§53. The Influence of Helium Co-Implantation on Ion-Induced Hardening of Low Activation Ferritic Steel Evaluated by Micro-Indentation Technique

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Low activation ferritic / martensitic steels are, so far, the most promising materials for structural components of D-T fusion demonstrative devices due to their maturity as industrial materials as well as their superior irradiation resistance in physical and mechanical properties. However, to ensure the feasibility and safety of fusion energy systems employing low activation ferritic steels, there still are several issues to be solved, which include the synergistic effects of fusion-relevant helium generation and atomic displacement damage on microstructural stability and mechanical properties. The combination of dual-beam charged particle irradiation using MV range accelerators and an ultra low-load indentation is a potential technique to evaluate the mechanical property changes due to the synergistic effects. In a typical dual-beam irradiation experiment in a fusion material study, the primary beam of heavy ions is used to introduce the atomic displacement damage and the additional beam is employed to inject helium ions to simulate the effect of transmutation through (n, a) reactions. An ultra low-load indentation technique is applicable to evaluate the indentation hardness of a surface layer as thin as a few hundred nanometers. The objective of this series of studies is to develop an experimental technique to determine the hardness properties in dual-ion irradiated solid materials, which possess uneven hardness profiles within a surface layer of typically about 1μm, by means of an ultra-low load indentation and then apply the developed technique to evaluate the irradiation-induced mechanical property changes of a low activation ferritic steel.

The micro-hardness for unirradiated specimens was 2.24 GPa in average. This micro-hardness corresponds to a Vickers hardness number of 206, which agrees well to the Vickers hardness, 213-222, measured with the load of 98N on the same material. The pre-irradiation electrolysis removed the surface layer nominally by 10μm for the 573K-irradiated specimens, which resulted in a higher average value of 2.37GPa in unirradiated condition, compared to the rest of the specimens with surfaces removed by 20μm. The point-to-point data scatter range was approximately ±0.2GPa, which was significantly larger than typical micro-hardness scatter in annealed austenitic alloys, probably due to the influences of inhomogeneous dislocation microstructure, crystallographic orientation and anisotropic martensitic lath structures. In this work, therefore, at least five indentation measurements were made in distinct prior austenitic grains within a single specimen and the average was taken as the specimen's micro-hardness for a given h_c range. In addition, the amount of irradiation-induced hardening was determined by comparing the micro-hardness corresponding to the irradiated layer to that of the substrate within the same prior austenitic grain. The amount of scatter in the hardening was significant and so averaging was again necessary for a trend analysis.

The microstructural examination by TEM was an important part of this work. But it is not simple to determine the influences of irradiation condition on microstructure because of its inhomogeneity. In specimens irradiated at 673K, irradiation-produced dislocation loops were observed. The characteristics of dislocation loops were greatly affected by the pre-existing dislocations, which were spatially inhomogeneous even in a single martensitic lath as well as over the lath structures. However, as a general trend, it was confirmed that the number density of the dislocation loops increased and their mean size decreased with increasing helium concentration. Such a correlation between the helium injection rate and the dislocation loop characteristics was much weaker than that reported for austenitic stainless alloys irradiated with dual-ions at the same accelerator facility.

At higher temperatures, or above 773K, isothermal annealing for 10^4 s caused significant softening which is limited to near surface regions. The average micro-hardness of thermal control specimens for the 773K and 873K experiments were 1.97 and 1.87 GPa, respectively, at h_c = 200 nm. Single-ion irradiation at 873K, as shown in Fig.3 (c), did not apparently cause hardening but rather suppressed the thermal softening[14]. Irradiation-induced or –assisted softening was not observed at 873K at a displacement rate of 1×10^{-4} dpa/s. The microstructural examination of the single-ion irradiated specimen exhibited dislocation network structures which were less inhomogeneous than the typical pre-existing dislocation structures. This observation suggests that the reactions between pre-existing and irradiation-induced dislocations might generate a dislocation network through irradiation-enhanced dislocation migration and the formation of network might work against a quick recovery of the pre-existing dislocation structures.

The average micro-hardness data obtained from the entire specimen set are summarized in Fig.4. The 573K data are less reliable compared to the others, because of insufficient surface finishing as described above. In all other temperature cases, hardness increased almost monotonically with the increasing He/dpa ratio. However, the amounts of hardening in most irradiation conditions were no more than 10 percents of the hardness in unirradiated materials. The effect of He/dpa ratio tended to be more pronounced as the irradiation temperature increased, within the range of irradiation conditions in this study.

References

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