Investigating the Influence of Stress on Helium Bubble Formation and Swelling in RAFM Steel

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1. Introduction

Reduced-activation ferritic/martensitic (RAFM) steel is a promising material for nuclear fusion reactors. However, the high-energy neutrons generated during reactor operation produce helium atoms, which can coalesce into helium bubbles and cause swelling, ultimately affecting the material's lifespan and properties. The formation and growth of these bubbles have been extensively studied, with reports indicating that temperature plays a significant role in the process, and that dislocations, grain boundaries, and precipitates can trap helium and cause bubble nucleation. However, in real-world fusion reactor environments, materials are subjected to high stress levels, which can further influence the behavior of helium bubbles. To better understand this phenomenon, we investigated the swelling caused by helium bubble formation under stress by injecting He ions into two newly developed steels (10Ta1Ti-T700 and 10Ta1Ti-T730) and a reference steel using specially fabricated jigs. By simulating the fusion reactor environment as closely as possible, we aimed to provide insights into how stress affects helium bubble growth and its impact on RAFM steel.

2. Experimental

The specimens used in this study had dimensions of 30mm x 3mm x 0.5mm. To apply stress to the specimens, we fabricated jigs, as shown in the schematic diagram in Figure 1. The amount of deformation applied to the specimen was controlled using an M3 screw at the end of the jig, with the pitch distance of the screw thread.

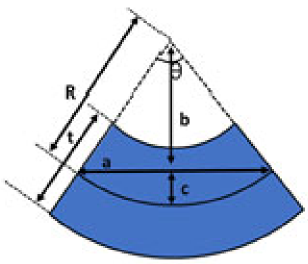

Fig. 1. Length and height change according to the stress applied to the specimen

The amount of deformation was calculated using the geometry illustrated in Figure 1, which takes into account the thickness (t), the radius value when the specimen is bent (R), the initial length (l), the length when deformed (a), and the change in height when deformed (c), as follows:

$$\sigma = -E \cdot \frac{t}{2R}$$

$$a = 2R \cdot \sin\left(\frac{l}{2R}\right)$$

$$c = R - b = R \cdot \left\{1 - \cos\left(\frac{l}{2R}\right)\right\}$$

The values for the change in c of the specimen in Fig. 1 were determined assuming elastic stresses were applied and are presented in Table 1.

To simulate the extreme environment of a nuclear fusion reactor, we categorized the elastic and plastic regions separately, resulting in five distinct stress conditions, including the zero state. The values of c were chosen as 0.62 mm for elastic stress of 300 MPa and 2.06 mm for plastic stress, taking into account the yield strength of RAFM steel. The stress level for c=2.06 mm differs from the value given in Table 1 because it corresponds to the plastic region. Each stress condition was applied in both tension and compression.

The change in height of the specimen was measured using the panoramic function of an optical microscope after applying stress. Subsequently, we attached a TEM Cu grid, as shown in Figure 2, and implanted helium ions at 0.5×10^{17} ions/cm^2 and 1×10^{17} ions/cm^2 at 120 keV energy. The change in He ion concentration according to the irradiation depth was calculated through SRIM simulation, as shown in Figure 3. After removing the TEM grid, we carried out a 2-hour heat treatment at 300℃ and observed the change in surface step using a 3D surface profiler.

Stress (MPa)	100	200	300	500	630	700	1000
C (mm)	0.21	0.41	0.62	1.04	1.30	1.45	2.06

Table 1. The deformation values calculated as a function of stress change, for a specimen with a length of 30mm and thickness of 0.5mm.

Fig. 2. Panoramic optical microscope (O.M.) photos taken before and after applying stress to the specimen using a jig, and the specimen was prepared with a TEM grid attached for further analysis..

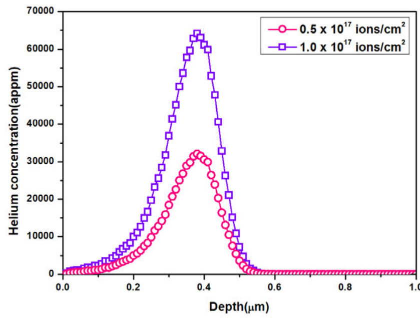

Fig. 3. The distribution graph depicts the concentration of ions as a function of implantation depth for 120 keV He ion implantation, calculated using SRIM.

3. Result and Discussion

The results presented in [Fig 4, table 2] demonstrate the effect of stress state on the swelling surface step. The surface step increased in most stress conditions compared to the zero stress condition, with a greater change observed in the plastic region than the elastic region. Additionally, when tensile stress was applied, the surface step difference was larger than under compressive stress, with the largest change observed in specimens in the plastic region under tensile stress.

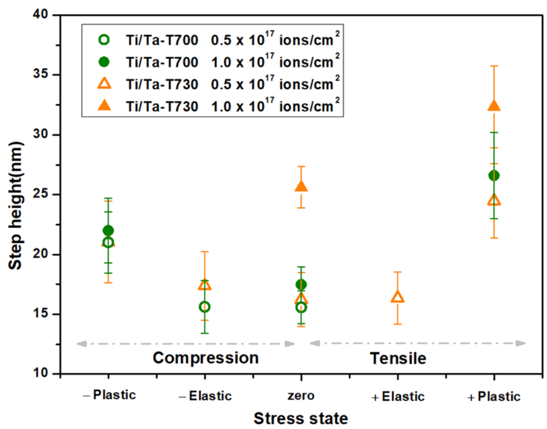

Fig. 4. The graph displays the variation in surface step resulting from swelling across different stress states.

Table 2. Results of surface step change according to stress state.

	T730				T700			
	0.5×10^{17} ion/cm^2		1.0×10^{17} ion/cm^2		0.5×10^{17} ion/cm^2		1.0×10^{17} ion/cm^2	
	Step height(nm)	STDEV	Step height(nm)	STDEV	Step height(nm)	STDEV	Step height(nm)	STDEV
-Plastic	21.06	3.42			21.01	2.56	22.00	2.70
-Elastic	17.38	2.87			15.63	2.20		
zero	16.22	2.24	25.62	1.72	15.58	1.38	17.48	1.49
+Elastic	16.36	2.17						
+Plastic	24.48	3.12	32.36	3.42			26.60	3.60

These findings are consistent with previous studies by Hao Chen et al. [1] and D.N. Braski et al. [2] who observed the behavior of helium bubbles under stress conditions. Chen et al. observed a decrease in the number of helium bubbles along the crack direction and coarsening of the bubbles when tensile stress was applied. Braski et al. observed accelerated growth of helium bubbles at grain boundaries under tensile stress, with the largest bubble growth observed where three grains were in contact. Stress was found to accelerate the formation of helium bubbles, particularly those located at grain boundaries or cracks. The stress gradient at the grain boundary was found to affect the movement of the helium bubbles [1].

Further analysis will be conducted using TEM to examine the size and density of the helium bubbles. In addition, changes in hardness will be analyzed through nanoindentation mapping.

REFERENCES

[1] Hao Chen, Yangming Cheng, Chenghui Lin, Jianchao Peng, Xue Liang, Jie Gao, Wenqing Liu, Hefei Huang, In-situ TEM observation of nanobubbles evolution in helium-irradiated aluminium upon tensile stressing, Journal of Nuclear Materials, Volume 520, 2019, Pages 178-184.

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