Evaluation of Radiation Damage to Tungsten in a Nuclear Fusion Environment

Junhyun Kwon[a*], Dong Hyun Ahn[a], Hyung-Ha Jin[a], Dong Won Lee[a], Sungjin Kwon[b]
[a]*Korea Atomic Energy Research Institute, 989-111 Daedeok-daero, Daejeon 34057, KOREA*
[b]*Korea Institute of Fusion Energy, 169-148 Gwahak-ro, Daejeon 34133, KOREA*
[*]*Corresponding author: jhkwon@kaeri.re.kr*

Keywords : *divertor, tungsten, displacement damage, helium, stopping range*

1. Introduction

Radiation damage to the structural materials of a fusion device is one of the serious barriers to realization of fusion power. The most promising fusion reaction is the D-T (Deuterium-Tritium) one, where a deuterium nucleus fuses with a tritium nucleus to produce a helium-4 and a high-energy neutron.

$$ {}^{2}_{1}D + {}^{3}_{1}T \rightarrow {}^{4}_{2}He + {}^{1}_{0}n + 17.6\ MeV \qquad (1)$$

It is probable that 14.1 MeV neutrons collide with the inner structure of the fusion reactor, which results in displacement damage due to the production of point defects. As well as the direct damage, the neutrons also cause transmutation resulting in a buildup of impurity elements within the material. The generation of radiation damage leads to changes in microstructure, which in turn affect the thermal and mechanical properties of the material.

Tungsten is a candidate material for a divertor in a fusion device because of its high energy threshold sputtering and low erosion under high heat loads [1]. However, the surface exposure to high-flux He atoms can cause the formation of W fuzz and He bubbles, which will affect the plasma stability and the plasma-facing materials (PFMs) lifetime [2]. In this study, we estimated the amount of basic radiation damage to W for the given neutron spectra in the vicinity of the divertor region of a fusion DEMO reactor, including the displacement damage and production of transmutation gas. Then, in order to investigate the He-atom behavior, the ranges of plasma He were calculated. These results will be applied to the prediction of the performance of W in a fusion environment in the future.

2. Methods

In this section computer codes used for evaluating the radiation damage are described. The neutron spectrum is required to perform the damage calculation. Since the proper spectrum in the vicinity of a divertor is not available at the moment, we employed the spectrum in the blanket region of Korean fusion DEMO reactor (K-DEMO) [3]. An emphasis is placed on the evaluation methods, rather than the calculated values.

2.1 Neutron Spectra

The neutron spectrum used for this work is shown in Fig. 1, where we can see the peak at 14.1 MeV produced by the D-T reaction. These energetic neutrons can cause significant atomic displacements and transmutation in structural materials.

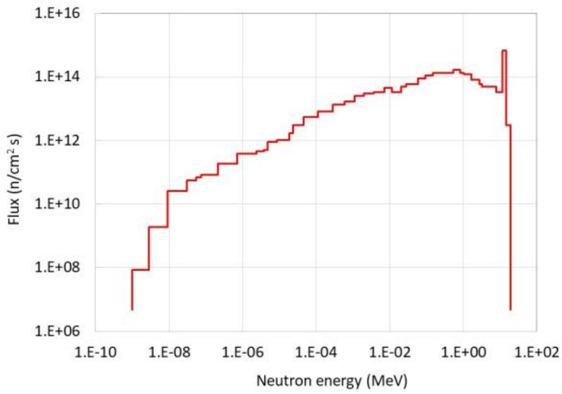

Fig.1. Neutron spectrum for near divertor region in K-DEMO

2.2 Damage by Neutron Irradiation

The SPECTER code was used to obtain neutron damage parameters for the given neutron spectrum. The primary damage parameters include atomic displacement (displacement per atom, *dpa*), H/He gas production and averaged primary knock-on atom (PKA) energy spectra [4].

2.3 Bombardment of Plasma Helium

To evaluate the interaction of plasma α-particles with W, the SRIM computer code was applied [5]. The SRIM calculates the stopping range of He and sputtering yield, which is defined as the average number of sputtered W atoms per incident α-particle. The W-surface exposure to α-particle, with an average energy of 3.5 MeV, can lead to the penetration of He into W and possibly the physical sputtering of W atoms on the surface. Although initially the number of α-particles is large and their energy is quite high, the majority of produced particles would be confined in the magnetic fields, slowed down in the plasma. Only a small fraction of the initial α-particles will reach the PFMs and their mean energy is expected to be approximately a few hundred of eV [6].

Tungsten is known to be resistant to sputtering as the minimum energy to sputter a W atom is about 105 eV. Over time, the cumulative processes of particle collisions can produce W-erosion and shorten the divetror lifetime. In this work, we calculated the sputtering yield of W due to the bombardment of α-particles. Under the assumption that the incident energy of He ranges from 100 to 1000 eV, the angular dependence of sputtering yields at various energies are investigated using the SRIM code.

In estimating the sputtering yield, three parameters are required, which include the displacement energy (E_d), surface binding energy (E_{SBE}) and lattice binding energy (E_{latt}). Whereas the E_d for W is 90 eV, given in Ref. [7], the others are not fixed. Hence, we determined the E_{SBE} and E_{latt} using the LAMMPS code [8].

3. Results

3.1 Neutron Damage

The evaluated damage parameters are listed in Table I by assuming that W was exposed to the neutron spectrum for 10 years, shown in Fig. 1. All damage parameters were produced by the SPECTER code. The average PKA energy represents the available energy for initiating a displacement cascade, which will be used for a cascade simulation.

Table I: Evaluated neutron damage parameters

Displacement (dpa)	H Production (appm)	He Production (appm)	Avg. PKA Energy (keV)
274.5	776.1	365.6	11.65

3.2 Helium-Ion Stopping

When a divertor material is bombarded by a plasma He ion, various processes can take place, including the direct penetration and backscattering of He, and the sputtering of W. Above all, we evaluated two parameters of E_{SBE} and E_{latt} for W by using the LAMMPS, which are key parameters to the calculation of sputtering yields. The difference between the two binding energy of E_{SBE} and E_{latt} is schematically illustrated in Fig. 2, which are dependent on the initial position (surface or internal lattice) of a target atom. Using the LAMMPS code, the values of E_{SBE} and E_{latt} were determined to be 3.54 eV and 8.9 eV, respectively, which are input to the SRIM calculation.

The stopping ranges of He in W are shown in Figs. 3,

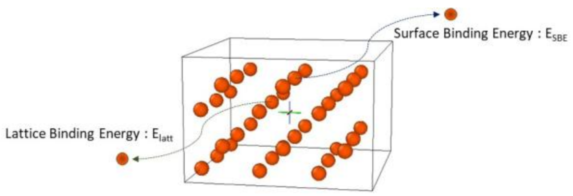

Fig. 2. Schematic illustration of binding energies of E_{SBE} and E_{latt}.

where the incident He energy is assigned between 100 and 1000 eV. The ranges are primarily dependent on the He energies, while they are not a strong function of the incident angle (ϕ). Fig. 4 displays the fraction of backscattered ions as a function of incident ion-angle, which is independent of He energy. The backscattered fraction is over 50% for given energy ranges, implying more than half of the incident He ions do not penetrate into the target. And no sputtering yields of W were found in the simulation,

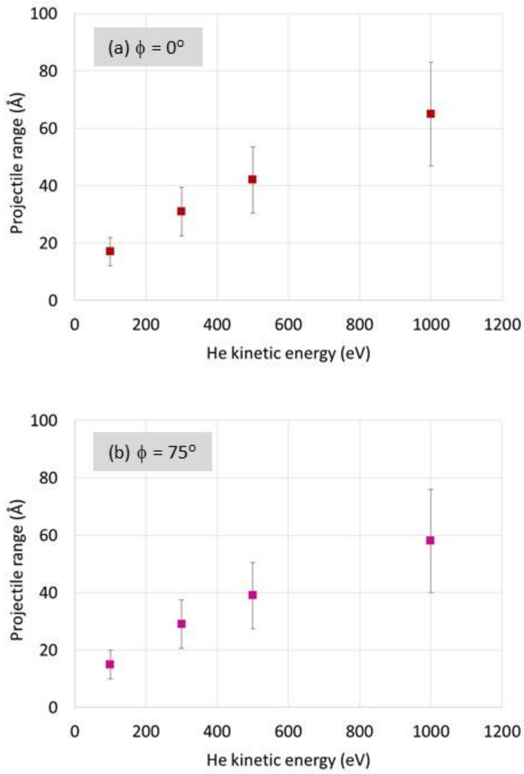

Fig. 3. He-stopping ranges in W as a function of He kinetic energy for two incident angles (a) ϕ = 0° (normal to surface) and (b) ϕ = 75°.

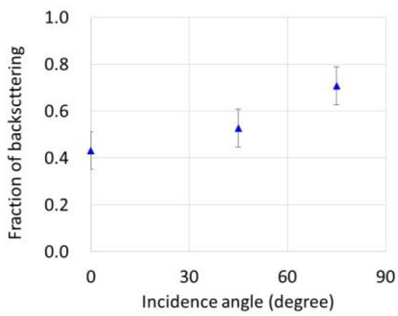

Fig. 4. Fraction of backscattered He ions in collision with W as a function of the incident angle. (0 degree - normal to surface)

4. Discussion

We demonstrated the procedure of radiation damage calculation by various simulation techniques, including the SPECTER, SRIM and LAMMPS code. Under the assumption that the neutron spectrum in the vicinity of a divertor is given, the neutron damage to W was evaluated using the SPECTER. The displacement damage might lead to changes in microstructure by combining the H/He production, which in turn affect the thermal and mechanical properties of W. These damage parameters are useful in predicting the degree of materials degradation.

Divertor surface exposure to plasma He is another concern since the surface damage is known to be created in the form of W-fuzz and blisters. For this reason, the basic parameters affecting such damage were evaluated by employing the SRIM and LAMMPS. It was found that less than half of the He ions penetrates into W with tens of Å in depth and no sputtering of W was estimated. It would be interesting to investigate the evolution of surface damage to W due to two types of He source, including the neutron transmutation and the penetration of plasma He ions.

Acknowledgements

This research was supported by the National Research Council of Science & Technology (NST) grant by the Korea government (MSIT) (No. GTL25031-410).

REFERENCES

[1] R.G. Abernethy, Predicting the performance of tungsten in a fusion environment: a literature review, Materials Science and Technology, Vol.33, p. 388, 2017.
[2] K. Whittle, Nuclear Materials Science, IOP Publishing, London, 2016.
[3] S. Cho et. al., Neutronic assessment of HCCR breeding blanket for DEMO, Fusion Engineering and Design 146, p.1338, 2019.
[4] L. R. Greenwood, R.K. Smither, "SPECTER: Neutron Damage Calculations for Materials Irradiations", ANL/FPP/ TM-197, US, 1985.
[5] J.F. Ziegler, J.P. Biersack, M.D. Ziegler, SRIM – The Stopping and Range of Ions in Matter, SRIM Co., MD, 2015.
[6] H. Ullmaier, The Influence of Helium on the Bulk Properties of Fusion Reactor Structural Materials, Nuclear Fusion, Vol. 24, No.8, p.1039, 1984.
[7] Standard Practice for Investigating the Effects of Neutron Radiation Damage Using Charged-Particle Irradiation, ASTM E521-25a, ASTM International, 2025.
[8] A. P. Thompson et al., LAMMPS - a flexible simulation tool for particle-based materials modeling at the atomic, meso and continuum scales, Comp. Phys. Comm. 271, p.10817, 2022.