§38. Effect of Ion-irradiation on Sub-surface Mechanical Properties of Low-activation Materials

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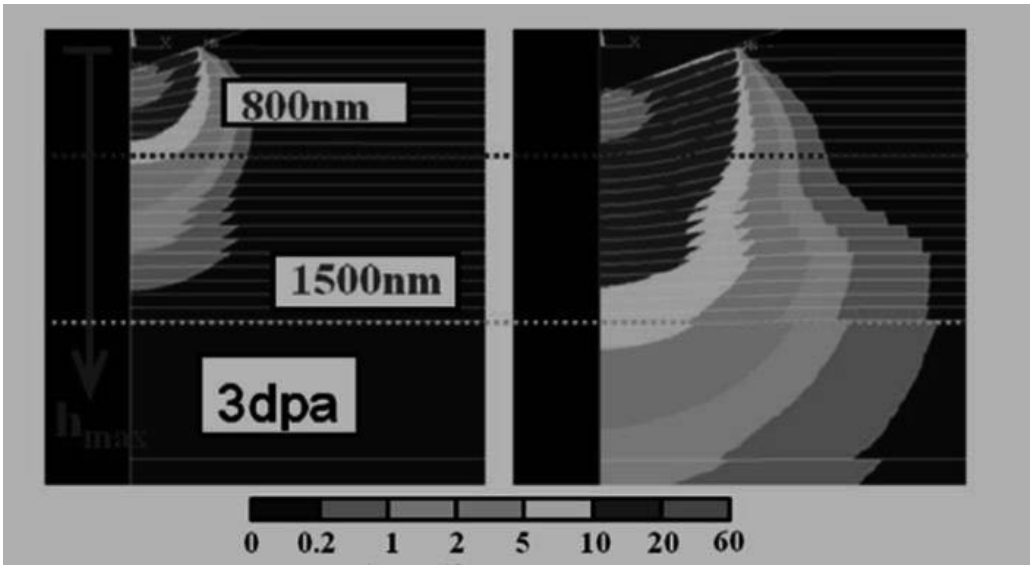
In research and development of low activation materials for nuclear fusion reactors, it is a long-standing issue that no available fusion neutron source with sufficient flux exist in the world. Therefore high-dose experiments have been performed using MeV heavy-ion accelerators. However the damage depth range in the heavy ion irradiated materials is as short as 1 μm order typically. Conventional mechanical tests are difficult to measure the irradiation hardening on the limited surface area.

Nanoindentation test is capable of strength tests on the ion-irradiated surface because of the highly-accurate depth-sensing loading method. Nevertheless it has been difficult to quantitatively evaluate the irradiation hardening of ion-irradiated surface because increase in the hardness of materials, so-called indentation size effect (ISE), is observed even in the unirradiated surface. One of the author (RK) has developed an experimental analysis models to estimate the bulk equivalent hardness by extending Nix-Gao model to explain the ISE (R. Kasada et al., FED 2011). Here nanoindentation hardness of ion-irradiated materials can be theoretically converted to the bulk equivalent hardness which is related to the Vickers hardness. However it is necessary to estimate the softer substrate effect (SSE) which is the effect of unirradiated depth area on the indentation behavior of the irradiated depth area.

In this study, we successfully reproduced the nanoindentation behavior of vanadium alloys before and after ion-irradiation by performing a finite element analysis (FEA) with constitutive equations phenomenologically introducing the Nix-Gao model (Fig.1). The FEA was carried out by ANSYS software. The indenter tip was a conical tip which makes a similar area function with Berkovich tip used in the nanoindentation tests. This modification can make the FEA two-dimensional analysis. The ion-irradiation experiment assumed here is 2.4 MeV Cu^{2+} ion irradiation up to 3 dpa at a peak depth of 800 nm and the damage range of 1500 nm. The constitutive equations used have depth-dependent forms which is derived from the Nix-Gao model. Effect of ion-irradiation on the mechanical properties were also examined. As can be seen in the left figure, plastic deformation zone due to the indent up to 200 nm spreads to 1300 nm in depth. In this condition, the hardness obtained should be independent of the softer substrate region (unirradiated region). In contrast, the right figure clearly shows that plastic deformation zone by the indent up to 400 nm overcomes the irradiated area, resulting in the occurrence of SSE. By using this model, we can estimate the amount of SSE on the bulk-equivalent hardness of ion-irradiated region.

In order to increase the accuracy of the developed model, we will investigate plastic strain distribution induced by nanoindentation experimentally. These efforts aim to establish a methodology to evaluate bulk-equivalent hardness of ion-irradiated materials.



Equivalent plastic strain (%)
Fig. 1. Plastic strain distribution under the nanoindentation on ion-irradiated vanadium alloy.