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Radiation Effects on Tungsten
タングステンの照射影響

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To understand the irradiation response of tungsten (W) in fusion reactors, irradiation effects on microstructure development, hardening and electrical resistivity of pure W and W alloys were summarized based on fission reactors irradiation up to about 1-1.5 dpa in the temperature range from 400 to 800°C. Voids were the major damage structure in pure W, and irradiation data of W-Re alloys showed that Re clearly suppressed void formation. Based on these results, a damage structure map of W in fusion reactor was suggested.

1. Introduction

Tungsten (W) is considered to be a candidate for the plasma-facing component (PFC) materials of magnetic confinement fusion reactors such as the first wall of a blanket and a diverter plate because of its high melting temperature and high resistant to sputtering. During fusion reactor operation, as a result of high-energy neutron exposure, not only displacement damage but also transmutation elements are produced in W. For example after 5 years of operation in DEMO-like reactor, the average neutron fluence would be 10 MWa/m^2 at the first wall and 5 MWa/m^2 at the diverter, the displacement damage and Rhenium (Re) content would be 30dpa and 6% in W of the first wall, and 15 dpa and 3% in the diverter, respectively[1,2]. Re is one of major solid transmutation elements of W in fusion reactor conditions [3], and also it is well known that Re affects physical properties of W [4].

In ITER, a displacement damage would be 0.7 dpa and transmutation of Re would be 0.15% in the W diverter after a neutron fluence of 0.15 MWa/m^2 at 200–1000°C[1]. The transmuted Re concentration would be small in ITER, therefore, transmutation may not be main concern of W in ITER, but neutron irradiation causes microstructure change and irradiation hardening even after the 0.7dpa irradiation. The irradiation behavior of W has been studied but the details have not been clarified yet. The irradiation induced defects affect various physical properties of W including mechanical property, size stability and thermal conductivity and so on. The defects and defects clusters are also considered as trapping sites of hydrogen (Tritium), therefore, damage structure information is required to estimate soundness, life time and Tritium inventory of W during neutron irradiation.

2. Neutron irradiation behavior

Previous neutron irradiation works on W using various fission reactors including JMTR, JOYO (Japan), EBR-II ad HFIR（USA）at temperature range from 400 to 800°C and dpa level was in the range from 0.15 to 1.54 dpa（E_d=90eV）were summarized[5-7]. The results of transmission electron microscopy showed that the major defect clusters of pure W under these irradiation conditions were voids. Dislocation loops were also observed in lower dpa region but its number density was 1/10 to 1/100 of void. Ordered void array structure, which was called void lattice, were observed above 1dpa at 538 and 750°C in JOYO. Void swelling of these irradiated specimens estimated by microstructure observation were below 0.1%[8]. The void lattice had also reported in the previous works carried out in 1970s in USA [5]. The void lattice formation conditions were clarified using these data. Void swelling data of heavy irradiated (9.5dpa) W obtained by density measurement was also reported[9]. The swelling peak temperature of W was 700-800°C and the swelling was around 1.6%. The microstructure of this irradiated W was not reported, but these data showed that void swelling of W up to 10dpa irradiation would not be so significantly.

It is well known that Re improves W properties and one of major transmuted element of W, therefore, Re effects on microstructure development of W after neutron irradiation have been studied. The irradiation data of the W-Re alloys showed that the void formation behavior up to 1.5 dpa were strongly affected by the Re concentration in W. Results of JOYO irradiation showed that the void size and number density tended to decrease significantly with increasing Re content [10]. The void number density of the W-Re alloys compared to pure W was less than about 1/10, and void size was also smaller than that of pure W. The defect types of 5 and 10%Re alloys in this irradiation conditions were similar, these were small amount of voids and fine precipitates. In the case of 26% Re content alloys, severe irradiation hardening was observed because of high density precipitates of W-Re intermetallic compounds (σ or χ phase) [11]. These results suggest that a small amount of Re (3-5%) may enhance microstructural radiation resistance of W. The mechanism of Re effects on void formation behavior of W is under investigating using first-principal study [12].

The microstructural development with Re concentration change of irradiated pure W and W-Re alloys by fission reactors irradiation were shown in Figure 1 [7]. The arrows indicate Re composition change during neutron irradiation. Schematic illustrations of defect structure such as voids and loops are also shown. Based on the fission reactor irradiation data (gray arrows), qualitative prediction of damage structure development of pure W in ITER and DEMO-like fusion reactors with lower transmutation rate of W to Re are also shown in Figure 1 as black arrows. The qualitative predictions of damage structure development in pure W are as follows: fine voids form at early stage of irradiation and void lattice structure appears at around 1 dpa at 600–800°C. This structure is expected to be stable up to several dpa because formation and annihilation balance of vacancy and interstitial atom is considered to compensate by the void lattice structure. With increasing neutron fluence up to around 10 dpa, the concentration of transmuted Re increases to several mass % even in a fusion reactor, the void lattice structure may be changed by Re effects on void formation. Precipitate of W-Re may form in the void lattice and disordering of the lattice and shrinking of the void may occur.

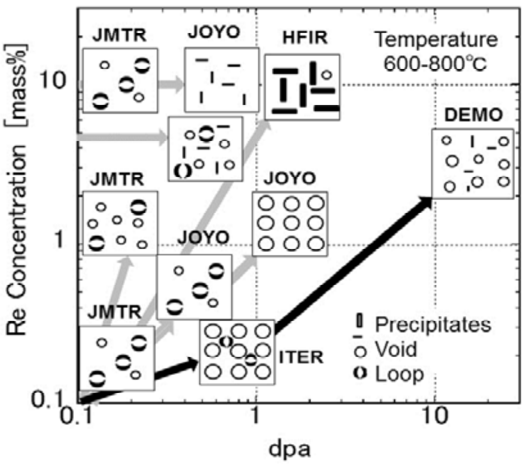

Figure 1. Prediction of microstructural development of W under fusion reactor conditions based on fission reactor irradiation data [7].

These microstructural changes caused mechanical property changes. Figure 2 shows irradiation damage (dpa) dependence on hardness of W and W-Re alloys [13]. Hardness is the resistance to permanent indentation and a relationship has been established between the yield stress and Vickers hardness. Vertical axis in Figure 2 corresponds to yield stress increase qualitatively by neutron irradiation. With increase displacement damage, yield stress increase and the hardening depend on the Re concentration in W. Irradiation induced defects such as void and loop affect the increase of hardness. Precipitates of W-Re also induce large hardening of W-Re alloys. Ductility loss cannot be estimated by hardness test, therefore other evaluation methods were used to obtain ductility change. Irradiation effects on various property changes were also summarized and some examples will be presented.

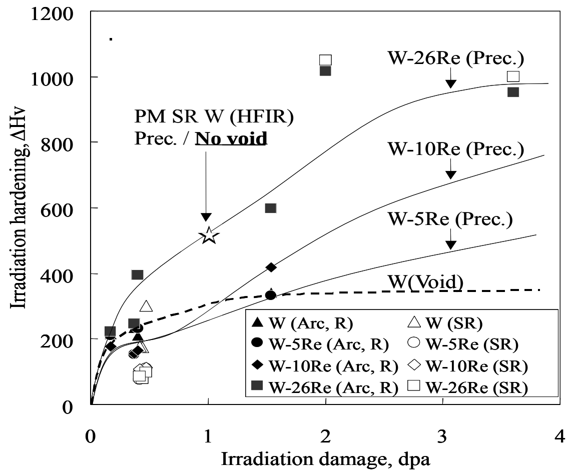

Figure 2. Irradiation hardening of W and W-Re.

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