Fusion Engineering and Design 107 (2016) 44–50

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Analysis of the temperature and thermal stress in pure tungsten monoblock during heat loading and the influences of alloying and dispersion strengthening on these responses

Makoto Fukuda [a,*], Shuhei Nogami [a], Wenhai Guan [a], Akira Hasegawa [a], Takeo Muroga [b]

[a] Tohoku University, 6-6-01-2 Aramaki-aza Aoba, Aobaku, Sendai, 980-8579, Japan
[b] National Institute for Fusion Science, 322-6 Oroshi-cho, Gifu, 509-5292, Japan

HIGHLIGHTS

- The heat load response of pure W and its alloys monoblock was investigated by FEA.
- The effect of alloying on heat load response of W was not clearly observed.
- The possibility of cracking during cooling phase after heat load was suggested.
- The effects of recrystallization and irradiation embrittlement were discussed.
- W alloys will show better reliability than pure W during fusion reactor operation.

ARTICLE INFO

Article history:
Received 6 November 2015
Received in revised form 26 March 2016
Accepted 6 April 2016
Available online 22 April 2016

Keywords:
Tungsten
Monoblock
K-doped W
K-doped W-3%Re
Finite element analysis
Heat load

ABSTRACT

The effects of 3% Re addition and K-bubble dispersion on temperature and stress values and the distributions thereof in a W monoblock during heat loading were investigated using finite element analysis. K-doped W-3%Re exhibited the highest recrystallization resistance but showed a higher surface temperature than pure W or K-doped W during the heat loading. The effect of K-bubble dispersion and 3% Re addition on thermal stress distribution during heat loading was not clearly observed, and residual tensile stress after heat loading, which could possibly cause cracking, was observed at the top surfaces of all materials. Because of the higher strength and temperature at which recrystallization starts for the K-doped W-3%Re and K-doped W, the probability of crack formation at the top surface might be lower compared to that in pure W. The improvement in the material properties and resistance to crack initiation and propagation in W during cyclic heat loading is crucial for the design and development of plasma-facing components. This work suggests possibility of the crack formation in a pure W monoblock in the cooling phase after a 20 MW/m^2 heat loading cycle and the effectiveness of K-bubble dispersion and Re addition for improving the heat loading resistance of monoblock W.

1. Introduction

Tungsten is a promising candidate as a plasma-facing material (PFM) in a fusion reactor because it has many suitable material properties, such as high melting temperature, high thermal conductivity, high sputtering resistance, and low tritium retention. However, crack formation andcooling ability losses in W monoblocks during cyclic heat loading based on ITER specifications have been reported [1–4]. After hundreds or thousands of cycles at 10–20 MW/m^2, recrystallization was observed in a pure W monoblock [3], and recrystallization embrittlement could assist crack initiation and propagation. Therefore, improvements in the mechanical properties and recrystallization resistance are desired to enhance the reliability of W as a PFM during cyclic heat loading in a fusion reactor.

For a PFM in the DEMOnstration reactor (DEMO), degradation of the mechanical and thermal properties, caused by both heat loading and neutron irradiation, is predicted. Neutron irradiation causes the formation of irradiation defects such as voids, dislocation loops, and irradiation-induced precipitates [5–12]. These defects and precipitates cause irradiation hardening and embrittlement of W. To improve the reliability of W as a PFM, the mechanical properties and

* Corresponding author.
E-mail address: makoto.fukuda@qse.tohoku.ac.jp (M. Fukuda).

http://dx.doi.org/10.1016/j.fusengdes.2016.04.013
0920-3796/

resistance to both recrystallization and irradiation embrittlement must be improved.

Grain structure refining is one method used to improve the mechanical properties and irradiation resistance. The yield stress of W increases with decreasing grain size based on the Hall–Petch relation. With decreasing grain size and increasing dislocation density, the densities of the sinks for irradiation-induced point defects increase, which suppress defect cluster formation and irradiation hardening [13,14]. As an alloying element, Re is well known to improve the ductility and recrystallization resistance of W. In our previous works, we fabricated different W plates (i.e., pure W, K-doped W, and K-doped W-3%Re) by powder metallurgy and hot rolling on the industrial scale to improve the mechanical properties and resistance to recrystallization and irradiation, and investigated the mechanical and thermal properties [15,16]. K-doped W-3%Re showed a higher tensile strength than pure W and K-doped W, especially above 1300 °C [17]. In addition, the low-temperature ductility and recrystallization resistance were improved by K-bubble dispersion and Re addition. The temperatures at which recrystallization started were estimated as 1100, 1300, and 1800 °C for pure W, K-doped W, and K-doped W-3%Re, respectively, based on grain structure observation and hardness measurements of the samples before and after annealing [16]. In this work, we aim to investigate the stress and strain values and distributions thereof in a W monoblock during heat load, and assess the effects of K-bubble dispersion and 3% Re addition to W during heat loading using finite element analysis (FEA).

2. Analysis method

The temperature, stress values, and their distributions thereof were investigated in a W monoblock during heat loading using FEA. The FE model was based on the dimensions of a monoblock for ITER, and consisted of W, oxygen-free high-conductivity (OFHC)-Cu, and CuCrZr as the PFM, buffer layer material, and cooling tube material, respectively. As the PFMs, pure W, K-doped W, and K-doped W-3%Re were used. A 1/4 model of the monoblock was used for this analysis, as shown in Fig. 1. The material property data were obtained from literature and our previous experimental results [16–20]. Anisotropy was considered for the yield stresses of the W materials in this analysis, because the W plates fabricated by hot rolling in our previous work showed anisotropic grain structures and therefore anisotropic tensile properties [15–17]. Table 1 shows the Young's modulus and yield stress of the W materials used for the FEA. The yield stress values were referred to our previous experimental data,estimated by a 0.2% offset method. The X-, Y-, and Z-directions were defined as parallel to the rolling direction, perpendicular to the rolling direction, and the thickness direction, respectively. To consider the anisotropic strength of W materials in FEA, the Hill yield criterion was used [21]. Thermo-mechanical

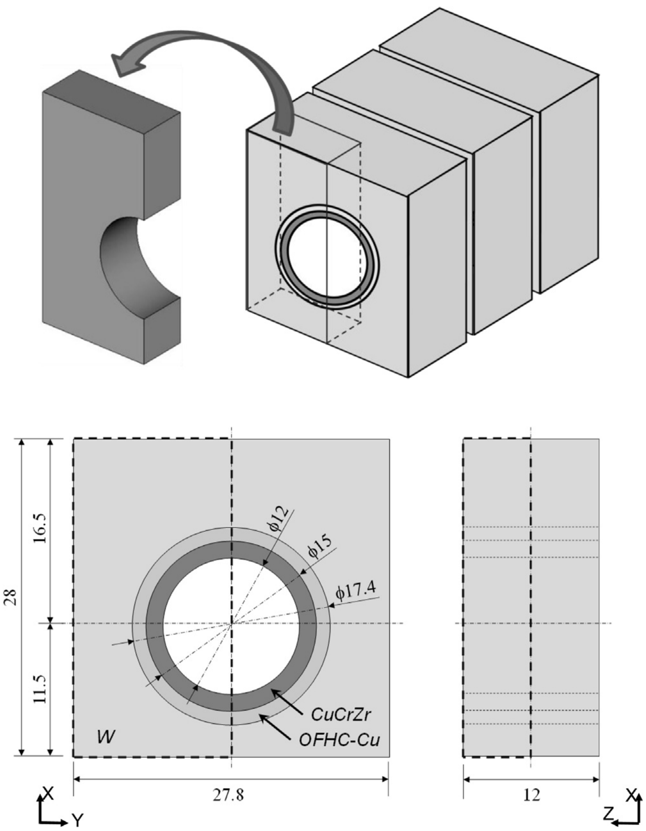

Fig. 1. The model for FEA.

analysis was carried out using ANSYS ver. 15.0. All materials were defined as perfect elasto-plastic solids in this analysis. The thermal conductivity of each W material is listed in Table 2. The thermal conductivity was calculated based on the specific heat, thermal diffusivity, and density. The specific heat and thermal diffusivity of all materials were experimentally obtained at below 1400 and 1100 °C, respectively; at higher temperatures, these values were determined by approximations. The density values were obtained from the literature [19]. Anisotropy in thermal diffusivity was investigated in our previous work; anisotropic thermal diffusivity was not observed. Therefore, anisotropy in thermal properties was not considered in this work. The material properties of CuCrZr and OFHC-Cu were obtained from the literature [20]. The axial symmetry surfaces of the X- and Y-axes in the 1/4 model were fixed. The heat loading conditions were 10 and 20 MW/m^2 heat loads with a dwell time of 10 s at the top surface of the monoblock; the cooling duration was 20 s. The temperature and strain change from 8.3 to

Table 1
Young's modulus and yield stress values of W materials.

Temp., °C	Young's modulus, GPa	Yield stress, MPa								
		Pure W			K-doped W			K-doped W-3%Re		
		X	Y	Z	X	Y	Z	X	Y	Z
20	409.4	859[a]	536[a]	193[a]	1425	733[a]	235[a]	1139	503[a]	277[a]
300	399.3	589	642	490[a]	740	734	570[a]	703	731	554[a]
500	391.3	565	620	330	642	652	598	613	606	534
700	382.7	494	544	490	592	610	548	559	616	508
900	373.4	484	504	421[a]	503	599	476[a]	538	569	382
1300	352.8	52	50	60	205	168	146	401	383	347
1500	341.5	58	58	58	54	54	54	111	111	111
1800	323.2	32	32	32	36	36	36	83	83	83
2500	274.4	–	–	–	–	–	–	–	–	–

[a] Fracture stress.