§26. Mechanisms of Irradiation Hardening Due to He Bubbles

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Introduction

In the fusion reactor environment, 14 MeV neutrons generated by fusion reactions induce not only radiation defects but also transmutation hydrogen (H) and helium (He) into the structure materials. As for such a body centered cubic (BCC) alloy as the structure materials, it has been well known that the high energy particle irradiation caused an increasing ductile brittle transition temperature (DBTT), which called irradiation embrittlement. The irradiation embrittlement was caused by hardening effect due to irradiation defects and non-hardening effect due to a decreasing of the strength of grain boundaries. Hasegawa et al. reported that DBTT of He implanted H82H up to 1000 appm was increased, and the fracture mode was changed from transgranular fracture to intergranular fracture[1). Yabuuchi et al. revealed that the intergranular fracture was caused by He bubbles formed at the beneath of grain boundaries. The DBTT shift and the fracture mode was affected by irradiation defects in the matrix such as He bubbles. The objective in this study is to investigate the mechanisms of irradiation hardening due to He bubbles.

Experimental

Pure Fe (99.99%) was used for this study. Disc shaped specimens with a diameter of 3 mm were punched out from the sheets of pure Fe. The specimens were austenitized at 1273 K for 24 h and then at 1073 K for 1 h, after which they were water cooled. He implantation was carried out using Dynamitron accelerator at Tohoku University with 3 MeV He^+ ions. Energy degrader system was used to obtain the uniform depth distribution of He atoms in specimens. The typical depth profile of He concentaration was calculated by SRIM code, and is shown in Fig. 1. The nominal He concentration was 3000 appm, and implantation temperature was 333 K. He implanted specimens were heat treated at 873 K for 0.5 h in order to form He bubbles in the matrix.

To investigate the irradiation hardening due to He bubbles, a nanoindentation test was conducted using a nanoindenter (Agilent Technologies Inc. Model NanoIndenter G200) with a Berkovich type indentation tip. The indentation was performed on the implantation surface in the direction parallel to the incident He^+ beam. The constant stiffness measurement (CSM) technique was used to obtain the depth profile of hardness. The test temperature was 298 K and the nominal strain rate was 0.05 s^{-1}.

Microstructure was observed by transmission electron microscope, JEM-2010 with the accelerated voltage of 200 kV.

Results and Discussion

The depth profile of hardness of before and after implantation was shown in Fig. 2. In order to remove the indentation size effect, Nix-Gao model was applied for the results. The square of nanoindentation hardness plotted against the reciprocal of indentation depth ($1/h$) to compare with the Nix-Gao model was also shown in Fig. 2. The bulk hardness H_0, which is the square root of the intercept value, was estimated at 1.2 GPa for unimplanted pure Fe and 2.06 GPa for implanted and annealed pure Fe. The irradiation hardening due to He bubbles, ΔH, was 0.86 GPa.

Fig. 3 shows the micrograph of implanted and annealed pure Fe. He bubbles were observed and the number density was about 7.4 x 10^{21} m^{-3} and the average size was 2.1 nm. The strength factor of He bubbles were calculated on the basis of Orowan type equation, α = 0.9 was obtained.

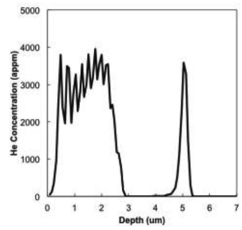

Fig. 1. Depth profile of He concentration in pure Fe

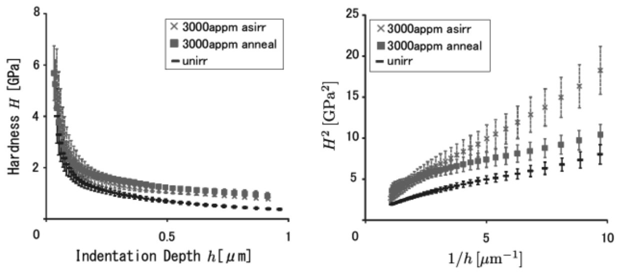

Fig. 2. Depth profile of nanoindentation hardness of He implanted pure Fe up to 3000 appm.

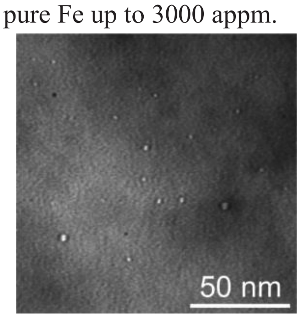

Fig. 3. TEM micrograph of He implanted pure Fe up to 3000 appm after annealing

1) Hsegawa, A. et al., J. Nucl. Mater., 386-388 (2009) 241.