Thermo-mechanical analysis of tungsten and its alloys monoblock divertor under heat load conditions relevant to a fusion reactor

Makoto FUKUDA[a], Shuhei NOGAMI[a], Akira HASEGAWA[a], Kiyohiro YABUUCHI[a], Koichiro EZATO[b], Satoshi SUZUKI[b], Hitoshi TAMURA[c], and Takeo MUROGA[c]

[a]*Department of Quantum Science and Energy Engineering, Tohoku University, Sendai, Japan*

[b]*Japan Atomic Energy Agency, Ibaraki, Japan*

[c]*National Institute for Fusion Science, Gifu, Japan*

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To evaluate the applicability of tungsten alloys as the plasma-facing materials in a fusion reactor, thermo-mechanical analysis of monoblocks of pure W and its alloys under heat load was carried out in this work. Potassium (K) and rhenium (Re) doped W (namely K-doped W-3%Re) showed the highest recrystallization resistance because of its high temperature where the recrystallization starts, although its thermal conductivity was lower than those of pure W and K-doped W. Thermal stress in the monoblock under the heat load was relatively high at the top surface and in the neighborhood of the interface between W and OFHC-Cu. The distribution of thermal stress was similar in pure W, K-doped W, and K-doped W-3%Re.

Keywords: Pure W, K-doped W, K-doped W-3%Re, thermo-mechanical analysis, finite element analysis, divertor

1. Introduction

Tungsten (W) is attractive as a plasma-facing material (PFM) for use in divertors and blankets in fusion reactors because of its high melting point, high thermal conductivity, and high sputtering resistance. On the other hand, improvement of its material properties, such as mechanical properties and irradiation resistance, is desired to increase the reliability of W as the PFM of a divertor. W is subjected to a high heat load and high energy of neutron irradiation during the operation of a fusion reactor. It has been reported that crack formation and recrystallization can occur in a W monoblock due to the cyclic heat load relevant to ITER [1]. Crack formation may decrease the heat transfer ability and cause contamination of the plasma. Recrystallization decreases the mechanical properties of W significantly [2, 3]. In addition, changes in material properties due to neutron irradiation might become an issue for the application of W as a PFM in DEMO because of its long-term operation. The neutron irradiation induces the irradiation defect clusters, such as voids, dislocation loops, and irradiation-induced precipitates. As a result, degradation of the mechanical and thermal properties may occur [4-11].

Based on these backgrounds, we fabricated the W alloys (i.e. potassium (K)-doped W and K-doped W-3% rhenium (Re) alloy) to increase their mechanical properties and resistances to recrystallization and irradiation. The details of the material design are described in the literature [12]. The point to be considered to evaluate the applicability of the W alloys as PFMs is the trade-off between the thermal properties and the improved properties, such as mechanical properties and resistance to recrystallization and irradiation. In this case, the decrease of the thermal conductivity by 3% Re in K-doped W-3%Re should be considered at below ~800 °C.

The objective of this work is to investigate the effects of the trade-off relationship between the decrease in thermal conductivity and the improvements in other properties, such as recrystallization and irradiation resistance and mechanical properties in pure W, K-doped W, and K-doped W-3%Re.

2. Finite element analysis

This work calculates the temperature and stress values and their distributions in a W monoblock used for an ITER divertor made of pure W, K-doped W, and K-doped W-3%Re during the heat load condition relevant to a fusion reactor. A three-dimensional thermo-mechanical analysis was conducted for the W monoblock by the finite element analysis (FEA). **Figure 1** shows the dimensions of

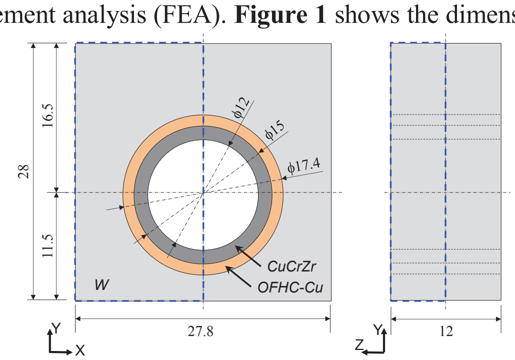

Fig. 1 Dimensions of the FE-model (1/4 of monoblock).

author's e-mail: fukuda@jupiter.qse.tohoku.ac.jp

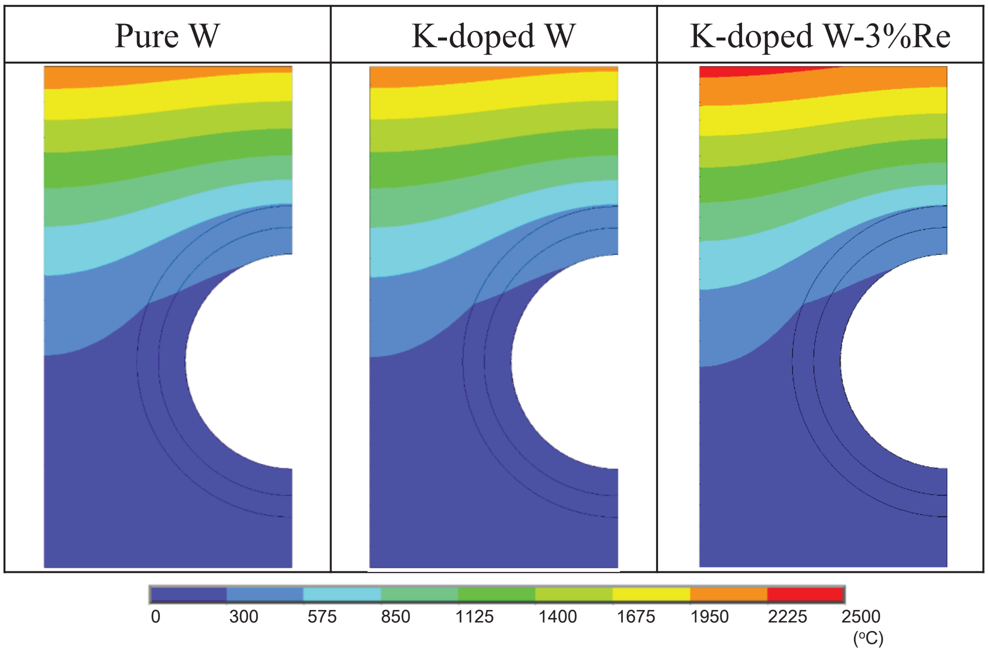

Fig. 2 Temperature distribution in 1/4 model of W monoblock after a heat load of 20 MW/m^2 for 10 s.

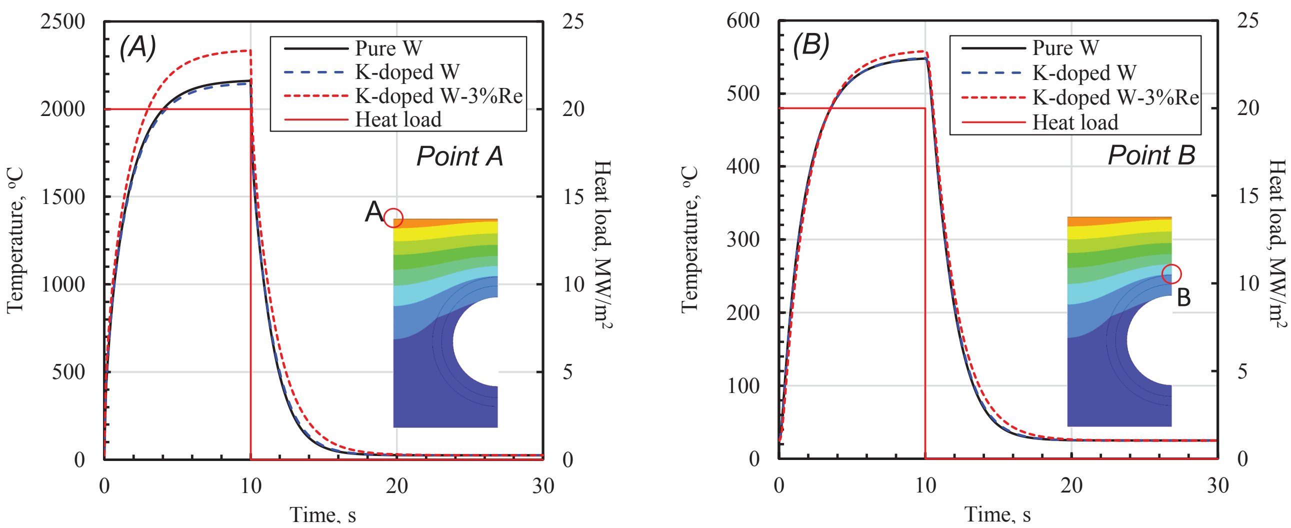

Fig. 3 Temperature change during heat load at selected points.

the FE-model, and the 1/4 model of the monoblock (blue dotted line). The thermo-mechanical analysis was conducted using ANSYS ver. 15.0. The materials used in the analysis were pure W and its alloys (K-doped W and K-doped W-3%Re), CuCrZr, and OFHC-Cu. CuCrZr and OFHC-Cu are the coolant channel material and the buffer material between W and CuCrZr, respectively. The assigned temperature-dependent thermal and mechanical properties of W were based on experimental results and literature [13, 14]. The material properties of CuCrZr and OFHC-Cu were based on the literature [15]. In this analysis, W materials were defined as elastic solids. The OFHC-Cu and CuCrZr were defined as perfect elastro-plastic solids. As a heat load condition, a heat flux of 5 - 20 MW/m^2 with a dwell time of 10 s was applied at the top surface of the W block. The cooling water temperature was 25 °C, and its pressure was 2 MPa. The axial symmetry surface of the X and Y axes were fixed.

3. Results and discussions

Figure 2 shows the temperature distributions in pure W, K-doped W, and K-doped W-3%Re after a heat load of 20 MW/m^2 for 10 s. Temperature change profiles at the selected points were plotted as shown in **Fig. 3**. The edge of the top surface showed a higher temperature than other parts because of its greater distance from the cooling channel. This trend was the same for all W materials. The maximum temperature on the top surface during the heat load changed depending on the W materials, and K-doped W-3%Re showed a ~200 °C higher maximum temperature

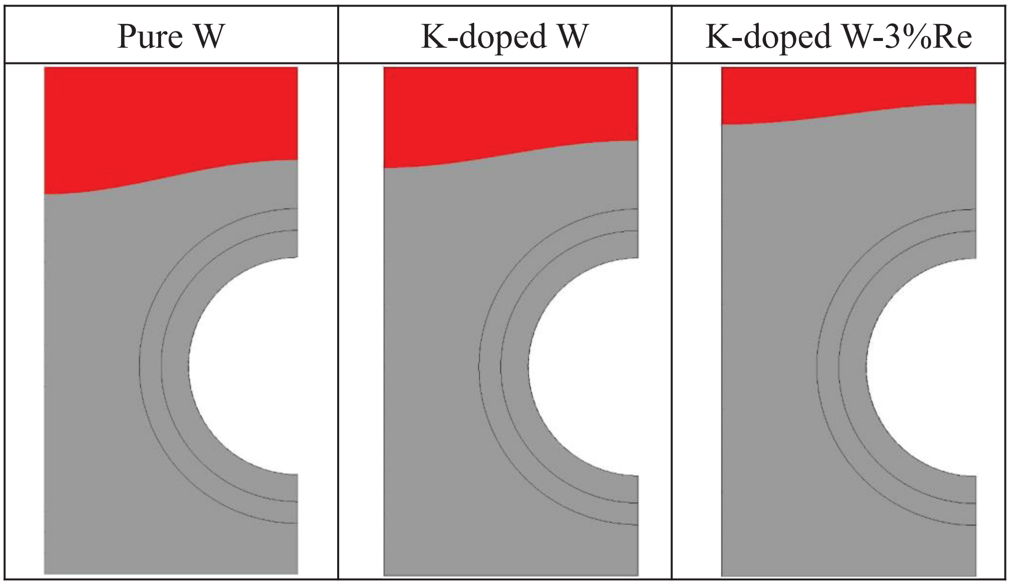

Fig. 4 The area above the temperature where the recrystallization starts in W monoblocks after a heat load of 20 MW/m^2 for 10 s.

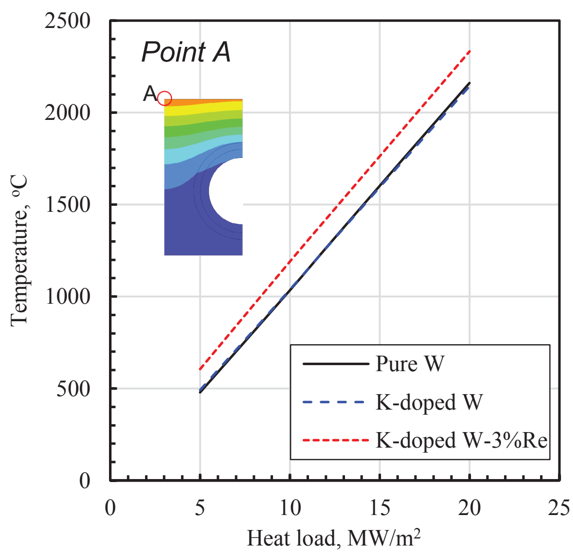

Fig. 5 Relationship between the heat load and the top surface temperature in a W monoblock.

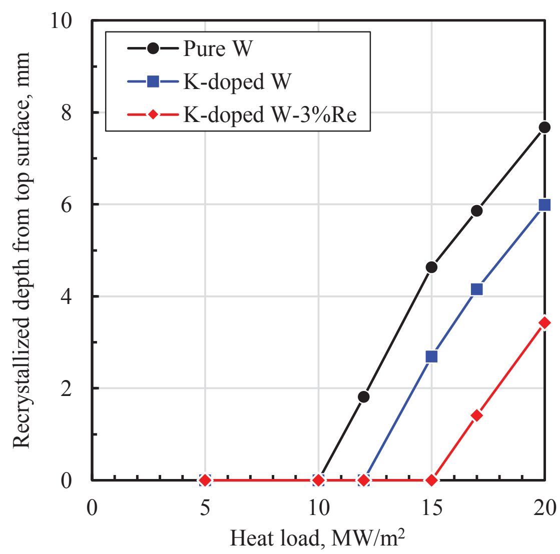

Fig. 6 Relationship between the heat load and the recrystallized depth in a W monoblock.

than pure W and K-doped W. This was caused by the lower thermal conductivity of K-doped W-3%Re than the others due to the 3% Re addition. K-doped W showed almost the same temperature and distribution as did pure W, and the effect of the K dope was not clearly observed.

Figure 4 shows the area above the temperature where the recrystallization starts in W materials after a 20 MW/m^2 heat load for 10 s. The temperature where the recrystallization starts of pure W, K-doped W, and K-doped W-3%Re were experimentally obtained by grain structure observation and the Vickers hardness measurement [13]. The temperatures where the recrystallization starts of pure W, K-doped W, and K-doped W-3%Re were ~1100, ~1300, and ~1800 °C in our previous works, respectively. For pure W, the depth of the area above the temperature where the recrystallization starts was ~8 mm from the top surface. The area above the temperature where the recrystallization starts in K-doped W and K-doped W-3%Re was smaller than that of pure W, and its depth were 6 and 3 mm from the top surface for K-doped W and K-doped W-3%Re, respectively. Although the thermal conductivity of K-doped W-3%Re is lower than those of pure W and K-doped W, the effect of the increase in recrystallization resistance was clearly observed in the heat load condition of this work. K-doped W also demonstrated the effectiveness of the K dope on the recrystallization behavior of pure W during heat load.

Figure 5 shows the relationship between the heat load and the maximum temperature on the top surface. The maximum temperature linearly increased with increasing heat load. The threshold heat load of the recrystallization was estimated as ~10, ~12, and 15 MW/m^2 for pure W,

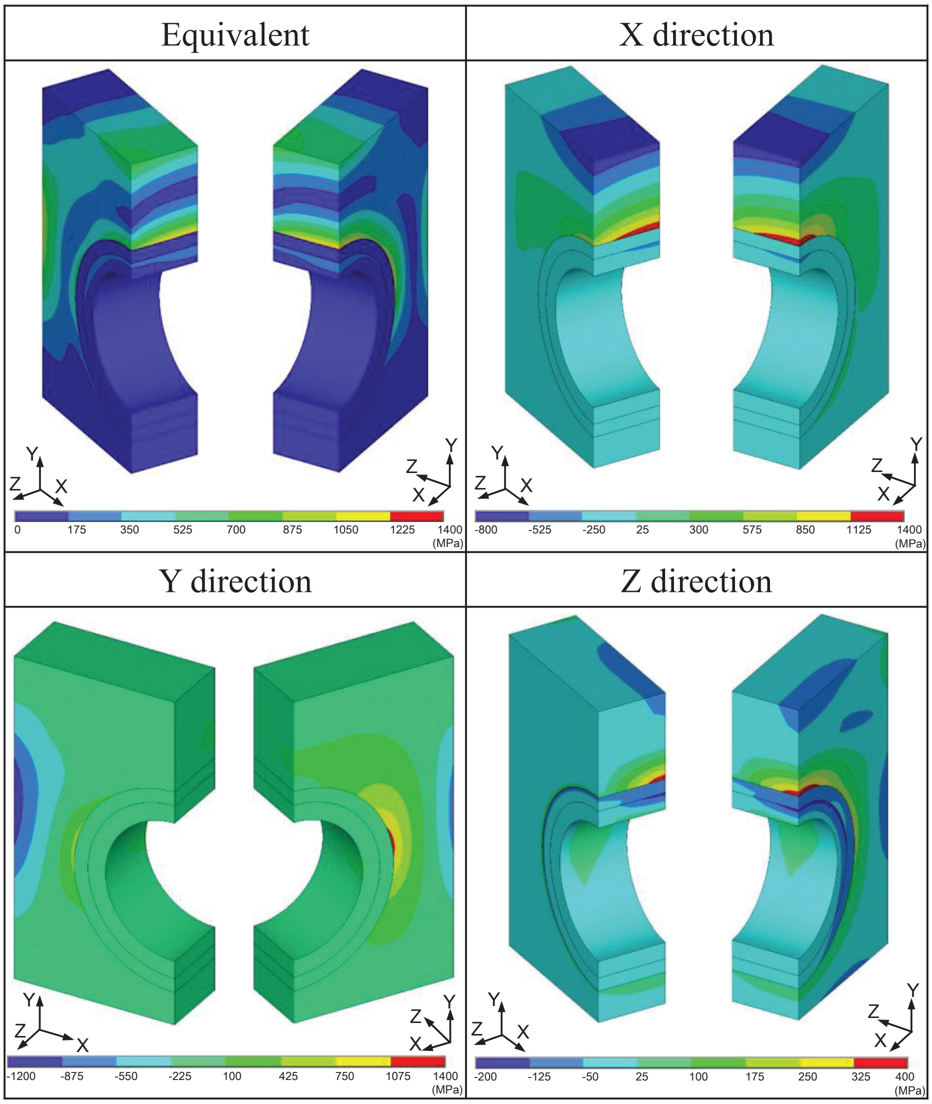

Fig. 7 Stress distribution in a pure W monoblock after a heat load of 20 MW/m^2 for 10 s.

K-doped W, and K-doped W-3%Re, respectively. The heat load dependence of the recrystallization depth is shown in **Fig. 6.** The recrystallization depth increased linearly with increasing heat load.

Figure 7 shows the stress distribution in the pure W monoblock after a 20 MW/m^2 heat load for 10 s. High stress was observed at the top surface and the interface between W and OFHC-Cu. Tensile stress at the top surface and compression stress in the vicinity of the OFHC-Cu in the center of the monoblock were observed in the X-direction. The high tensile stress in the vicinity of the OFHC-Cu layer and compression stress at the side surface in the monoblock were observed in the Y-direction. In the Z-direction, the high tensile stress was observed in the vicinity of the OFHC-Cu layer; however, the magnitude of the stress was lower than that in the X-direction. Although the magnitude of the stress depends on the W materials, the stress distribution was not changed between pure W, K-doped W, and K-doped W-3%Re. Because the K-doped W and K-doped W-3%Re shows higher strength than does pure W, it is expect that these W materials will show higher resistivity to deformation and crack formation during a cyclic heat load. The thermo-mechanical analysis of pure W, K-doped W, and K-doped W-3%Re monoblocks considering plastic deformation and hardening is a future work.

4. Summary

The thermo-mechanical analysis of pure W, K-doped W, and K-doped W-3%Re monoblocks under a heat load of up to 20 MW/m^2 was performed in this work. The results of this work are summarized as follows:

- K-doped W-3%Re showed the highest surface temperature, as compared to pure W and K-doped W under the same heat load condition because of its lower thermal conductivity due to 3% Re addition.
- K-doped W and pure W showed almost the same temperature distribution during heat load, and the effect of the K dope was not clearly observed because the thermal conductivity of K-doped W is almost the same as that of pure W.

- The recrystallization threshold heat load and recrystallization depth were estimated. K-doped W-3%Re showed the highest resistance to recrystallization due to the increased the temperature where the recrystallization starts resulting from Re addition and K dope.
- Higher stress was observed at the top surface and the vicinity of the OFHC-Cu layer in each direction. The stress distributions of pure W, K-doped W, and K-doped W during the heat load were almost the same.

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