Abstract

Radiation effects such as He bubble formation behavior, swelling, hardening and phase stability were investigated for three type ODS ferritic steels Y-Ti-ODS, Y-Al-ODS and Y-Al-Zr-ODS, which were mostly strengthened by (Y, Ti), (Y, Al) and (Y, Zr) oxide dispersoids, respectively.

In the two ODS ferritic steels (Y-Al-Zr-ODS, Y-Ti-ODS) with/without Al and Zr co-addition, which were irradiated with He^+ ions up to 0.2 dpa/3500 appm at 300 °C, 550 °C, 700 °C, He bubbles were observed at the above irradiation conditions by means of transmission electron microscope (TEM). The size and number density of He bubbles were increased and decreased, respectively, by the simultaneous addition of Al and Zr. Although both two ODS steels showed good resistance to He-bubble induced swelling, the Y-Ti-ODS steel possessed a better swelling resistance than Y-Al-Zr-ODS steel. It was considered that the oxide particles were the main contributors for the swelling resistance of ODS steels by providing a number of defect sinks with a high sink strength. The swelling increased with increasing temperature in both two ODS steels, indicating that the de-trapping He at higher temperatures enhanced the He-bubble swelling. Nanoindentation (NI) tests were carried out to investigate the temperature dependent hardening, revealing that in the Y-Al-Zr-ODS irradiated to 0.2 dpa/3500 appm He, a limited hardening was found at all irradiation temperatures and decreased with increasing the temperature. In addition, the post-implantation annealing (PIA) at 800 °C/100 h was conducted on the Y-Al-Zr-ODS specimen irradiated at 300 °C. The PIA caused no further hardening, while TEM images revealed that there was an evident change in the cavity distribution morphology. The cavity diameter increased from 2.5 ± 0.4 nm to 5.0 ± 1.7 nm and the corresponding number density decreased from $(22.2 \pm 1.6) \times 10^{22}$ m^{-3} to $(6.7 \pm 0.5) \times 10^{22}$ m^{-3} before and after the PIA. The negligible hardness change produced by cavities was interpreted in terms of the Orowan-type dislocation barrier model with the corresponding barrier strength factor of cavities to be less than 0.1.

In order to investigate the effects of oxide particles on radiation responses such as hardness change and microstructural evolution, the three sorts of ODS ferritic steels, Y-Ti-ODS, Y-Al-ODS and Y-Al-Zr-ODS, were simultaneously irradiated with iron and helium ions at 550 °C up to a damage of 30 dpa and a corresponding helium (He) concentration of ~3500 appm in the range of 1000 to 1300 nm. Single iron ion beam irradiation was also performed for reference. TEM observations revealed that after the dual ion irradiation helium bubbles of 2.8, 6.6 and 4.5 nm in mean diameter with the corresponding number densities of 1.1×10^{23}, 2.7×10^{22} and 3.6×10^{22} m^{-3} were observed in Y-Ti-ODS, Y-Al-ODS and Y-Al-Zr-ODS, respectively, while no such bubbles were observed after single ion irradiation. About 80% of intragranular He bubbles were adjacent to oxide particles in the three ODS ferritic steels. Although the high number density He bubbles were observed in the ODS steels, the void swelling in Y-Ti-ODS, Y-Al-ODS and Y-Al-Zr-ODS was still small and estimated to be 0.13%, 0.53% and 0.20%, respectively. The excellent swelling resistance is dominantly attributed to

the high sink strength of oxide particles that mainly depends on the dispersion morphology rather than the crystal structure of the particles. In contrast, no dislocation loops were produced in any of the irradiated steels. NI measurements showed that no irradiation hardening but softening was found in the ODS ferritic steels, which was probably due to irradiation induced dislocation recovery. The helium bubbles in high number density never contributed to the irradiation hardening of the ODS steels at these irradiation conditions.

Irradiation effects on hardness and phase stability were investigated for the Y-Ti-ODS ferritic steel strengthened by (Y, Ti) oxide nano-particles after irradiation with 6.4 MeV Fe^{3+} at room temperature (RT) up to nominal damages of 2, 10 and 50 dpa. With increasing displacement damage up to ~20 dpa, nano-sized oxide particles slightly shrank, while the corresponding number density drastically reduced by almost two orders of magnitude compared to that of before irradiation. It is considered that ballistic dissolution should be responsible for such reductions in the particle size and number density. Dislocation loops consisting of 1/2<111> type (> 80%) and <100> type were observed under weak beam dark field (WBDF) condition in the specimen irradiated to a nominal damage of 50 dpa. The average size and number density of all the dislocation loops were 2.8 ± 0.7 nm and $(4.1 \pm 0.7) \times 10^{22}$ m^{-3}, respectively, at the local damage of ~72 dpa. Although the oxide particles were almost completely dissolved, NI hardness measurements revealed that the hardening went up continuously with increasing displacement damage and estimated to be 1.63 ± 0.39 GPa by the Nix-Gao model at the nominal damage of 50 dpa. The irradiation hardening accompanied by the dissolution of oxide particles was interpreted in terms of loss of oxide particles, solid solution hardening and formation of fine dislocation loops. The contribution of dislocation loops observed by TEM to the hardening was insufficient to overcome the loss of strengthening by dissolution, suggesting the importance of solid solution hardening and the larger strength factor of dislocation loops as a hardening contributor.