ELSEVIER

Journal of Nuclear Materials 283–287 (2000) 1220–1223

journal of nuclear materials

www.elsevier.nl/locate/jnucmat

Effect of weld thermal cycle and restraint stress on helium bubble formation in stainless steels

S. Kawano [a,*], K. Fukuya [a,1], F. Kano [a], M. Satou [b], A. Hasegawa [b], K. Abe [b]

[a] Power and Industrial Systems R&D Center, Toshiba Corporation, 8 Shinsugita-cho, Isogo-ku, Yokohama 235-8523, Japan

[b] Faculty of Engineering, Tohoku University, Aramaki-aza-Aoba, Aoba-ku, Sendai 980-0845, Japan

Abstract

Helium bubble structure was examined in helium-implanted stainless steels after applying thermal cycles and tensile stresses using a weld thermal and stress cycle simulator. SUS304 specimens implanted with helium ions to 5 appm were heated at 1473 K for 2 s in an argon gas atmosphere. The heat-up rate and cooling rate were controlled to be 90 and 130 K/s, respectively. Tensile stresses ranging from 0 to 4 MPa were applied immediately after reaching a temperature of 1473 K. TEM observation revealed that bubble formation occurred even after short annealing times and that the size of the helium bubbles was strongly dependent on the tensile stress during heating.

1. Introduction

Helium produced by neutron irradiation is known to degrade the weldability of irradiated stainless steels [1–5]. The mechanism of weld cracking in irradiated materials is considered to be rapid growth of helium bubbles formed at grain boundaries (GBs) under the influence of high temperatures and thermal stresses, to a size sufficient to cause GB separation.

Some theoretical models of helium bubble behavior during welding have been proposed for predicting weldability [5–7]. In order to understand the mechanism of weld cracking in irradiated materials and verify the proposed models, details of bubble evolution during welding are necessary. The growth of bubbles in helium-implanted stainless steels has been investigated thoroughly with respect to thermal annealing conditions at constant temperature [8]. However, welding gives a different thermal history with a higher temperature and shorter time than possible in annealing experiments. The behavior of the helium atoms and the lattice defects during welding are considered by the current authors to be different from those in the annealing case. Helium bubble morphology in the welded helium-containing stainless steels has also been studied [5,9,10]. However, the effects of thermal history and stress state on bubble evolution have not been examined.

In the present study, the helium bubble structure was examined in helium-implanted stainless steels after applying thermal cycles and tensile stresses using a weld thermal and stress cycle simulator.

2. Experimental procedures

The material used was SUS304 stainless steel, with a grain size of about 20 μm. The chemical composition is as follows: 0.06 C, 0.57 Si, 1.03 Mn, 0.025 P, 0.007 S, 8.57 Ni and 18.22 Cr in weight percent. Tensile specimens, the gauge sections of which were 14 mm long, 3 mm wide and 0.2 mm thick, were implanted with 3-MeV helium ions at room temperature. The implanted area was limited to 3 mm in diameter at the center of the specimen. A beam energy degrader was applied to obtain a uniform helium-implanted layer which existed between 1.5 and 3.5 μm in depth from the surface. The helium concentration was controlled to be 5 appm.

* Corresponding author. Tel.: +81-45 770 2372; fax: +81-45 770 2483.

E-mail address: shohei.kawano@toshiba.co.jp (S. Kawano).

[1] Present address: Institute of Nuclear Safety System, Incorporated, Mihama, 919–1205, Japan.

0022-3115/00/$ - see front matter
PII: S0022-3115(00)00174-4

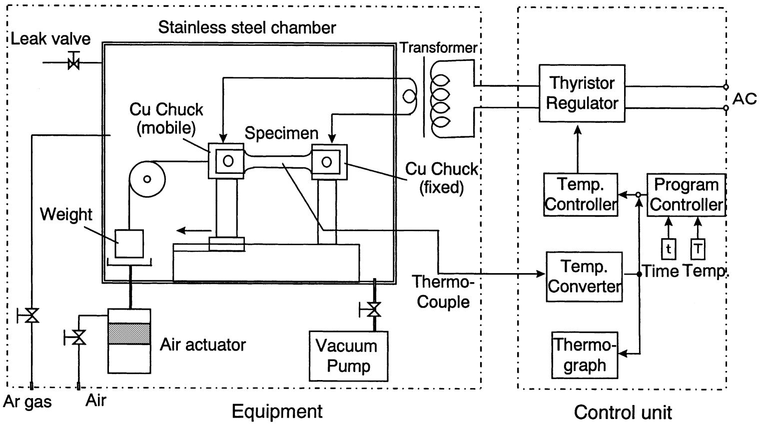

Fig. 1. Schematic diagram of the weld thermal and stress cycle simulator.

The heat cycle was applied on the specimens by a weld thermal and stress cycle simulator, a schematic diagram of which is given in Fig. 1. The two ends of the specimen were horizontally clamped using two copper chucks. One chuck was fixed on to the base and the other was mobile only along the axial direction of the specimen, in order to enable application of tensile stress and thermal expansion of the specimens. The specimens were heated in an argon atmosphere by passing an electrical current through them. A thermocouple for temperature control was spot-welded 2 mm from the center of the helium-implanted area. The correction for temperature was determined using an axial temperature distribution on specimens in order to apply the desired thermal cycle at the center of the specimen. Tensile stress was applied by a dead weight through a wire attached to the free end of the specimen.

Fig. 2 shows a schematic figure of the applied thermal and tensile stress cycles. The specimens were heated at 1473 K for 2 s. The heat-up rate and cooling rate were controlled to be 90 and 130 K/s, respectively. This thermal cycle was selected to simulate temperature history during the tungsten inert gas welding at 20 kJ/cm heat input at the position of 1 mm from the fusion line. Tensile stresses varying between 0 and 4 MPa were applied immediately after reaching a temperature of 1473 K. The stress levels were selected below 8 MPa, a stress at which the specimens showed rupture at 1473 K in this study. After applying the thermal and stress cycles, TEM disks 3 mm in diameter were punched out from the helium-implanted area of the specimens. These TEM disks were electropolished to a depth of 2 μm from the implanted surface and back-thinned for perforation in a 10% $HClO_4 + CH_3COOH$ solution. Microstructural observation was conducted using an FEG-TEM (TOPCON EM-002BF) operated at 200 kV.

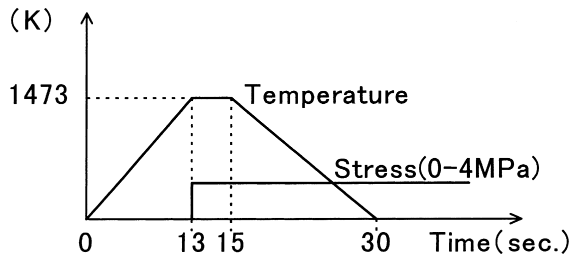

Fig. 2. Applied thermal and stress cycles.

3. Results and discussion

In the specimens implanted with helium before heating, few bubbles were observed. Fig. 3 shows TEM microstructures of the implanted specimens after applying thermal and tensile stresses varying between 0.2 and 1.2 MPa. Helium bubbles with diameters ranging from 20 to 60 nm were observed both at GBs and in the matrix. Some bubbles were observed at triple points as shown in Fig. 3(d). Most of the observed bubbles were crystallographically faceted in shape. Fig. 4 shows TEM microstructures of the heated specimens to which different tensile stress levels were applied. In the case of the stress free condition, helium bubbles were rarely observed at GBs or in the matrix. In the specimens to which tensile stresses ranging from 0.2 to 4 MPa were applied, helium bubbles with diameters of up to 100 nm were observed. Table 1 shows the average GB bubble diameter observed in the specimens after applying different stresses. The bubble size was larger for specimens with higher tensile stress. The tensile stress tends to enhance helium bubble growth at the elevated temperature.

Reported TEM observations of helium bubble in the HAZ of welded, helium-containing stainless steels are as follows. Goods et al. [9] reported helium bubble growth

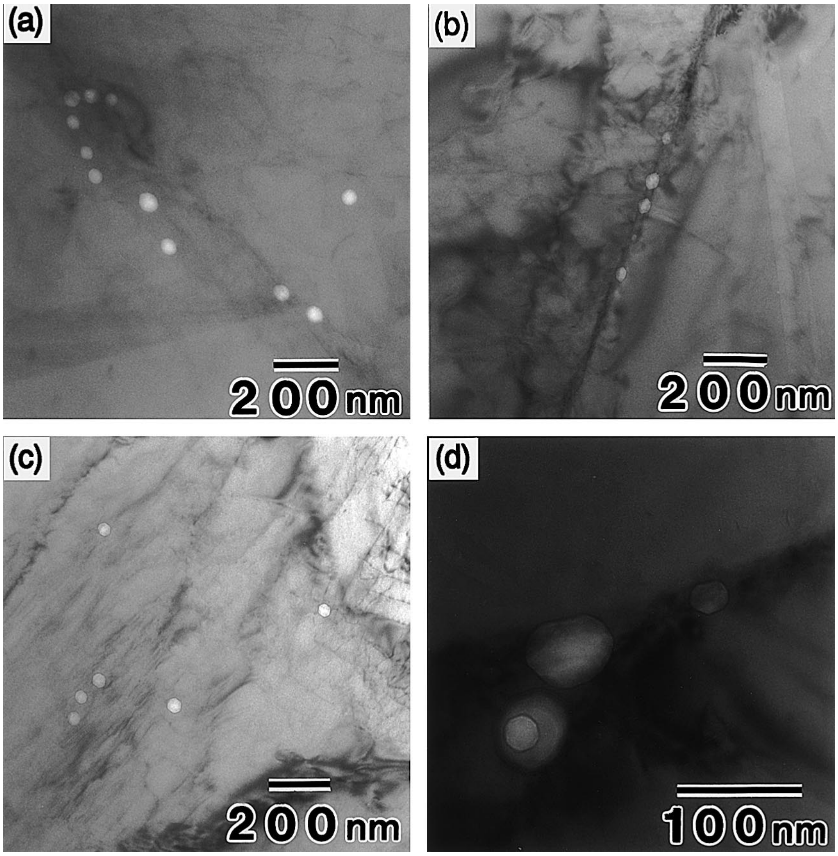

Fig. 3. Helium bubble microstructure after applying thermal and stress cycles. (a) 0.2 MPa at GB, (b) 0.5 MPa at GB, (c) 0.5 MPa in matrix, (d) 1.2 MPa at triple point.

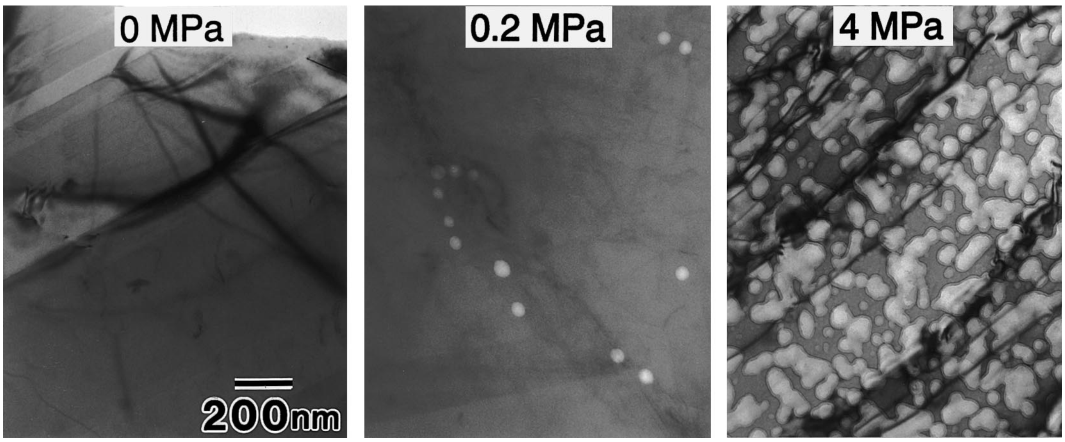

Fig. 4. The influence of applied stress on helium bubble microstructure.

in 304 stainless steels containing 85 appm helium after gas metal arc welding. Bubbles with diameters of up to 150 nm were observed at GBs and in the matrix beneath the weld overlay. Lin et al. [5] reported helium bubble growth in the HAZ after gas tungsten arc welding at 0.7 kJ/cm in 316 stainless steels with helium concentration equal to and greater than 2.5 appm. The observed bubbles were faceted in shape [5]. In the case of welding,

Table 1
GB bubble diameter in specimens after applying different stresses

Applied stress (MPa)	0	0.2	1.2	4
GB bubble diameter (nm)	<1	77	108	>150

high temperature was applied by the welding arc and the tensile stress was generated upon cooling the constrained specimens. Although the welding condition simulated in this study was not equivalent to those reported in literature, the electron microscopic evidence presented here strongly suggests that the bubble growth observed in welded helium-containing stainless steels is caused by the thermal cycles and tensile stresses during welding.

At elevated temperatures during welding, it is considered that helium atoms in the grains diffuse and nucleate bubbles at GBs and in the matrix, following which tensile stress induces bubble growth due to vacancy absorption. Large amounts of vacancy absorption may cause bubbles to be faceted in shape. In this study, the tensile stress tends to enhance bubble growth even for short annealing times. This result suggests that bubble growth in HAZ is attributed to stress-induced vacancy absorption, which is often adopted in models for bubble growth during welding. In one proposed model, the growth rate of GB bubbles under tensile stress is given by [6]

$$\frac{\mathrm{d}r}{\mathrm{d}t} = \frac{2\pi\delta\Omega D_{\mathrm{gb}}\sigma}{LrkT}, \quad (1)$$

where r is the bubble radius, δ the GB thickness, Ω the atomic volume, D_{gb} the self-diffusion coefficient in the GB, σ the tensile stress normal to the GB, L the bubble spacing, k Boltzmann's constant and T is the temperature. Fig. 5 shows the bubble diameter change under conditions of the present study, calculated using this model [6]. The final bubble size is estimated to be 71 nm with 0.2 MPa and it increases with increasing tensile stress. The calculated bubble sizes seem to be comparable to the results of the TEM observations in this study.

The present results showed that the number density of bubbles formed at a tensile stress of 4 MPa was higher than that formed at 0.2 MPa. Such a tendency is inconsistent with the bubble behavior observed in the annealing case [10]. Further investigations on the effects

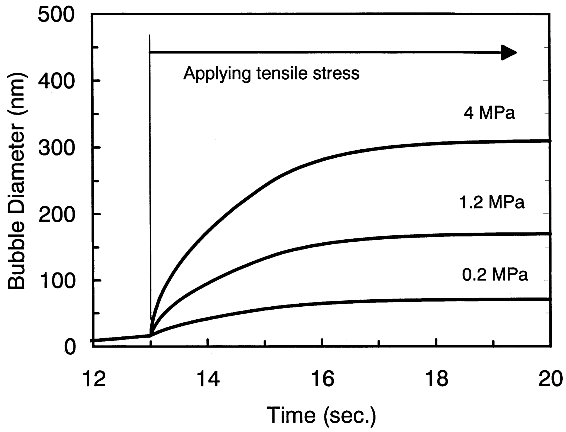

Fig. 5. Calculated bubble diameters as a function of time for different tensile stresses.

of thermal/stress cycles and helium concentration are important in understanding helium bubble behavior during welding processes.

4. Conclusions

Helium bubble structure was examined in helium-implanted 304 stainless steels after applying thermal and stress cycles using a weld thermal and stress cycle simulator. TEM observation revealed that bubble formation occurred after annealing at 1473 K for 2 s and that the size of helium bubbles was strongly dependent on the tensile stress during heating.

References

[1] W.R. Kanne Jr., Weld. J. (August 1988) 33.
[2] W.R. Kanne Jr. et al., J. Nucl. Mater. 225 (1995) 69.
[3] C.A. Wang et al., J. Nucl. Mater. 239 (1996) 85.
[4] K. Asano et al., J. Nucl. Mater. 264 (1999) 1.
[5] H.T. Lin et al., Metal. Trans. A 21 (1990) 2585.
[6] S. Kawano et al., J. Nucl. Mater. 258–263 (1998) 2008.
[7] T. Hashimoto et al., ASTM 1366 (2000) 973.
[8] T.R. Armstrong et al., Radiat. Eff. 77 (1983) 35.
[9] S.H. Goods et al., Metal. Trans. A 23 (1992) 1021.
[10] J. Rothaut et al., J. Nucl. Mater. 103&104 (1981) 1023.