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

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The outermost surface region of the fusion reactor blanket material will suffer from irradiations of charged particles and fusion neutrons simultaneously. In addition, vanadium alloys developed by National Institute for Fusion Science has been required to expand their irradiation database. 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 several 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 model 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. Until the 2013 fiscal year, the model was applied to ion-irradiated vanadium alloys and was validated by finite element method (FEM) [1]. However, it is necessary for irradiated materials to consider the irradiation hardening in the constitutive equations.

In the 2014 fiscal year, we investigated pile-up behavior at around nanoindentation imprint and effect of ion irradiation by FEM. Despite the nanoindentation is performed in a small region, the scale of deformation is quite large in a view of plastic strain. Therefore we examined a cone having a Berkovich indenter equivalent area function for use in the nanoindentation method for the elastic-plastic analysis by ANSYS for two-dimensional cross-section of the indenter. The FEM simulation was performed assuming a austenitic stainless steel which was already evaluated by nanoindentation experimentally. Here the constitutive equation used does not consider the indentation size effect, i.e., the non-irradiated material is uniform and the ion-irradiated materials are modeled as having a uniform harder surface area on the non-irradiated material. Reults of FEM simulations on the pile-up or sink-in behavior around the nanoindentation imprint of non-irradiated and irradiated material is shown in Fig. 1. Pile-up and sink-in behavior depends on the the ratio of the yield stress to the Young's modulus. As a result, the model qualitatively explained the indentation depth dependence of the pile-up or sink-in behavior of the non-irradiated and ion-irradiated austenitic stainless steel.

[1] T. Miyazawa, T. Nagasaka, R. Kasada, Y. Hishinuma, T. Muroga, H. Watanabe, T. Yamamoto, S. Nogami and M. Hatakeyama, "Evaluation of irradiation hardening of ion-irradiated V-4Cr-4Ti-0.15Y alloys by nano-indentation techniques", Journal of Nuclear Materials 455 (2014) 440.

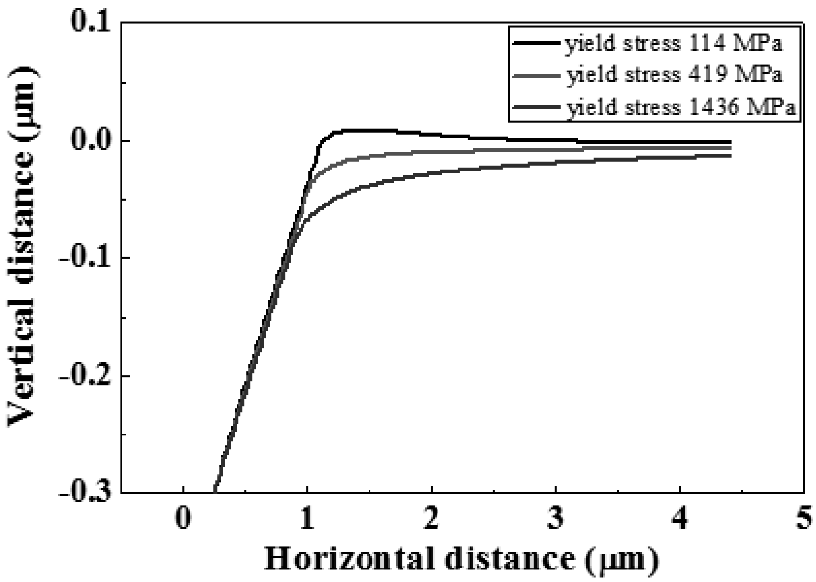

Fig.1 FEM simulation results of pile-up or sink-in behavior at around nanoindentation imprints.