Radiation Hardening and Swelling in Ti-bearing Reduced Activation Ferritic-Martensitic Steels

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1. Introduction

The blanket of DEMO nuclear fusion reactor is exposed to harsh environments such as high temperature and high neutron flux. Resistance to radiation damage as well as high temperature is required for the materials used as the blanket. RAFM (Reduced Activation Ferritic / Martensitic) steel is a strong candidate material for the structural materials of a fusion reactor, and the radiation damage of RAFM steel has been an interest for recent studies [1-3].

In this study, we investigated the radiation-induced hardening and swelling in ion irradiated Ti-bearing RAFM steels. Ti is added as an alloying element in order to induce the precipitation of (Ti,W)C nano-particles [4]. The radiation-induced hardening was characterized by compressing micro-pillars fabricated on the cross-sections of the self-ion irradiated sample. Swelling was experimentally measured by implanting He ions on the polished surface at nominal room temperature, and annealing the irradiated specimens at 700 K. The radiation damages of Ti-bearing RAFM steel are compared with other RAFM steels such as Eurofer97 and F82H.

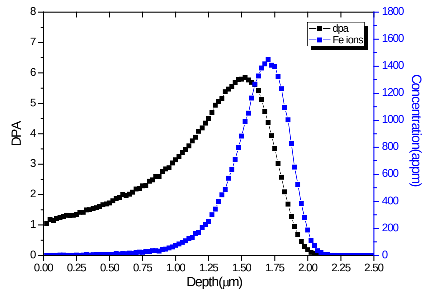
2. Experimental Methods

2.1 Specimen preparation

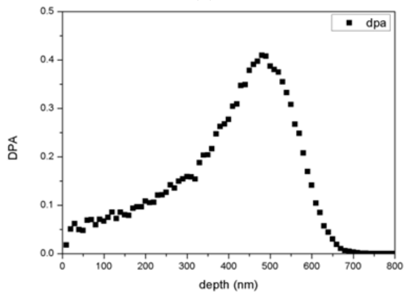
The composition of three materials is given in Table 1, and the materials were fabricated by vacuum induction melting and hot-rolling process. The samples were normalized at 1000°C for 30 minutes and tempered for 2 hours at a temperature of 650°C for E97+Ti, and 750°C for Eurofer97 and F82H.

2.2 Ion-irradiation

RAFM steels were self-ion (Fe) irradiated at the DuET (Dual-Beam Facility for Energy Science and Technology) facility in Kyoto University. The specimens had been irradiated by 6.4 MeV Fe^{3+} ions with a dose of 6×10^{15} ions/cm^2. The irradiation temperature was ~700 K. The depth profiles of dpa and ion-concentration are calculated by SRIM code [5] and presented in Fig. 1(a). The calculated peak damage was ~6 dpa at a depth of 1.5 μm.



(a)



(b)

Fig. 1 Damage-depth profile of (a) self-ion irradiation, (b) He implantation

2.3 He implantation

He irradiation has been performed at nominal room temperature by 200 keV He ions at Korea Multi-purpose Accelerator Complex (KOMAC) facility in Gyeongju. The fluence is approximately 6×10^{16} ions/cm^2. Depth profile of the dpa is shown in Fig. 1(b). TEM grid was placed on the polished surface of the samples in order to induce locally He-implanted region as shown in Fig. 2. The irradiated samples were annealed for 2 hours at 350 ^{o}C after irradiation. The surface steps were measured by using the Surface Profiling System (NV-2700, Nanosystem) [6].

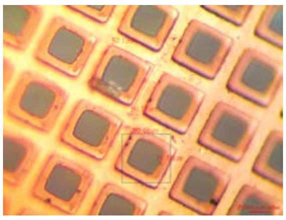


Fig. 2 Inducing He-implanted regions by using a TEM grid

Table I: The composition of materials

	C	C	W	Si	Mn	V	Ta	Ti	N	B
F82H	0.1	8	2	0.1	0.2	0.15	0.02	-	0.006	-
Eurofer97	0.11	9	1.1	0.05	0.4	0.2	0.1	-	0.03	<0.001
E97+Ti	0.1	9	1.1	0.05	0.4	0.2	0.1	0.5	0.03	<0.001

2.4 Fabricaiton of micro-pillars

The ion-irradiated surface was bonded to the same material by using G1 epoxy resin. The cross-sectional surface of the bonded samples was polished, and micro-pillars were fabricated at the cross-section of the ion-irradiated layer. The diameter-to-length ratio of the micro-pillars was approximately 1:3, and compressed by using nanoindenter [7].

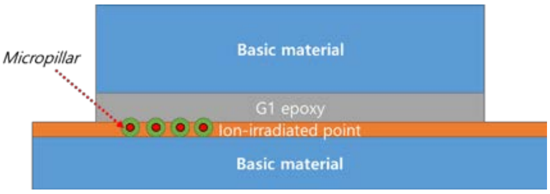


Fig. 3 Cross-sectional sample preparation method

3. Results and Discussion

SEM micrographs of deformed pillars of the micro-compressed E97-Ti RAFM steels are displayed in Fig. 4. The slip traces on the pillar surface show that single slip occurred upon yielding.

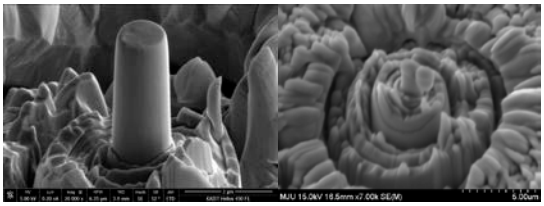


Fig.4 SEM images before and after micro-pillar compression

The results of the micro-compression experiments for various pillar diameters are displayed in Fig. 5. The engineering stress-strain curves of 6- μm-diameter down to 1 μm are comparable in magnitude; hence the size effect on mechanical properties for this material is negligible in this size range.

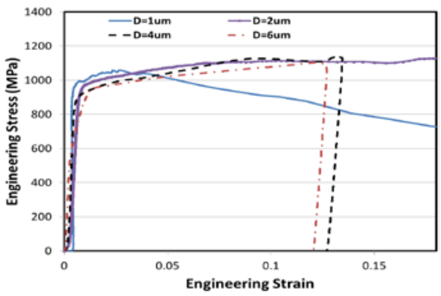


Fig.5 Stress-strain curves of E97+Ti micropillars

The measured heights of post-He-irradiation annealed samples are shown in Fig. 6. As is shown in Fig. 6, the swelling of F82H is smaller than Ti-bearing RAFM steel. The difference in swelling is induced by the difference in the formation of He bubbles. The microstructural features responsible for affecting the formation of He bubbles during post-irradiation annealing are of interest. TEM observation showed that fine (Ti,W)C particles with a size of 20~30 nm were precipitated in Ti-bearing RAFM steel.

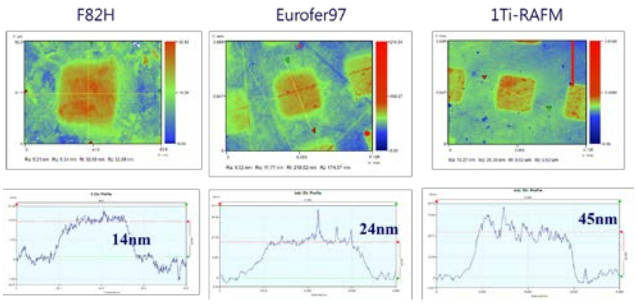


Fig.6 Surface Profiles of He ion-irradiated RAFM steels

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