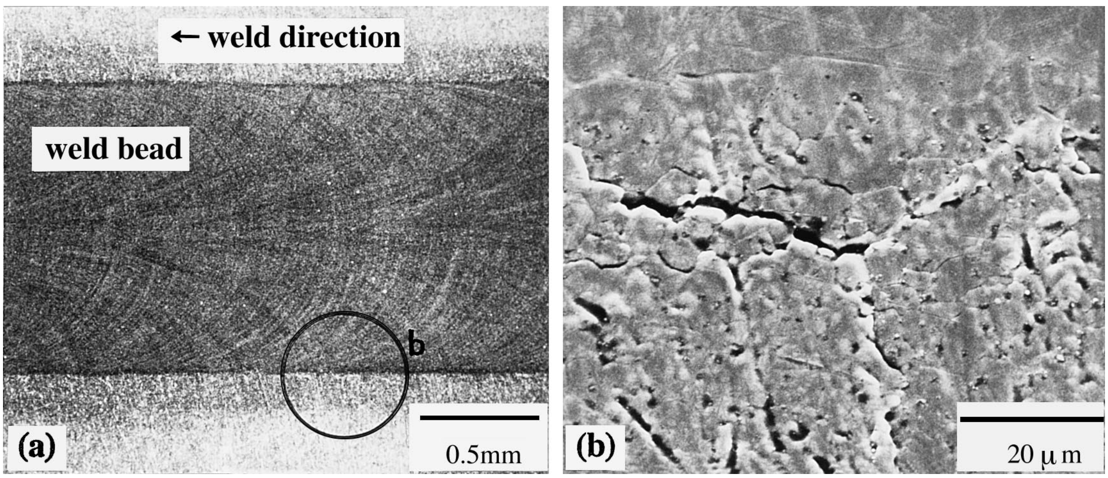

Fig. 3. A surface crack in the HAZ of the specimen containing 50 appm He welded at 20 kJ/cm: (a) weld bead; (b) cracks in the HAZ at higher magnification.

After welding, a liquid penetrant test and SEM observation of the surface and of a transverse cross-section of the weld bead were performed.

3. Results and discussion

Fig. 2 shows an example of the specimen appearance after welding. The bead width increased slightly from 1.3 mm at 1 kJ/cm to 1.5 mm at 20 kJ/cm. Fig. 3 shows shallow surface cracks observed in the HAZ of the specimen containing 50 appm He after welding at 20 kJ/cm. The cracks were intergranular in nature and were observed at 0.01 mm from the fusion line. No surface cracking was detected in the HAZ of other specimens. No cracks were observed on the weld metal in any specimens.

In cross-section, some defects in the HAZ and weld metal were observed after etching in 10% oxalic acid solution although no defects were detected in the as-mechanically polished condition. Fig. 4 shows typical SEM images around the fusion lines. Small pits along grain boundaries in HAZ and isolated pits in the weld metal were observed in the welded specimens with 5 and 50 appm He. In the case of 50 appm He at 20 kJ/cm, a wide array of pits along grain boundaries continued to the specimen surface, possibly at the origin indicated by the liquid penetrant test. The maximum depth of the weld bead was 0.48 mm (20 kJ/cm), 0.32 mm (4 kJ/cm) and 0.30 mm (1 kJ/cm) and was larger than the

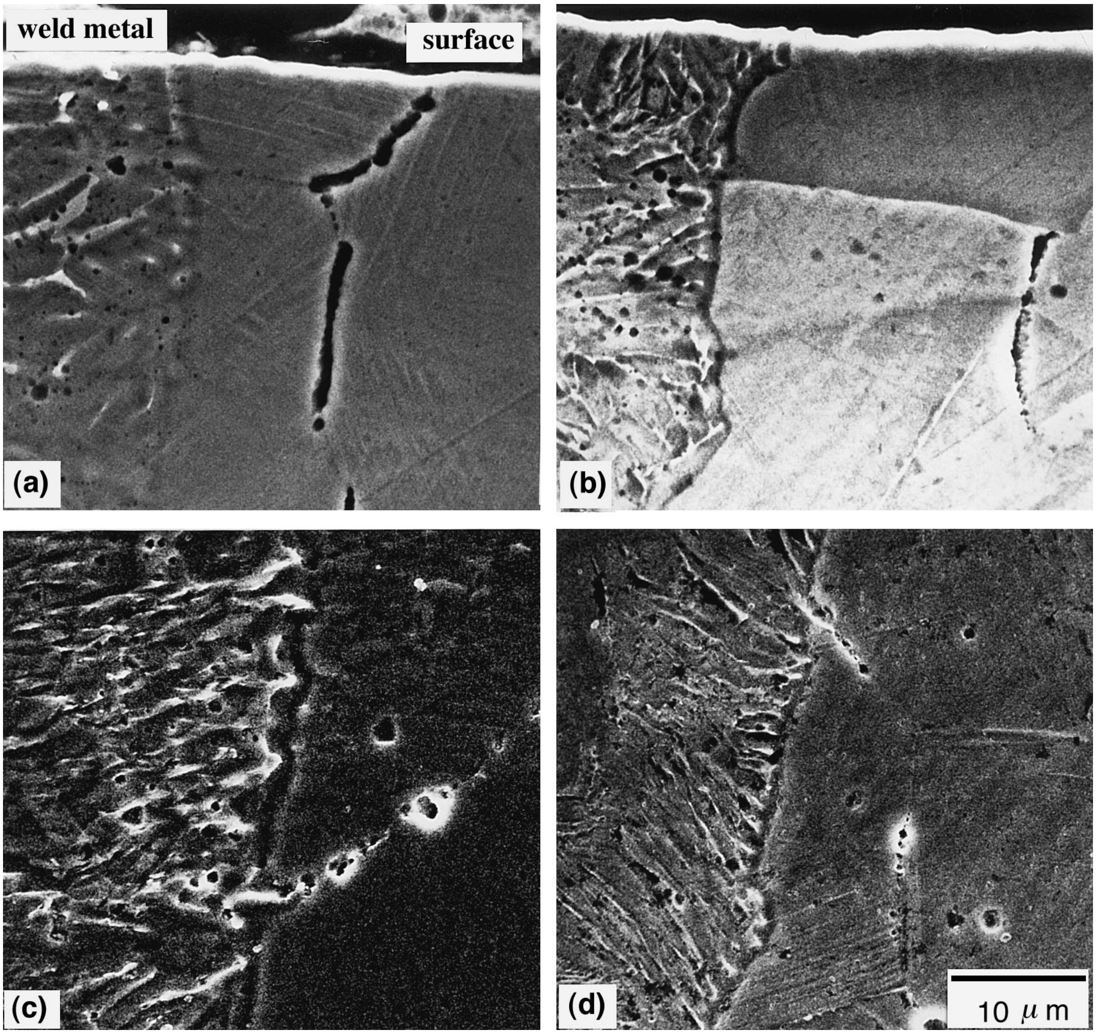

Fig. 4. SEM images of the HAZ in a transverse cross-section of a weld bead: (a) 50 appm He, 20 kJ/cm; (b) 50 appm He, 1 kJ/cm; (c) 5 appm He, 4 kJ/cm; (d) 5 appm He, 1 kJ/cm.

helium-implanted depth (0.25 mm), whereas small pits on grain boundary were formed only within the helium-implanted depth at a distance of less than 0.1 mm from the fusion lines. These results indicate that the grain boundary pits may be closely related to the existence of helium and to welding conditions, and were formed at helium bubbles. The direction of the grain boundary on which pits were formed was parallel to the fusion line in near surface region and was perpendicular to the fusion lines in the region around 0.25 mm depth. The isolated pits in the weld metal are also considered to be formed at helium bubbles because the pit density was higher for higher helium concentration. However, pit density was independent of heat input for the same helium concentration. Fig. 5 shows the effects of helium concentration and heat input on the total length of grain boundary with pits. The bubble growth is clearly dependent on both helium concentration and heat input. For laser welding with a heat input of 1 kJ/cm, bubble growth was much less than that for welding with 4 and 20 kJ/cm, which are typical heat inputs for GTA welding. Fig. 6 shows temperature change during welding at a position 0.01 mm from the fusion line, calculated assuming a Gaussian beam intensity distribution in the laser beam spot and a semi-infinite solid heat sink. The cooling-down time to below 773 K after the peak temperature is less than 1 s at 1 kJ/cm and is much shorter than that at 20 kJ/cm. A low heat input welding technique is beneficial for stainless steels containing helium as high as 50 appm.

In the present study helium was implanted using a cyclotron, and welding experiments with heat inputs as high as those for GTA welding were simulated using low-speed laser welding. The reported welding experiments on stainless steels containing helium under conditions similar to the present experiment are as follows. Asano et al. [8] reported underbead cracking in neutron-irradiated 304 stainless steels with 8 appm He using GTA bead-on-plate welding at 7 kJ/cm. Franco-Ferreira et al. [7] reported surface HAZ cracking in 304 stainless steel with 50 appm He introduced by the tritium trick method using GTA welding at 1.5 kJ/cm. These reports showed more severe helium effects on weldability than did the present experiments in which no cracking was observed except for 50 appm He at 20 kJ/cm. One reason for this difference is considered to be the difference in

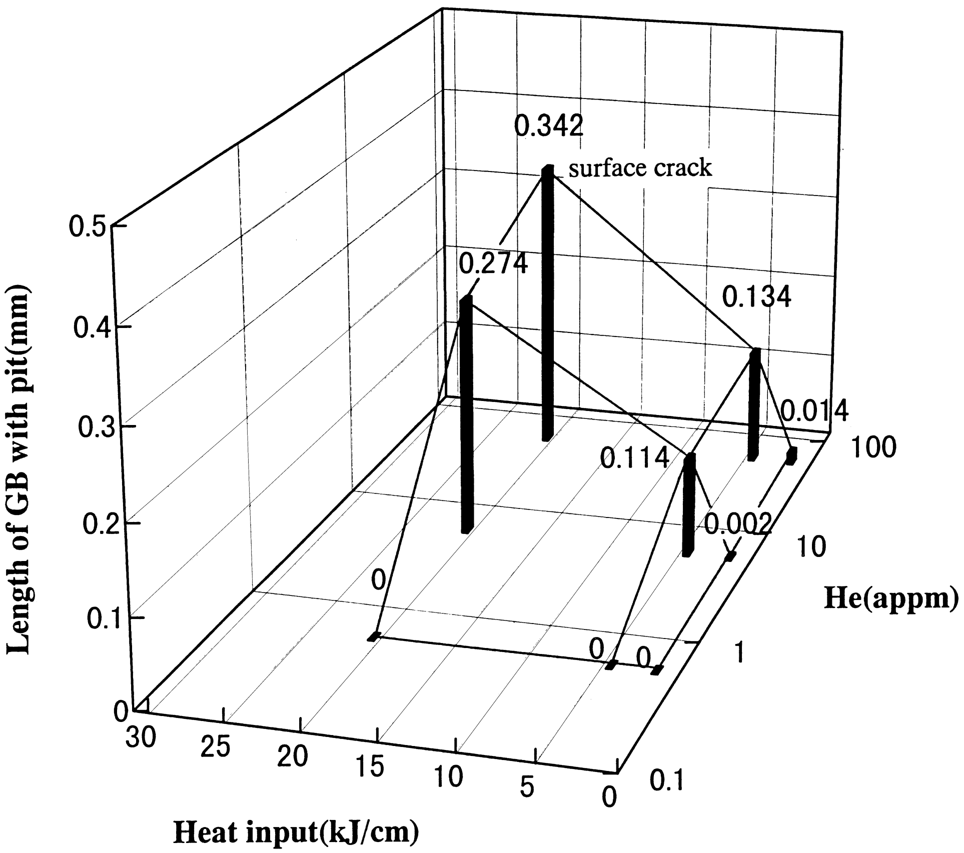

Fig. 5. Length of grain boundary with pits as a function of helium concentration and heat input.

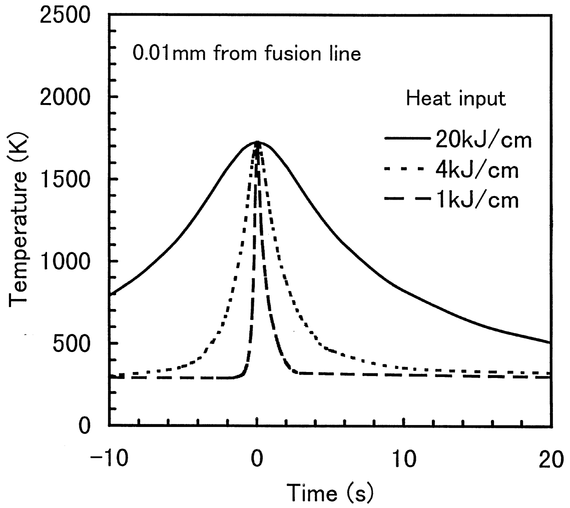

Fig. 6. Calculated temperature change at a position 0.01 mm from the fusion line during welding.

bead size. The transverse cross-sectional area of the bead in the present study was less than 0.5 mm^2, whereas the area is more than 1 mm^2 in conventional GTA welding according to the literature. Because a larger bead size causes higher stress in HAZ during bead shrinkage, bubble growth rate becomes higher in larger bead cross-section when the temperature history is similar [1,9]. Thus, a welding technique that results in low penetration and small bead size is considered to be beneficial for materials containing a high amount of helium.

4. Conclusions

YAG laser welding experiments performed with heat input up to 20 kJ/cm on SUS304 stainless steel containing helium have clearly shown the effect of helium and heat input on weldability. Low heat input YAG laser welding is a promising welding technique for stainless steel containing a high amount of helium.

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