Study of tungsten as a plasma-facing material for a fusion reactor

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Abstract

The paper presents the development of experimental investigations and recent results of the impact on tungsten at high level of radiation damage under steady-state deuterium plasma. Tungsten is considered as a plasma facing material for a fusion reactor. The effect of fusion neutron impact is simulated by surrogate irradiations with high-energy ions. The primary defects at 1-100 dpa were produced in tungsten samples by He and C ions accelerated in the Kurchatov cyclotron to 3-10 MeV at the total fluence of $10^{17}$-$10^{19}$ cm\textsuperscript{-2}. The irradiated material was studied in deuterium plasma on the LENTA linear divertor simulator at the plasma fluence $10^{21}$-$10^{22}$ D/cm\textsuperscript{2}. Erosion dynamics, development of the surface microstructure and deuterium retention were analyzed. Increased deuterium retention detected previously in tungsten pre-irradiated by He ions was also registered (ERDA) on C-irradiated samples at 2-3 dpa. In contrast, a significant decrease in the D uptake has been observed on those samples operated in the experiments at 500 °C.

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1. Introduction

The urgency of the problem to obtain materials capable of operating in a fusion reactor for a long time under plasma attack and neutron irradiation has excited an increased interest in the study of tungsten as a candidate plasma-facing material for the divertor application in ITER and probably for the first wall in the next step reactor. Neutron fluence (≥10^{26} n/m^2) is characteristic of the tokamak-reactor operating in steady-state. As a result, accumulation of radiation damage in the structure materials is induced that leads to degradation of their physical and mechanical properties [Wampler and Doerner (2009), Roth and Schmid (2011), Hatano et al. (2011), Mayer et al. (2014)]. We have studied a probable synergy of plasma effect on the fusion plasma facing materials with occurring radiation damage.

Carbon-based materials have been investigated at the first stage of our study including candidate composite SEP NB 31; enhanced erosion has been found in steady-state deuterium plasma for the materials damaged to 1-10 dpa [Khripunov et al. (2009), Ryazanov et al. (2012)]. Further experimental studies have been continued at the Kurchatov Institute in recent years to develop the adopted method of radiation damage production and to apply it to tungsten [Koidan et al. (2010), Khripunov et al. (2011, 2013)] and to study damaged tungsten under the impact of high flux plasma. The main objective of the study was to find out the influence of radiation damage occurring in tungsten on the result of the plasma effect relevant to the erosion of radiation-damaged material and to hydrogen isotope retention.

To date, we have obtained tungsten samples damaged to the level evaluated in displacements per atom as falling within an interval from 0.1 to 100 dpa. This interval covers practically the whole range corresponding to the fusion reactor forecast including the ITER and DEMO projects. It becomes possible to study materials at such a high damage level due to the use of accelerated MeV-range heavy ions for their production.

2. Production of radiation damage in tungsten

Polycrystalline tungsten (W, 99.95 wt.%, Russian grade) is under study. We have irradiated tungsten samples with different ion species: \(^4\)He\(^{2+}\) at 3.5-4 MeV and carbon ions \(^{12}\)C\(^{3+}\) at 10 MeV. The first case (irradiations with \(^4\)He\(^{2+}\) at 3.5-4 MeV) was investigated as corresponding to the alpha particle ash from the DT fusion reaction. W samples have been subjected to an ion beam in the cyclotron to accumulate doses from 10\(^ {17}\) cm\(^{-2}\) to 10\(^ {19}\) cm\(^{-2}\). The chosen irradiation conditions provided production of damage in the material to depth of 3.5 to 6 μm and the first direct comparison of these two irradiations performed by different ion species became possible. The results on He-irradiated tungsten (microstructure modification, swelling effect) have been reported elsewhere [Koidan et al. (2010)]. Here we give the results corresponding to C-irradiated tungsten.

Fig. 1 shows the calculated distribution of primary defect concentration in tungsten after irradiation by carbon ions \(^{12}\)C\(^{3+}\) at 10 MeV to the fluence of 10\(^ {17}\) ion/cm\(^{2}\). The distribution of implanted carbon ions is also shown in the figure. The average value is 4.2 dpa while the maximum damage is about 20 dpa at 3.5 μm deep in this figure.

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Fig. 1. Distribution of primary defects and of the implanted carbon in the surface layer of tungsten irradiated by carbon ions at 10 MeV.
Changes in the surface and damage layer microstructure were studied by SEM. Swelling effect was found on irradiated tungsten. It was observed both on helium-irradiated and carbon-irradiated samples by evaluation of linear dimension changes with a profilometer, showing 0.5-0.8 % in the last case.

3. Plasma exposure of irradiated tungsten

The irradiated tungsten samples were subjected to deuterium plasma exposures on the LENTA linear plasma device which is used for the divertor and SOL simulations of tokamak. The sequential plasma exposure parameters were chosen so that a notable sputtering of the material occurred (the ion energy exceeded the sputtering threshold and it was 250 eV, \( F=10^{21}-10^{22} \ \text{ion/cm}^2 \)). Surface erosion, surface and damaged layer microstructure changes were examined under these conditions. Fig. 2 shows the microstructure of the tungsten surface layer (damaged) \( \text{C}^{3+}, \ \Phi = 2\cdot10^{17}\ \text{cm}^{-2}, \ E = 10 \ \text{MeV} \) after exposure to deuterium plasma with erosion of 1 \( \mu \text{m} \) as a result (the view of fracture, depth of the damaged layer is about 3 \( \mu \text{m} \)).

![Fig. 2. Damaged layer microstructure (fracture) after D-plasma exposure of the sample resulted in erosion of one micron of tungsten.](image)

The surface of irradiated tungsten exposed to the plasma shows changes in the microstructure; for He and C ion pre-irradiations these changes are different [Koidan et al. (2014)]. C-irradiated samples have not shown so significant changes in the surface structure induced by plasma. Examples for this case are given in Fig. 3.

![Fig. 3. Surface of the irradiated tungsten (C\(^{3+}\), 10 MeV, (1.5-2)\(\cdot10^{17}\) ion/cm\(^2\)) after erosion in deuterium plasma to depth of (1-0.8) \( \mu \text{m} \) at different temperatures – room temperature and 500 °C.](image)
The SEM images of C-irradiated tungsten after deuterium plasma exposure are presented. The two pictures correspond to close levels of primary defects (2-3 dpa) but to different temperatures of the material during irradiation and plasma exposure – room temperature and 500 °C; the difference between these two cases being though not significant but quite visible.

Erosion rate was measured by weight loss in all plasma experiments. It was around 0.5-0.8 mg/cm²h for all cases. The obtained value of the average erosion yield of the tungsten in the study under deuterium plasma ions (250 eV) under the chosen conditions was \( Y_{d,w} \equiv (2-4) \cdot 10^{-3} \) at/ion. No influence clearly seen of displacement damage on erosion rate was found in this study. No correlation of the yield values was also found with the damage level for different doses for both He- and C-irradiated tungsten.

4. Deuterium retention

Hydrogen isotope retention was studied in this work by measurements of deuterium content in damaged tungsten after exposure of the irradiated samples to deuterium plasma at different steps of erosion from the initial surface to the termination of the damaged layer (about high-energy ion range). The Elastic Recoil Detection analysis was used to obtain the profile of deuterium concentration in the near-surface layer.

Here we report the results of deuterium retention obtained recently on C-damaged tungsten exposed to deuterium plasma. Experiments were conducted at different temperatures of the material during irradiations and plasma operation, namely, at room temperature and at \( T = 500 \) °C. The results for these two cases are given in Fig. 4. Profiles of the retained deuterium concentration are shown for two tungsten samples pre-irradiated by C ions after D plasma. While both distributions have maximum at about 20-30 nm in the layer between 10-140 nm, about ten-fold reduction of the deuterium uptake is registered on the high temperature tungsten sample in comparison with room temperature case: \( 8.7 \times 10^{16} \text{D/cm}^2 \) to \( 0.8 \times 10^{16} \text{D/cm}^2 \).

![Fig. 4. Deuterium retention in tungsten pre-irradiated by C ions after exposure to deuterium plasma for experiments performed at room temperature and at 500 °C. The surface corresponds to 2-3 dpa layer in both cases.](image)

5. Summary

High-energy ion beams of He\(^{2+}\) and C\(^{3+}\) have been used to produce high-level displacement damage in tungsten as a surrogate irradiation to simulate the neutron effect of a fusion reactor. Heavy ions accelerated to 3.5-10 MeV produced primary defects in the range of 1-100 dpa in the surface layer 3.5-6 μm thick at total ion fluences \( 10^{17}-10^{19} \) ion/cm\(^2\). The swelling effect has been observed on the irradiated tungsten. The irradiated material was subjected to deuterium plasma exposure on the LENTA linear simulator to the plasma fluence of \( \sim 10^{22} \) cm\(^2\). The behavior of this damaged layer under erosion condition has been investigated. Erosion of damaged tungsten was measured: the
erosion yield was $Y_{d_w} \equiv (2-4) \times 10^{-3}$ at/ion for different damage producing ions both He and C and for different damage levels of the layers facing plasma, and this was about the same as for undamaged tungsten. Thus, no correlation of erosion was found with the damage level or irradiation method.

The ERDA measurements of deuterium distribution in the damaged layer of tungsten after plasma exposures have been made. A very high difference in deuterium retention was found on C-irradiated tungsten subjected to the beam and the plasma at different temperatures. The increased deuterium uptake was registered in C-irradiated tungsten at room temperature (20 at.% in maximum at 30 nm depth, 0.9×10^{16} D/cm²) contrary to the result for 500 °C which was very close to retention in undamaged tungsten (2 at.%. at 30 nm). This observation may indicate avoidance of tritium accumulation in damaged tungsten at the elevated temperature.

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