

Role of carbon impurities on the surface morphology evolution of tungsten under high dose helium ion irradiation



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ABSTRACT

The effect of carbon impurities on the surface evolution (e.g., fuzz formation) of tungsten (W) surface during 300 eV He ions irradiation was studied. Several tungsten samples were irradiated by He ion beam with a various carbon ions percentage. The presence of minute carbon contamination within the He ion beam was found to be effective in preventing the fuzz formation. At higher carbon concentration, the W surface was found to be fully covered with a thick graphitic layer on the top of tungsten carbide (WC) layer that cover the sample surface. Lowering the ion beam carbon percentage was effective in a significant reduction in the thickness of the surface graphite layer. Under these conditions the W surface was also found to be immune for the fuzz formation. The effect of W fuzz prevention by the WC formation on the sample surface was more noticeable when the He ion beam had much lower carbon (C) ions content (0.01% C). In this case, the fuzz formation was prevented on the vast majority of the W sample surface, while W fuzz was found in limited and isolated areas. The W surface also shows good resistance to morphology evolution when bombarded by high flux of pure H ions at 900 °C.

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1. Introduction

Due to its higher melting point (3695 K) and lower sputtering yield, tungsten (W) has been selected as a potential candidate for plasma-facing component (PFC) in the international thermonuclear experimental reactor (ITER)-divertor design during the D–T operational phase [1–4]. In addition, W is a plausible candidate for in-vessel mirror material because of its good optical reflectivity in a wide wavelength range. These extreme conditions promote a considerable erosion of the W PFC due to sputtering and thermal evaporation [1,2]. During reactor operation, these PFC materials will be exposed to high flux of energetic particles along with high heat loads [5]. Recently it has been noted that helium bombardment on W PFC can cause wide variety of microstructural evolution, such as dislocation loops, helium holes/bubbles [6] and fibreform

nanostructure [7,8]. Note that surface morphology of PFC materials play vital role towards reliable steady state operation of Fusion devices. Formation of fine and brittle W nanostructure (Fuzz) on W surfaces after the exposure of low energy He⁺ ions or plasmas relatively higher flux at elevated temperatures, have been found recently [8–11]. The presence of such fragile structure represents a serious threat for the durability of the confined plasma. The presence of such materials, due to some abnormal events, even very tiny amount, in the confined D–T plasma may lead to immediate plasma cooling (quenching) due to radiation energy losses [5,12]. This scenario is expected if the extremely fragile W fuzz structure washed out into the confined plasma during transient events such as plasma instability [5,12].

Recently, it has been recognized that carbon (C) contaminants on W surface may significantly reduce the formation of such brittle W nanostructure (Fuzz) [13,14]. The fuzz layer growth rate does not depend on whether the He is the dominant, or a minority, species [13]. In fact, it can be inhibited if sufficient condensable impurities

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(in the case of ITER, beryllium (Be) or C) are contained within the incident particle flux to achieve a condition of net deposition and thereby allow an impurity surface layer to develop [13]. However, if the removal rate of impurities from the surface is greater than their arrival rate to the surface, then the fuzz layer may develop [13]. In the similar scenario a few studies were also performed on the understanding of plasma induced mixing on tungsten carbide (WC) [14,15], WBe, and WBeC [16].

It has also been noted that the sputtering yield of W bombarded by C ions at room temperature (RT) was dramatically decreased with C dose at certain angles [17]. The presence of C on W surface reduced the weight loss of W due to sputtering [17]. The enhanced diffusion of C at high temperature played a significant role in modifying the results primarily observed in the case of RT bombardment [18]. The temperature has a strong effect on the range distribution of C in W. At higher temperature, C atoms are expected to penetrate more in depth in the W sample, as a result of enhanced diffusion of C in W [15,18,19]. Due to the reduction in C concentration near the W surface at elevated temperature, W erosion rate (weight loss) was higher. Although currently there is no intention to use the CFC (Carbon Fiber Composites) as a PFC in ITER (according to the updated ITER design) [20], still the existence of C contamination in any fusion device's plasma chamber is always a possible scenario. Studies by Ueda et al. [14,15,21] are noteworthy, where they have shown that H^+ ions irradiation (using 3×10^{24} ion/ m^2 dose at 650 °C) having even ~ 1% C can deteriorate the surface significantly and form WC on the W surface [15]. WC is a very hard and brittle material and hence, its presence on the W surface could lead to degradation in the mechanical and thermal properties of the W. Similar carbon depth distribution was also obtained by simulation using ITMC-DYN models by us [22,23]. It was found that temperature has large influence on the chemical state of C in W substrate. In fact, the presence of C in the form of WC was favorable at higher temperature (above 700 °C) [24], and hence, unreacted C was found only near the surface, where the atomic concentration of C is higher than the stoichiometric ratio of WC (1:1) [15].

In the present study, we report on the effects of carbon impurities on the surface morphology evolution of W PFC under high dose He^+ ion irradiation in extreme conditions. Although few studies have already reported perversely on the similar topic [13–15,21,24]; the effects of intermixing of PFC materials, during plasma and/or ion exposure, are still not well understood. Our study shows the responses of the W as PFC surface during He^+ ion irradiation as a function of C concentrations (tiny amount). Note that the C divertor is no longer part of the current ITER design. The temperature and ion energy spectrum in the ITER divertor are currently believed to fall outside the fuzz formation window in the expected detached plasma regime. Nevertheless, fuzz formation window in the hypothetical W first wall DEMO could still be significant as well as unexpected abnormal ITER operations. In these devices, small amounts of C seeding might be considered, not just for the benefits of radiative cooling, but also to inhibit fuzz. Additionally small amounts of C in the DEMO may not necessarily be a retention problem due to the high operational temperature.

2. Experimental details

The experiments have been performed in the IMPACT (Interaction of Materials with Particles and Components Testing) laboratory of center of materials under extreme condition (CMUXE) at Purdue University. Multiple pure (99.95%) W sheets (0.5 mm thick) were cut in 10×10 mm and mechanically polished to a mirror like surface finish. After that, each sample was inserted into our irradiation chamber. Prior to He^+ ion irradiation, each sample was sputter cleaned by a high flux of 1 keV Ar^+ ions for around

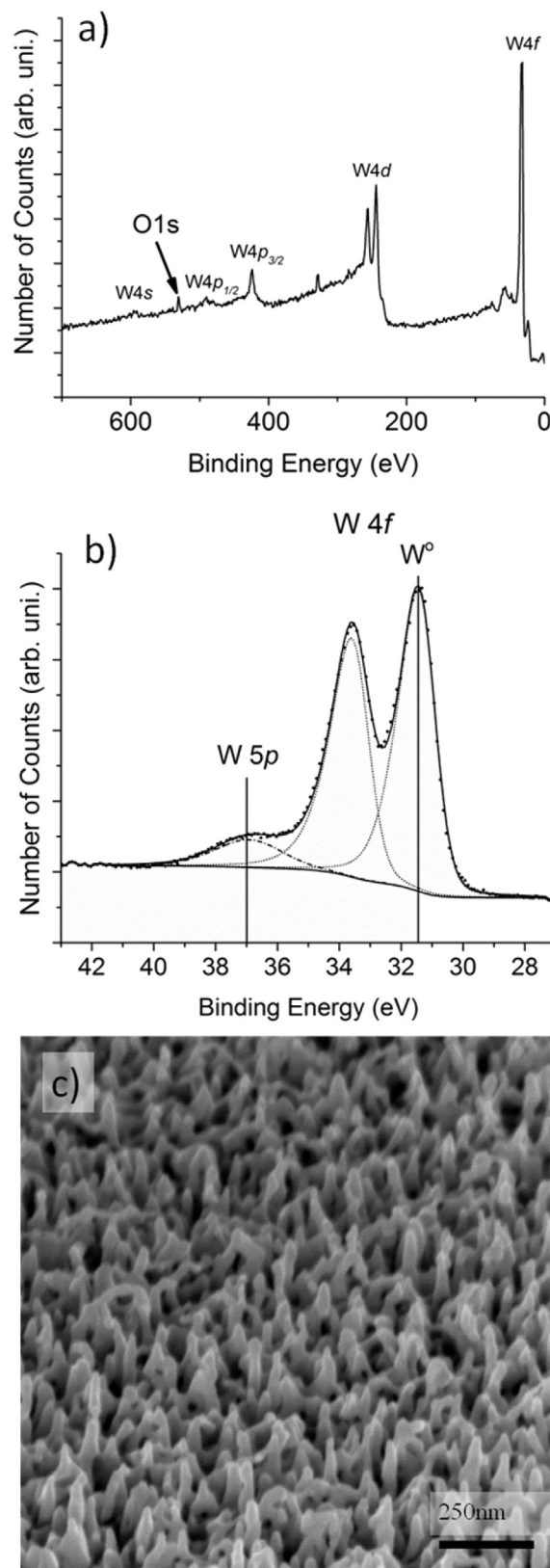


Fig. 1. XPS of the sample irradiated by pure He^+ ion beam. XPS full spectrum (a), and high resolution XPS spectrum for the W 4f region (b). Part (c) shows a SEM image of the nanostructure (Fuzz) covering on the W sample surface, the sample was irradiated by pure He^+ ions (1.0×10^{25} ion/ m^2 fluence) at 900 °C.

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