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TEM study of neutron radiation damage in tungsten

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Nuclear fusion provides a safe and abundant source of energy for a long period of time and offers several important additional advantages. These include: fusion does not contribute to greenhouse gas emissions or global warming (a), reduction of long-lived radioactive waste compare to the nuclear fission reactors (b) and inherent safety features (c). Tungsten (W) is considered a promising plasma-facing material for future fusion reactors since it has number of advantages such as high melting temperature, excellent thermal conductivity, high strength and low sputtering yield. Its application in the International Thermonuclear Experimental Reactor (ITER), which is being built in Cadarache, France, and in the future Demonstartion Power Plant (DEMO) has significantly increased interest in W behavior under neutron irradiation. Knowledge about the defect formation and their evolution in neutron irradiated W is essential not only for assessing its applicability as a structural material in fusion reactors, but also for understanding numerous irradiation experiments in fission reactors.

ITER grade W was neutron irradiated in the BR2 material test reactor (Mol, Belgium) at 600°C, 800°C, 900°C and 1200°C to a damage dose of 0.1 dpa, 0.2 dpa, 0.5 dpa and 0.8 dpa. The microstructure of the irradiated material was analyzed using the Talos F200X transmission electron microscope (TEM), which is equipped with four energy-dispersive X-ray detectors (Super-X). The precipitates were detected either by high resolution TEM or by EDX elemental mapping, where they are visible in elongated shape.

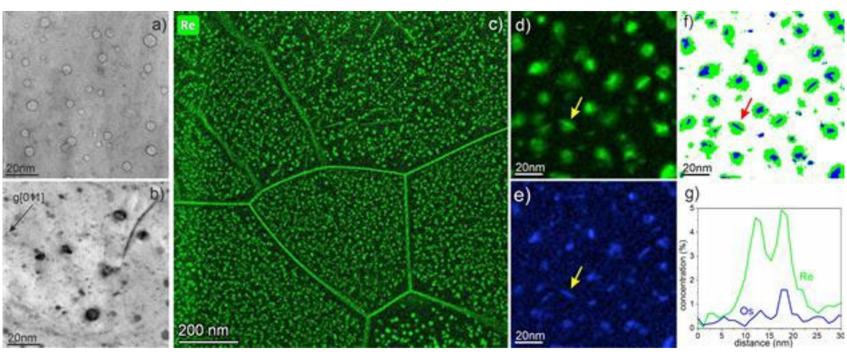
The detailed TEM characterization of the radiation-induced materials shows the formation of three types of defects, e.g. voids, dislocation loops and nano-sized precipitates. The source of the precipitates are the transmutation-induced elements such as rhenium (Re) and osmium (Os), which accumulate with the damage dose [1]. In addition, a dose-dependent segregation of Re and Os, i.e. the formation of clusters around defects, was observed [2].
The results of the TEM analysis are summarized in Figure 1. The parts (a) and (b) show the voids and dislocation loops formed in W under neutron irradiation. The voids have a round or almost round shape, but in a few cases faceted voids with a size of 3-4 nm have been observed (a). Dislocation loops are typically visible in DF images obtained using a defined g-vector with a “coffee bean” contrast (b). Most loops are between 3 and 10 nm, but individual loops can be up to 20 nm. The number density of dislocation loops at 0.1 dpa and 0.2 dpa is comparable to the number density of voids (about 1022 m-3), while for material irradiated to 0.5 dpa and higher, the number density is reduced by about two orders of magnitude.
Spatial distribution of Re and Os segregation was studied by STEM-EDX element mapping in the TEM, where their local presence was visualized by intensity variations of the different colors. The part (c) demonstrates the distribution of Re (green) in representative areas in the material. The clear segregation was observed at the grain boundaries, line dislocations and radiation-induced voids and loops. At 0.1 dpa and 0.2 dpa, the Re distribution was detected only around the voids, while the Re signal at the dislocation loops was seemingly below the detection limit. There was no Os signal detected in 0.1 dpa damage, while a weak Os signal was detectable in the material with 0.2 dpa. At 0.5 dpa and 0.8 dpa, Re and Os were detected around voids and loops.
The detailed analysis of Re and Os segregation on defects in the sample irradiated to 0.8 dpa is shown in Figure 1d-g. The distribution of Re (green) and Os (blue) are visualized in

corresponding elemental maps (d and e) and shown overlapped in the part (f). The overlapping clearly show that Os tends to form small rich areas inside Re clouds which mostly have a spherical shape. Os-rich areas often have a needle-like shape, indicating the formation of precipitates or their precursor. These Os-rich areas are formed on both voids and dislocation loops.

To provide a detailed visualization of the Os distribution, the intensity profiles were recorded across voids and loops. The example of segregation around a void marked by a yellow arrow is shown in part (d-e). The profile (g) was taken through the void marked with the arrow. It shows the typical reduction in Re-intensity at the void position and the formation of elongated, Os-rich regions adjacent to the void on one side. In the few cases the crystallinity of the precipitate was detected. The atomic spacing of 0.23 nm could correspond to the [111] atomic plane of the □-WRe_2 phase.
The study includes a detailed TEM characterization of the radiation-induced defects, which can be divided into three types, e.g. voids, dislocation loops and precipitates. In addition, a dose-dependent segregation of Re and Os, i.e. the formation of Re rich clusters around defects, was observed.

Figure 1: Extensive TEM analysis of radiation damage in W. TEM images of voids and dislocation loops a shown in parts (a) and (b) correspondingly. Part (c) visualize the Re-segregation on defects, dislocations and grain boundaries. Parts (d-g) demonstrate the analysis of Re- and Os-segregation on defects.

Graphic:



Keywords:

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Reference:

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