Nuclear Engineering and Technology 53 (2021) 1939–1941

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

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

Original Article

Study on sputtering yield of tungsten with different particle sizes: Surface roughness dependence

Tae Hyun Kwon, Sangjune Park, Jeong Min Ha, Young-Sang Youn*

Department of Chemistry, Yeungnam University, Daehak-ro 280, Gyeongsan, Gyeongbuk, 38541, Republic of Korea

A R T I C L E I N F O

Article history:
Received 14 November 2020
Received in revised form
30 November 2020
Accepted 27 December 2020
Available online 3 January 2021

Keywords:
Tungsten
Sputtering yield
Surface roughness
Fusion power
Divertor

A B S T R A C T

The sputtering yield of tungsten pellets composed of different particle sizes of <1, 12, 44–74, and 149–297 μm was systematically investigated by bombardment with Ar^+ ions accelerated at 2.0 keV in an ultra-high vacuum chamber. We found that the tungsten sample fabricated from larger particles had a higher surface roughness, based on the surface profile results. Using the data of the surface roughness for the four types of tungsten pellets, we confirmed that the sputtering yield for a tungsten pellet with the highest surface roughness was 7 times lower than that of the lowest surface roughness. This could be due to the redeposition of sputtered tungsten particles onto neighboring asperities.

1. Introduction

Nuclear fusion has attracted attention as an energy source that can be used as an alternative to fossil fuels in terms of environmental and safety aspects [1–4]. To successfully operate a fusion device, various factors that degrade its performance should be curtailed [5,6]. Among these factors, the influx of impurities into the plasma must inevitably be minimized, as it decreases the plasma temperature for fusion reactions [7,8].

Tungsten is considered as a candidate for plasma facing material of divertor to be used in fusion devices, because of its outstandingly low sputtering yield and high sputtering threshold energy. These characteristics make it possible to minimize the influx of tungsten into the plasma due to physical sputtering, which is substantially responsible for the degradation of plasma temperature [9–11]. However, if a high-Z element such as tungsten is utilized as the plasma facing material in a fusion device, there is an issue to be solved. The sputtered tungsten particles, which are a source of impurities, lead to fuel dilution and strong core radiation loss even at very low quantities [8,10,12–15]. Therefore, the reduction of the sputtering yield of tungsten should be preferentially investigated, and it is an essential prerequisite for successfully using tungsten as a plasma facing material.

It was previously reported that the surface roughness of tungsten positively influences the sputtering yield due to the redeposition phenomenon; the higher the surface roughness, the lower the sputtering yield [16–20]. Although the relation between surface roughness and sputtering yield of tungsten was described in the literature, a strategy to reduce the sputtering yield by increasing the surface roughness with controlling the tungsten particle sizes has not been attempted to date.

Herein, the sputtering yield of tungsten pellets manufactured from different tungsten particle sizes (<1, 12, 44–74, and 149–297 μm) was explored. We found that the tungsten sample with the largest particle size of 149–297 μm demonstrated the highest surface roughness. Furthermore, after bombardment with Ar^+ ions, the sputtering yield for the sample with the largest surface roughness was the lowest compared to the others. We confirmed that surface roughness and sputtering yield of tungsten are inversely proportional; we suggest that the redeposition of tungsten particles sputtered from the sample gives rise to this phenomenon.

2. Materials and methods

Disc-shaped tungsten pellets with a diameter of 10 mm and thickness of ~2.6 mm were prepared through mechanical pressing at 13.8 MPa using tungsten powder (Alfa Aesar) with particles of sizes of <1 (99.95%), 12 (99.9%), 44–74 (99.95%), and 149–297 μm

* Corresponding author.
E-mail address: ysyoun@yu.ac.kr (Y.-S. Youn).

https://doi.org/10.1016/j.net.2020.12.024

(99+%). A tungsten sample without any treatment after the manufacture was mounted on a sample stage in an ultra-high vacuum (UHV) chamber equipped with an IG2 ion source package (RBD Instruments). Sputtering of the tungsten at room temperature was performed for approximately 12 h at the surface normal using Ar^+ ions accelerated at 2.0 keV in the UHV chamber. The sputtering current was recorded using a Fluke 287 multimeter with the FlukeView Forms software. The weight loss in the tungsten pellets caused by sputtering was measured with a Pioneer PX125DKR semi-micro balance (OHAUS).

The sputtering yield (Y, atoms/ion) was calculated using the weight loss method with the following equation reported in the literature [9,21,22].

$$Y = \frac{\Delta m N_A}{M_2 n_1}$$

where Δm is the weight loss of the tungsten due to sputtering, N_A is the Avogadro number (6.022×10^{23} atoms/mol), M_2 is the atomic mass of tungsten (183.84 g/mol), and n_1 is the number of incident Ar^+ ions obtained from the product of the sputtering current and sputtering time ($n_1 = 1$ C means incident 6.25×10^{18} Ar^+ ions).

Scanning electron microscopy (SEM) images were obtained with an S-4200 (HITACHI) instrument, and an electron accelerating voltage of 15 keV was used during image collection. The X-ray diffraction (XRD) data were recorded in the range of 25–120° with a scanning step of 0.02° for 0.24 s using a MiniFlex600 system (Rigaku) with Cu K_α radiation operated at 15 mA and 40 kV. The surface roughness (Ra; roughness center-line average) of the tungsten pellets was recorded using a Dektak 150 surface profiler (Veeco) with a stylus force of 1 mg, over a scanning length of 1 mm. All the values of the surface roughness have an error rate of 95% of the confidence interval.

3. Results and discussion

Fig. 1 shows SEM images obtained from the four types of tungsten samples, consisting of different particle sizes. As shown in Fig. 1, we observed different surface morphologies depending on the type of tungsten pellet.

In addition to the SEM experiments, we obtained XRD spectra for the four tungsten samples. XRD data (Fig. 2) showed that all the diffraction peaks obtained from each tungsten sample correspond to those of the body-centered cubic (BCC) crystal structure of tungsten [4]. Based on the SEM and XRD results, we verified that the four types of tungsten pellets with different surface topographies were fabricated without any change in the crystallographic characteristics.

Prior to the experiments on the sputtering yield, we evaluated the surface roughness of the four tungsten samples using a surface profiler. Fig. 3 shows the surface roughness values for the four types of tungsten pellets prepared from particles of sizes of <1, 12, 44–74, and 149–297 μm to be 0.11 ± 0.01, 1.18 ± 0.11, 9.78 ± 1.85, and 11.35 ± 0.90 μm, respectively. As expected, the value of surface roughness was the highest for the tungsten pellet comprising particles of the largest size (149–297 μm) among the four samples. We found that the surface roughness of the tungsten sample with particle size of 149–297 μm was 100 times greater than that of the sample with particle size of <1 μm.

Using four types of tungsten samples with particle sizes of <1, 12, 44–74, and 149–297 μm, we performed experiments on sputtering yield by bombarding the samples with Ar^+ ions accelerated at 2.0 keV at the surface normal in a UHV chamber at room temperature. As shown in Fig. 3, the values of the sputtering yield for the tungsten pellets of particle sizes of <1, 12, 44–74, and 149–297 μm were estimated to be 6.82, 2.26, 1.31, and 0.97 atoms/ion, respectively. These results are similar to the values of approximately 1–3 atoms/ion for tungsten, as reported in previous studies under an atmosphere of Ar^+ ions accelerated at 2.0 keV [22,23]. Moreover, we determined that the lowest sputtering yield among all the tungsten samples was observed in the one with the largest surface roughness, which is consistent with the results of previous studies [16,18,20]. The sputtering yield for the tungsten sample with a particle size of 149–297 μm was 7 times lower than that of the sample with a particle size of <1 μm. This difference is substantially large, considering that the sputtered tungsten particles bring about fuel dilution and strong core radiation loss even at very low amounts. We successfully decreased the sputtering yield of tungsten up to a factor of 7. Furthermore, we identified that the surface roughness and sputtering yield of tungsten are inversely

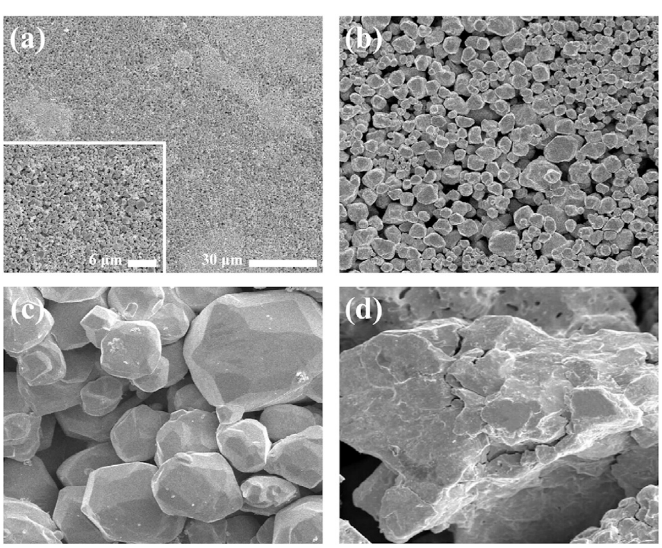

Fig. 1. SEM images (× 500 magnification) of the tungsten pellets fabricated at particle sizes of (a) <1, (b) 12, (c) 44–74, and (d) 149–297 μm. Insert: Enlarged SEM image (× 2000 magnification) of the corresponding tungsten pellet.

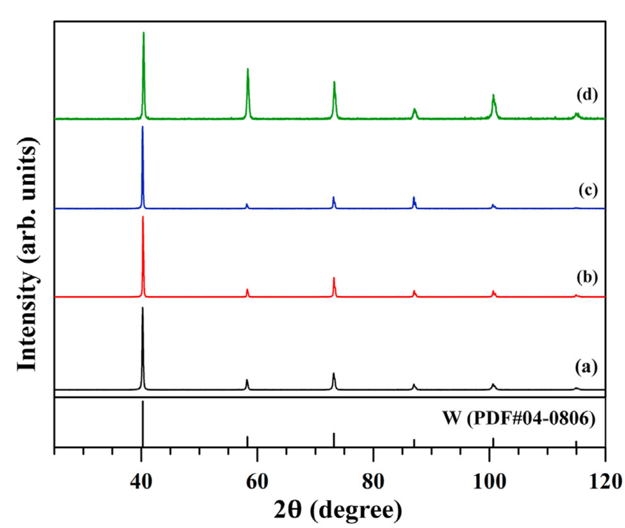

Fig. 2. XRD spectra acquired from the tungsten pellets with particle sizes of (a) <1, (b) 12, (c) 44–74, and (d) 149–297 μm. Bottom panel: Diffraction patterns for the BCC structure of tungsten (PDF#04–0806) extracted from PDF-2 database.

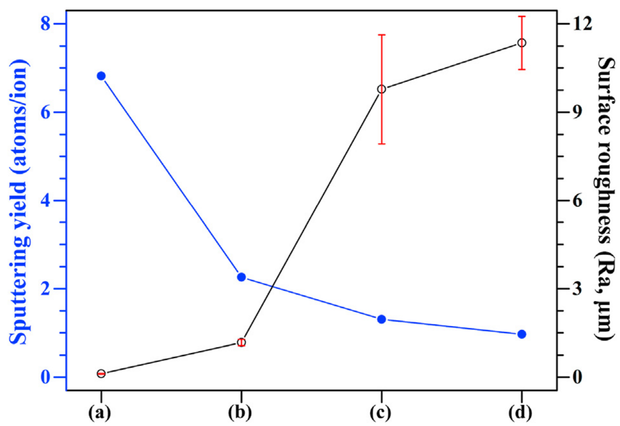

Fig. 3. The values of sputtering yield and surface roughness for the tungsten samples of particle sizes of (a) <1, (b) 12, (c) 44–74, and (d) 149–297 μm. Surface roughness and the sputtering yield of tungsten are inversely proportional. All the values of the surface roughness were indicated with an error rate of a 95% confidence interval.

proportional (Fig. 3), which implies that the redeposition of particles sputtered from tungsten onto neighboring asperities occurred more on pellets with relatively rough surfaces than on ones with flat surfaces.

4. Conclusions

The sputtering yield for tungsten pellets fabricated with different particle sizes of <1, 12, 44–74, and 149–297 μm was systematically investigated by bombardment with Ar^{+} ions at 2.0 keV. We found that the surface roughness for a tungsten pellet composed of larger particles is higher, based on surface profile data. In addition to surface roughness, we identified that the sputtering yield for tungsten sample with the largest particle size is up to 7 times lower than that of those obtained from smaller particles. Consequently, we confirmed that surface roughness and sputtering yield of tungsten exhibit an inverse relationship. This observation can be significant in the reduction of impurities sputtered from tungsten. This would allow the successful use of tungsten as a plasma facing material of diverter in fusion devices.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was funded by the National Research Foundation of Korea (NRF) funded by the Korean government (MSIP), grant number 2019M1A7A1A02085179. This work also supported by the 2020 Yeungnam University Research Grant.

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