§29. A Study on Microstructural Development of Neutron Irradiated W-Re Alloys for High-Heat-Flux Materials of Fusion Reactors

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Tungsten (W) is one of the candidates for high-heat-flux materials in fusion reactors, because of its high melting point, high thermal conductivity, high resistance to erosion and sputtering . The addition of Rhenium (Re) to W increases the recrystallization temperature and ductility. Under fusion irradiation conditions, transmutation by 14MeV neutron irradiation is one of major concerns. In the STARFIRE studies, 4at.%Re and 0.5at.% Osmium (Os) form after neutron irradiation of pure W at 10 dpa. Thus, study of mechanical properties and physical properties of W-Re alloys after neutron irradiation is required to predict transmutation effects on irradiated W. In a previous study of neutron irradiated W-Re alloys, drastic radiation induced embrittlement and hardening by precipitation was reported. In the case of other refractory metals such as molybdenum (Mo), we have reported that irradiation embrittlement of Mo and Mo-Re can be suppressed by pre-irradiation heat treatment. The aim of this work is to study the influence of pre-irradiation thermal treatment and irradiation temperature on the microstructural development of W-26wt.%Re after neutron irradiation.

A sheet of powder metallurgical W-26wt.%Re alloy was supplied by Plansee Co. ltd.. This was hot-worked and cold-worked by the supplier. A disk specimen (thickness: 0.15 mm, diameter 3.0 mm) was punched out from the sheet, and two different pre-irradiation heat treatments were carried out in vacuum. These were; a recrystallization treatment (grain size: 2.0mm) at 1873 K for 1 hour, and a stress relief treatment (grain size: 0.6mm) at 1573 K for 1 hour. The specimens were irradiated in the Materials Open Test Assembly of the Fast Flux Test Facility (FFTF/MOTA-2A cycle 11) up to $\sim 1x10^{27} n/m^2$ (E_n > 0.1MeV), in a helium filled capsule. After irradiation, thin specimens for microstructural observation were prepared by electro-polishing. The polishing solution was 2%NaOH with water (0.5mol/l). Polishing was carried out at 85V and 1.2A at a the temperature of 278 K. The microstructure of the specimens was observed using a transmission electron microscope (JEOL 2000FX) at 200kV. Vickers hardness testing was carried out at room temperature at a load of 1.96 N for 20 second. X-ray diffraction (JEOL JDX3530, 40kV, 40mA) was then used to detect the precipitates in the specimen.

In a typical microstructure of W-26Re after neutron irradiation to 11 dpa at 873 K, no voids, no dislocations, no dislocation loops, but two types of fine and dense precipitates were observed in all irradiated specimens. The precipitates were classified to (1) equiaxed type precipitates and (2) platelet type precipitates. The platelet-type precipitates were also observed at the grain boundaries. However it is only in the case of the grain boundary is parallel to (110) plane of matrix. The diffraction patterns and the dark field images indicates that the equiaxed type precipitates are sigma-phase with a CrFe structure, and the platelet type precipitates are chi-phase with a αMn structure.

The size of the chi-phase precipitates increased with the irradiation temperature, and the number density, did not depend on irradiation temperature. The effect of pre-irradiation heat treatment on precipitation behavior of chi-phase was not clearly observed. Also the effect of radiation damage on precipitation behavior was not clearly observed in the range of 2~11dpa. The image of sigma-phase was not as clear as that of chi-phase, so the densities are not as certain as that for the chi-phase. Nevertheless, it is concluded that the size of sigma-phase precipitates increased with an increase in irradiation temperature (5nm-15nm).Vickers hardness of recrystallized specimen increased slightly after thermal aging for 1 month. For example, the increments of Vickers hardness are 38 for 1073K, 42 for 873K and 33 for 673K respectively. Hardness of as-recrystallized sample is 466. Equiaxed type precipitates were observed in the thermally aged specimen. No precipitates were observed in the specimens thermally aged at 673 K and 873 K. The size of the precipitates (50nm) was greater, and the density ($4.5x10^{22}/m^3$) was lower than that was observed in irradiated specimens.

In our previous work, all of the W-26Re irradiated specimens in FFTF/MOTA-2A showed irradiation induced embrittlement and hardening. The microstructural observation of this work suggests that the hardening and the embrittlement may be due to precipitation of sigma and chi phases. The sigma and chi phases have hardness values of 1400 and 500 Hv respectively. Those precipitates are brittle, so they would be initiate points of cracking, and if they are on the grain boundary, they would weaken the grain boundary strength. In addition, they would harden the matrix. Especially the chi phase is on the (011) plane, so it would be the strong obstacle for dislocation gliding on the (110) plane in W. In the results of the thermal aging experiment, only the sigma-phase precipitates were formed. Therefore chi-phase precipitates can be considered as radiation induced precipitates.

The results of this work suggest that a reduction in precipitation in W-Re alloys is required for satisfactorily use in fusion reactors with an optimum Re content that may be less than 26wt.%. To predict irradiation embrittlement by the irradiation induced precipitates, Re and Os contents produced by transmutation under irradiation should be estimated, and should be considered in the design of the alloy. Additional study of the effects on Re content in W-Re alloys after neutron irradiation is required to predict transmutation effects of W on microstructural development and irradiation induced embrittlement.