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Effect of weld thermal cycle on helium bubble formation in stainless steel

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Abstract

Helium bubble structure was examined on a helium-implanted stainless steel after applying two kinds of heat input. Helium ions were implanted on Type 304 stainless steel at 573 K from 2 to 200 appm to a peak depth of 0.5 μm from the surface. After that, weld thermal history was applied by an electron beam. The cooling rates were selected to be 370 and 680 K/s from 1023 to 773 K. TEM observation revealed that nucleation and growth of helium bubbles were strongly dependent on the cooling rate after welding and the helium concentration.

1. Introduction

Helium produced by neutron irradiation is known to degrade weldability of irradiated stainless steels. It has been reported that the cracking after welding was caused by helium embrittlement [1], and that this embrittlement was attributed to the nucleation and growth of helium bubbles at grain boundaries during the welding process, resulted in ductile grain boundary cracking [2]. Details of the bubble evolution during welding are important for understanding the mechanisms of weld cracking in helium-containing materials [3]. The growth of helium bubbles in helium implanted stainless steels has been well investigated for the thermal annealing conditions [4]. However, welding gives a different thermal history with a higher temperature and shorter time than annealing conditions. The behavior of helium atoms and point defects during welding is different from that during annealing. However, such experiments are scarce.

In the present study, helium bubble structure was examined on a helium-implanted stainless steel after applying heat input by an electron beam for simulating YAG laser and tungsten inert gas (TIG) welding conditions. Taking notice of the difference of the cooling rate between YAG laser welding (quick cooling) and TIG welding (slow cooling), the behavior of helium bubble in the heat affected zone (HAZ) and weld zone was examined with scanning electron microscopy (SEM) and transmission electron microscopy (TEM).

2. Experimental procedures

Helium ions with an energy of 200 keV were implanted in the specimens of Type 304 stainless steel at 573 K to 2, 5, 10, 20 and 200 appm to a peak depth of 0.5 μm from the surface. The specimen, which was $25 \times 8 \times 0.7$ mm^3, was solution annealed before implantation at 1323 K for 30 min. The simulated weld thermal history was applied on the back of the specimens (not on the He- implanted surface) by a 35 kW electron beam in high vacuum atmosphere (10^{-6} Pa) to prevent oxidation of the implanted surface. The setup of the specimen for electron beam heating is shown in Fig. 1. The specimens were tightly fixed to the specimen holder on both sides. The specimen holder had sufficient

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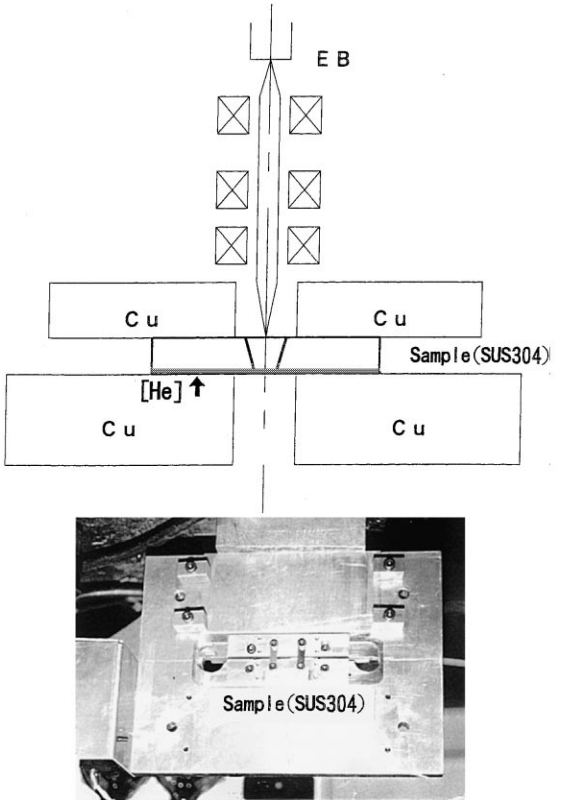

Fig. 1. Schematic illustration of the experimental setup and the photo of the sample stage.

thermal conductivity from the specimen to the copper block. Width of copper block set at both sides and the electron beam intensity were changed to control the cooling rate of the specimen. The cooling rate from 1023 to 773 K in HAZ where TEM observation is carried out is used as the parameter to indicate the cooling curves of the weld thermal cycle on the specimens. This was selected to be 39 and 128 K/s which are typical to TIG welding and YAG laser welding, respectively. Fig. 2 shows the cooling curves in HAZ where TEM observation is carried out at a distance of 1.5 mm from the center of the melted area. They were obtained by thermal conduction calculations [5], and measurements of the temperature change on dummy specimens. The electron bombarded area in the back surface was melted and the width of melted area on the back surface was about 2 mm. The melted zone extended to the front surface of the specimen. TEM discs of 3 mm in diameter were punched out at the center of the melted area and at the HAZ area as shown in Fig. 3. TEM discs were electropolished to 0.2 μm on the implanted surface and back-thinned for perforation in 10% $HClO_4$ + CH_3COOH solution. After that, TEM observation was

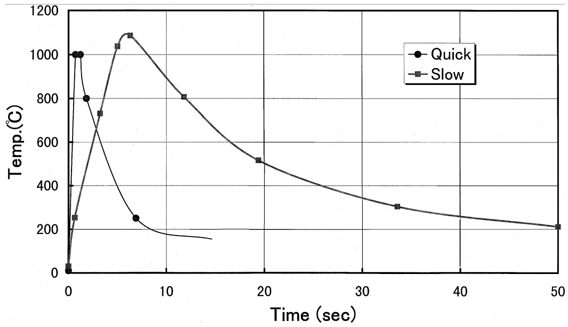

Fig. 2. Cooling curve as a function of the time for the different cooling rates.

carried out as shown in Fig. 4. Microstructural observation was conducted using an FE-TEM (TOPCON EM-002BF) operated at 200 kV.

3. Results and discussion

In the specimen implanted with helium before electron bombardment, few bubbles were observed. Fig. 4 shows TEM microstructures of HAZ implanted with different amounts of He after electron bombardment with a cooling rate of 128 K/s. Helium bubbles with a diameter up to 100 nm were observed in the specimens with 20 and 200 appm He. Helium bubbles in HAZ were quite homogeneously distributed in grains and at grain boundaries with this quick cooling rate. With increasing helium concentration the bubble density was higher. However, the size of the bubbles was larger with increasing helium up to 10 appm and was independent of helium concentration at more than 10 appm He. There were no helium bubbles in the HAZ in the specimen with 2 appm He.

It is clear that the helium bubble size in the specimen with a cooling rate of 39 K/s was larger than that in the specimen with a cooling rate of 128 K/s as shown in Fig. 5. The largest bubbles in the present experiment were located on grain boundaries and dislocations in the HAZ of the slow cooled specimen implanted to 200 appm He as shown in Fig. 6. In the fusion zone there are a few bubbles with quick cooling rate and there are a lot of them with slow cooling as shown in Fig. 7. From the observations the change of the bubble distribution was conspicuous with increasing helium amount. Although it is considered that most of the implanted helium is released from the melted area, it is retained in the HAZ. The bubble size was larger for the specimens with a lower cooling rate, both in the HAZ and fusion zone. The bubble nucleation and growth were strongly dependent on the cooling rate and helium concentration.

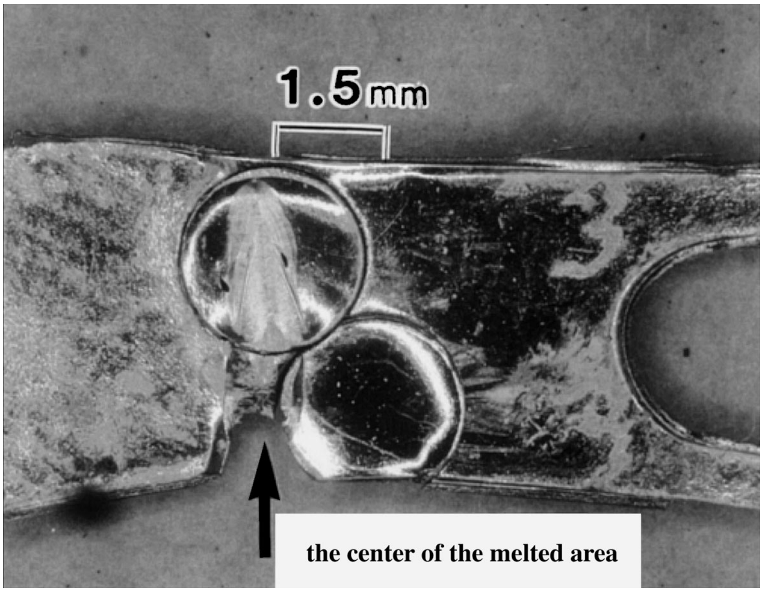

Fig. 3. Punched and electropolished TEM specimens in the fusion zone and HAZ.

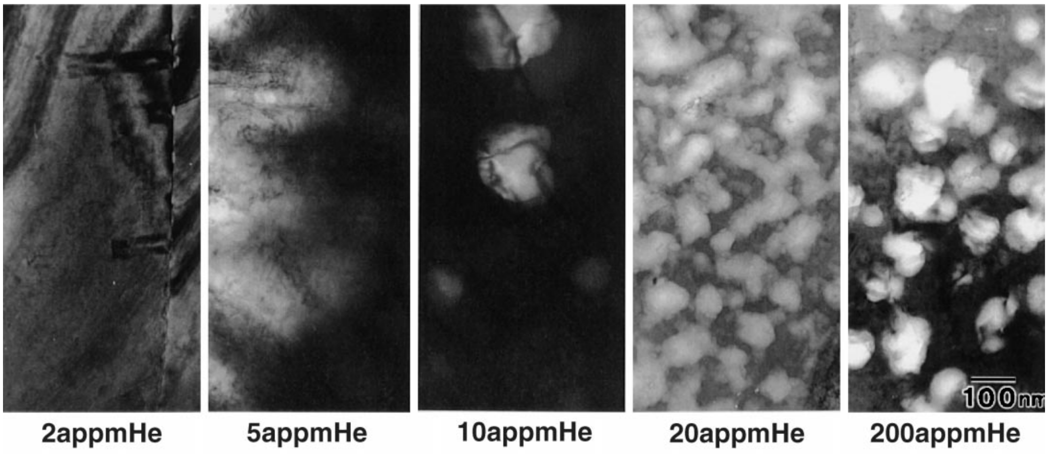

Fig. 4. Helium bubble microstructure in HAZ with a cooling rate of 128 K/s containing 2, 5, 10, 20, 200 appm He.

Weld thermal history contributes to nucleation, growth and coalescence of microvoids in material containing helium. The number of helium bubbles increases with increasing helium. The growth of helium bubbles is controlled by the thermal history during welding. The concentration of equilibrium point defects also becomes higher as the temperature becomes higher, and it is highest near the fusion zone. Some of the surplus vacancies are supplied to the matrix during cooling after welding. These vacancies are easily annihilated due to moving during cooling. If there are a number of helium atoms present, those surplus vacancies are trapped by helium. As the time at high temperature in the case of the slow cooling is longer than in the case of quick cooling, helium bubbles grow more easily in the case of a slow cooling rate. If the total heat input and peak temperature are constant, the better way of welding irradiated stainless steel to prevent helium embrittlement is a quick cooling welding.

4. Summary

With increasing helium concentration the bubble density was higher. However, the size of the bubbles

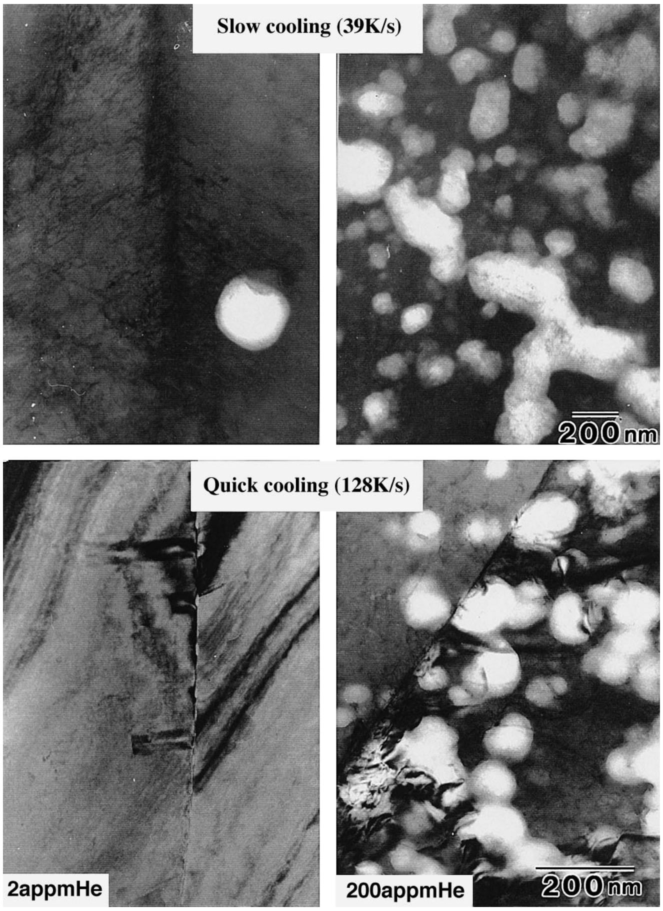

Fig. 5. Comparison of helium bubble microstructure in HAZ on the 128 K/s quick cooling with the 39 K/s slow cooling (2 and 200 appm He).

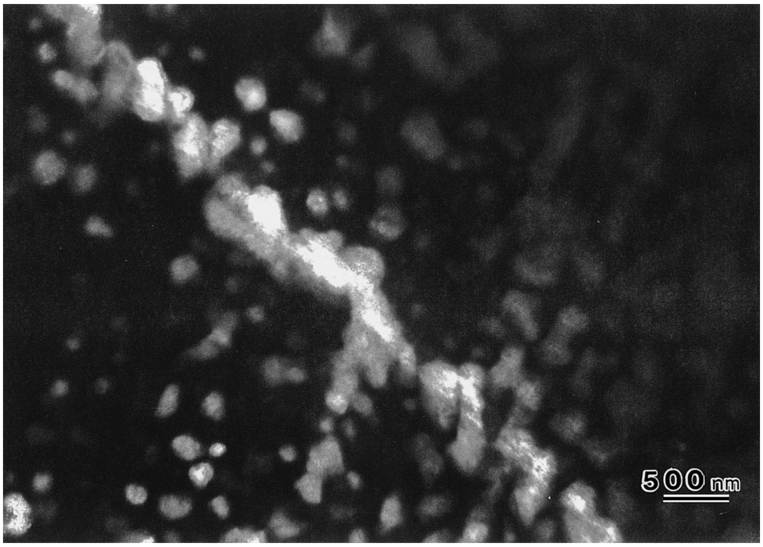

Fig. 6. Microstructure of helium bubbles along dislocation in HAZ with a cooling rate of 39 K/s.

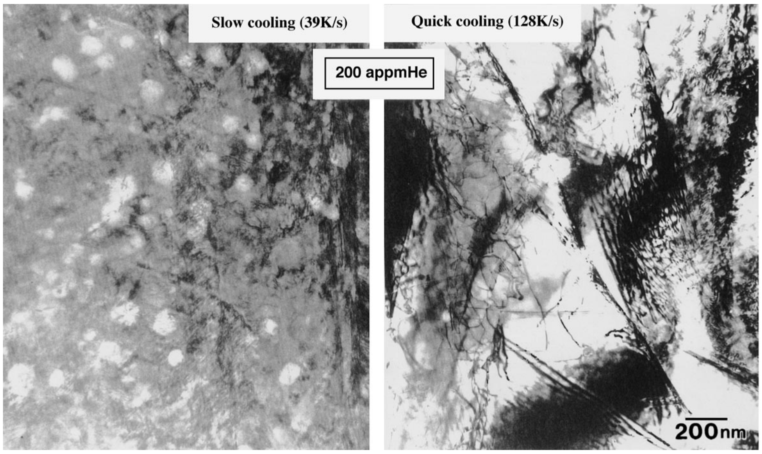

Fig. 7. Helium bubble microstructures in the fusion zone with a cooling rate of 39 and 128 K/s (200 appm He).

was larger with increasing helium up to 10 appm and was independent of helium concentration at more than 10 appm He. Weld thermal history promotes nucleation and growth of bubbles in material containing helium.

It is suggested that the cooling rate is an important parameter to control when welding of irradiated material is carried out.

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