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Mechanical property evaluation of proton irradiated Inconel X-750

Sangeun Kim, Hyung-Ha Jin, I Seul Ryu, Gyeong Geon Lee*

Nuclear Materials Research, Korea Atomic Energy Research Institute,
111, 989 Beon-gil Daedoek-daero, Yuseoung-gu, Daejeon

**Corresponding author: kse91@kaeri.re.kr*

1. Introduction

The spacer, one of the fuel channel parts in the CANDU reactor, is made of high-strength nickel-based alloy, and serves to prevent the embrittlement of the pressure tube by suppressing the contact between the pressure tube the calandria tube.

The X-750 alloy containing high density of nanometer sized gamma phase has been known to exhibit intergranular grain boundary failure because of high thermal neutron flux spectra and internal production of helium and hydrogen. Radiation-induced defects act as barriers to dislocation motion, and the inter-defect distance creates a new internal material length scale. This causes irradiation hardening and affect the mechanical properties of the material **[1, 2]**.

The main purpose of this work is to evaluate the effect of irradiation on the strength of Inconel X-750 using micro hardness and micro-compression tests.

2. Methods and Results

The experimental material in this study is a solution annealed nickel based alloy (Inconel X-750) plate. The chemical compositions of the experimental sample are given in Table 1. Some of X-750 alloy were heat-treated at 730°C for 16 hours to emulate one of typical microstructures (the formation of γ`) of the annular garter spring spacer component, and are referred hereafter as H00 (as-received) and H16 (heat-treated), respectively.

Table 1 Chemical composition of experimental sample

Al	C	Co	Cr	Cu	Fe	
0.72	0.05	0.09	14.85	0.01	6.80	
Mn	Nb	S	Si	Ta	Ti	Ni
0.09	1.03	0.003	0.18	0.01	2.61	Bal

Proton irradiation was performed in the Michigan Ion beam laboratory. 2MeV proton ions were irradiated into the Inconel X-750 steel with the dose of 1.0×10^{19} ion/cm^2 in a vacuum chamber at 360°C. **Fig. 1** shows the depth profile of displacement damage calculated using SRIM code (displacement threshold energy 40eV) **[3]**.

G1-epoxy resin was applied to the proton-irradiated surfaces of the samples that were bonded to a dummy bar of Inconel X-750, as shown in **Fig. 2.** The purpose of this procedure was to prevent the edge of the irradiated surface from being rounded during the subsequent mechanical polishing.

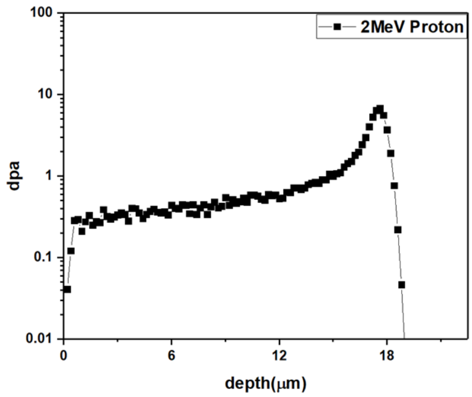

Fig 1. Calculated dpa-depth profiles of Inconel X-750 using the SRIM

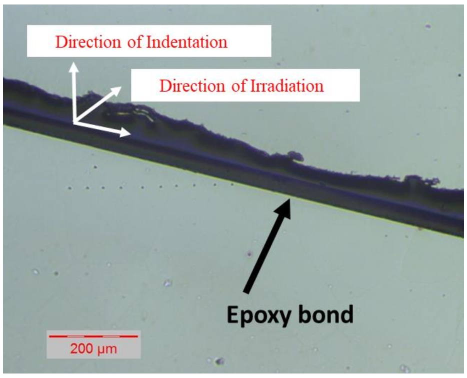

Fig 2. Surface preparation of the proton-irradiated layer for micro hardness and micro-pillar test.

Micro-hardness test was performed with a nan-indenter (NHT2, CSM Instrument) to measure the changes in nano-hardness. The load was 5Mn for the indentation. The indenting distance from the surface was measured after each indentation and was converted with a specific radiation damage value based on the SRIM calculation result.

EBSD analysis was performed on the irradiation-damage zone of the cross-sectional experimental samples to identify the crystal orientations of the grains. We utilized FIB milling to fabricate micropillars from the interior of the identified single grains. An example of this EBSD analysis and the fabrication of a micropillar is shown in **Fig. 3**.

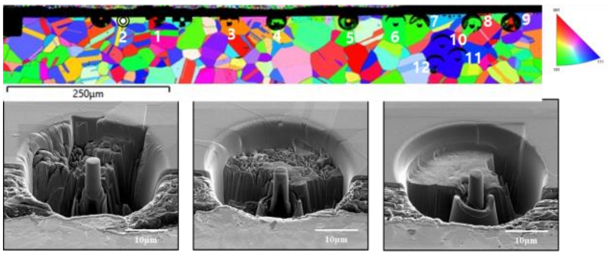

Fig 3. EBSD analysis of grains in the proton-irradiated layer and SEM image of the resulting micropillar.

3. Result and discussion

Fig. 4 shows the engineering stress-strain curves evaluated from the micropillar compression tests of H16. The flow curves evaluated from the irradiated and unirradiated pillars are plotted as the dotted and solid lines, respectively. The irradiated area show higher strengths and work hardenings compared to the unirradiated area. Strain bursts were observed in the stress-strain curves during the compression of the unirradiated micropillars, whereas increased work hardening and smoother flow behaviors were observed in the irradiated micropillars. The same phenomenon was also seen in H00.

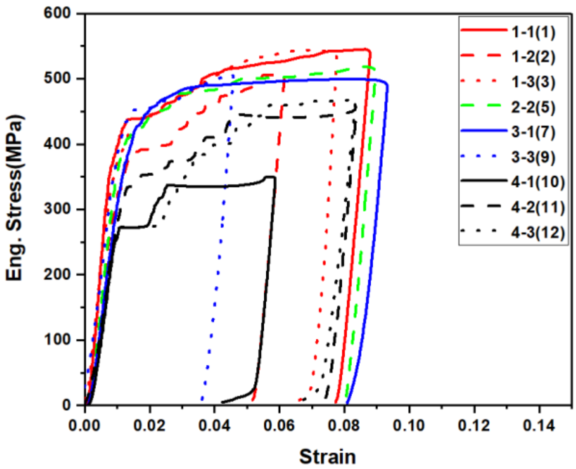

Fig. 3. Engineering stress-strain curves of 3μm irradiated and unirradiated micropillars for H16.

Figure. 5 shows the result of micro-hardness and micro-pillar tests for proton irradiated Inconel X-750 alloy. In the non-irradiated area, H16 had higher hardness and CRSS values than H00. This value is surmised to be because of the γ` phase formed inside H16. In the case of H00, the nano-hardness gradually increased and exhibited a greatest value of approximately 11GPa at a depth of approximately 20μm. In addition, the value of CRSS also showed the same tendency as the hardness. The micropillars at positions 4, 6 and 7 will be analyzed again through additional experiments.

In the case of H16, an increase in hardness and CRSS value according to proton irradiation was confirmed, but the degree was insufficient. Unlike H00, no changes in hardness and CRSS values were observed with increasing dpa. Since there is a nano-sized γ` phase inside H16, it is considered that irradiation hardening due to irradiation-induced defects is less. In this regard, further experiments at higher dpa are needed.

In the case of H16, the hardness and CRSS values according to the proton irradiation were increased, but there was no value according to the increase of dpa.

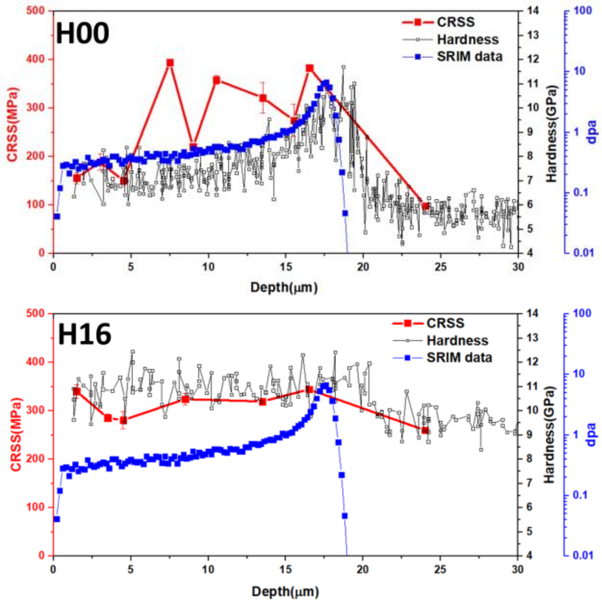

Fig. 5. Nano hardness and CRSS of Inconel X-750 as a function of depth. Radiation damage profiles are also displayed in the figures.

3. Conclusions

The irradiation hardening of Inconel X-750 alloy steel is evaluated by proton irradiation at 360℃. Through the micro-hardness test and micro-compression test, changes in mechanical properties due to proton irradiation of Inconel X-750(H00 and H16) was evaluated. In H00 and H16, irradiation hardening by proton irradiation was observed. However, in the case of H16, even when dpa increased, no significant change in hardness and CRSS value was observed. This is estimated by influence of the γ` phase inside H16.

REFERENCES

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