

KEY PROPERTIES OF MIXED W-C-D SURFACE RELATED TO TUNGSTEN EROSION

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The erosion of tungsten exposed to the mixed particle flux of carbon and deuterium ions is effected by several factors. The main factor is the formation of mixed W-C-D surface, which decreases content of tungsten atoms in the near-surface region. Other factors affect carbon content on the surface and attributed to elevated surface temperature: chemical erosion and radiation-enhanced sublimation.

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1. INTRODUCTION

The current ITER design envisages beryllium at the first wall, tungsten coatings in the baffle region of the divertor and graphite-based components for the target plates exposed to the high-heat flux [1]. The proximity of the tungsten and carbon surfaces will unavoidably lead to formation of the mixed surface, which will be exposed to mixed particle flux. Erosion of tungsten surface due to sputtering should occur under rather complicated conditions. The incident ion flux includes fuel ions, as well as neutrals and energetic carbon ions. This should lead to formation of the mixed W-C-D surface, which properties are generally different from properties of pure materials.

The erosion of the mixed surface may be further complicated by the temperature of the surface. At elevated temperatures carbon prone to chemical sputtering [2] and radiation enhanced sublimation [3]. The present paper reviews the system of W surface exposed to C and D ion flux, which demonstrate complicated physical effects, influencing each other and defining the lifetime of W surface.

2. FORMATION OF MIXED W-C-D SURFACE

The experiments and simulations on simultaneous bombardment of W surface with C and D/He ion beams have been performed in [4,5]. Because the usage of D and C simultaneously may disturb the measurements due to chemical erosion, one considers the formation of the mixed surface replacing D with noble He gas.

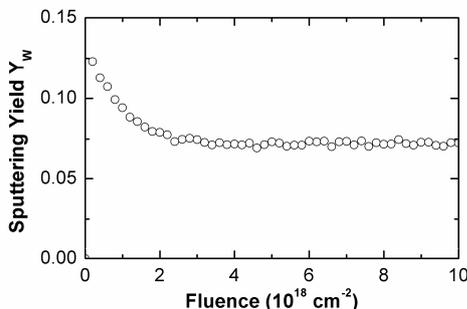


Fig.1. The evolution of W sputtering yield towards steady-state. Initially pure W surface is exposed to 3 keV He and 6 keV C ion beams (15% of C fraction)

When pure W surface is exposed to C and He ion beams simultaneously, the W sputtering yield changes

with fluence. Fig. 1 shows the evolution of the yield as obtained by TRIDYN [6] simulations.

The yield is high at the beginning due to purity of the surface. However, implanted C atoms create the layer of the mixed material with typical thickness of 10...15 nm. As a result, W erosion decreases, because its concentration at the surface is also decreases. This continues until the system reaches the steady-state; in this example it is reached at fluence $3 \times 10^{18} \text{ cm}^{-2}$, at higher fluence the sputtering yield remains constant.

In steady-state regime, the number of implanted C atoms equals to number of sputtered and reflected ones; the surface composition and depth elemental distribution remains the same. Fig. 2 shows the areal density of the retained C atoms as a function of the C fraction in the total flux. One can see that C areal density increases monotonically with C fraction in the total flux until the system switches into C deposition regime. The numerical simulations with TRIDYN show good agreement with experimental measurements.

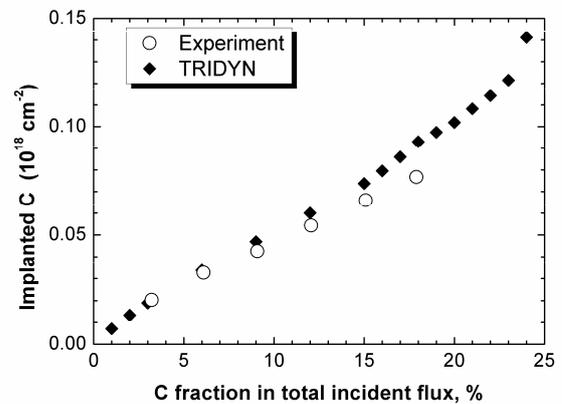


Fig.2. The dependence of C areal density on C fraction in total flux. W surface is exposed to 6 keV C and 3 keV He, the data are represented for the steady-state

While C content in the surface is increasing, the corresponding sputtering yield is remained approximately constant, as shown in Fig. 3. The results of experiment and the simulations agree well, with typical deviation of about 30%. The deviation is conditioned by error in the fluence measurement. The simulations indicate also that the sputtering yield drops dramatically approaching the transition from sputtering regime to C layer deposition one.

A linear growth of sputtering yield, as plotted with dots in Fig. 3, would only occur if it was independent of

the elemental composition of the mixed surface. In other words, the sputtering rate of W atoms Y_W in that case would be determined only by the fraction of the contributing ion species in the total incident flux (f_C or f_{He}):

$$Y_W = f_C Y_W^C + f_{He} Y_W^{He},$$

where Y_W^C and Y_W^{He} are sputtering yields of pure W due to C and He ion impact respectively. Obviously, neglecting the modification of the elemental composition can lead to large errors in the simulation of W sputtering by simultaneous impact of volatile and non-volatile elements.

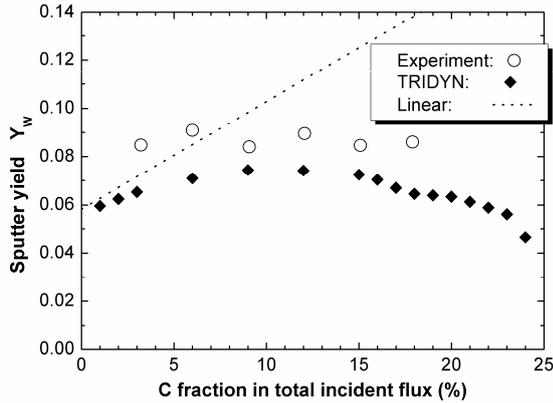


Fig.3. The dependence of W sputtering yield on C fraction in the total flux. W surface is exposed to 6 keV C and 3 keV He, data are represented for the steady-state

Therefore, the formation of the mixed surface leads to increase of C and decrease of W concentration. The number of W atoms available for sputtering is lower in comparison to the pure surface; instead, implanted C atoms take part in sputtering. As a result, the processes attributed to W sputtering are partly replaced with those providing C recycling (i.e. implantation and sputtering).

However, the balance defining the C recirculation can be disturbed by temperature effects, which may decrease the C concentration in the surface.

3. THE TEMPERATURE EFFECTS

Surface temperature introduces mechanisms, which may increase the erosion of C atoms. These mechanisms are known as chemical sputtering [2] and radiation enhanced sublimation [3].

The mechanism of chemical erosion envisages that C and D atoms create chemical bonds and form volatile molecules, mainly methane, which leave the surface and take away C atom. The methane production yield has been measured as a function of the surface temperature and this dependence has been studied experimentally in [7].

Typical example of such dependence is shown in Fig. 4. The methane production exhibit the highest rates at RT followed by a decreasing trend with increasing temperature to ~500 K, followed by a leveling off at higher temperatures. In order to compare the present methane production levels with published methane yields for graphite, we shall normalize the measured production rates by the D ion flux incident on the specimen. We note that the so derived 'apparent' yield is over-estimated due

to the inclusion of possible wall contributions. The magnitude of the near-RT yield appears to be approximately $(7...10) \times 10^{-3}$ CD_4/D . It is evident from Fig. 4 that the temperature-dependence of CD_4 production, obtained in this study, totally differs from published yields for pure carbon [8]. While the 'apparent' yields are approximately equal to those of pure graphite at RT, the normally seen graphite peak at ~750 K is not present.

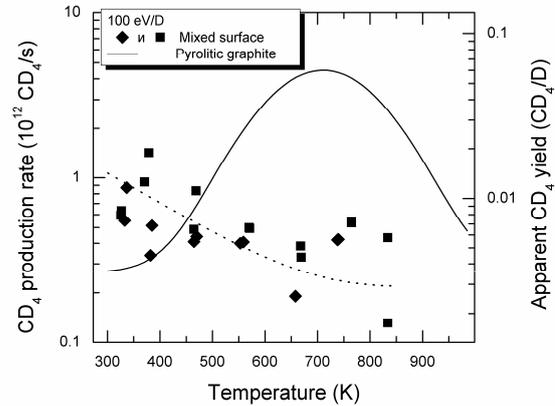


Fig.4. CD_4 production rate as a function of specimen temperature for simultaneous bombardment of W with 6 keV/C and 100 eV/D ions. Symbols of the same shape represent data obtained on the same day. Methane yield for pure carbon [8] is shown for comparison

The experimental results on the reemission of C due to radiation-enhanced sublimation from tungsten during irradiation with 6 keV C ion beam have been published in [9]. At temperature 1373 K the C reemission from the mixed W-C layer is generally lower than that from the pure carbon. Since the setup has not allowed to study the temperature dependence of C reemission from the mixed W-C surface, it has been left unknown, whether the generally lower value prevails at temperatures other than 1373 K.

In the temperature range below 1073 K, i.e., where diffusion does not deplete the carbon from the surface, the radiation-enhanced sublimation has been studied by comparing C profiles at room temperature and at temperature of 973 K. It has been confirmed that the profiles are quite similar: C concentration at the very surface is about 40-50%; it is decreasing deeper into the surface until a depth of ~10 nm. Therefore, there is no significant erosion mechanism (RES or otherwise) contributing to the removal of carbon at $T = 973$ K as compared to 300 K.

According to [10], the mechanism for RES relies on the transport of C interstitials to a surface where they may desorb. The nature of the mixed C-W surface layer may act to impede this transport, as compared to pure graphite.

4. CONCLUSIONS

This work has reviewed the main factors affecting the erosion rate of tungsten surface exposed to mixed C and D particle flux. The formation of the mixed surface is considered as the main factor, because the processes

attributed to W sputtering are partly replaced with those providing C recycling.

Other factors related to surface temperature, like chemical sputtering and radiation enhanced sublimation, regulate C content in the mixed surface. However, they have minor impact on tungsten erosion in the temperature range, expected on surface in ITER divertor. Therefore, the existing models simulating the interaction of ions and neutrals with surface are suitable for use in ITER design. The simulation programs (TRIDYN for example) can provide numerical data for the case of the mixed surface, which are well supported by experimental measurements.

One should take into account the dual influence of temperature effects on formation of the mixed surface. On the one hand, pure carbon surface, which may be formed due to deposition, is prone to higher sputter rates at higher temperatures. This should act preventing the carbon overlayer on top of mixed W-C-D surface. On the other hand, temperature effects are almost negligible for the mixed W-C-D surface in the temperature range, typical for ITER. Therefore, role of the temperature effects is uncovering of the mixed surface.

REFERENCES

1. R.E.H. Clark, D.H. Reiter. *Nuclear Fusion Research: Understanding plasma surface interactions*. Springer, 2005.
2. J. Roth, C. Garcia-Rosales. Analytic description of the chemical erosion of graphite by hydrogen ions // *Nuclear Fusion*. 1996, v. 36, p. 1647, with corrigendum in *Nuclear Fusion*. 1997, v. 37, p. 897.
3. J. Roth, J. Bohdanský, K.L. Wilson. Erosion of carbon due to bombardment with energetic ions at temperatures up to 2000K // *J. Nucl. Mater.* 1982, v. 111-112, p. 775.
4. I. Bizyukov, K. Krieger. Transition from tungsten erosion to carbon layer deposition with simultaneous bombardment of tungsten by helium and carbon // *Journal of Applied Physics*. 2007, v. 101, p. 104906.
5. I. Bizyukov, K. Krieger. Principal processes occurring at simultaneous bombardment of tungsten by carbon and deuterium ions // *Journal of Applied Physics*. 2007, v. 102, p. 074923.
6. W. Moeller, W. Eckstein, J.P. Biersack. TRIDYN - binary collision simulation of atomic collisions and dynamic composition changes in solids // *Comput. Phys. Commun.* 1988, v. 51, N 3, p. 355-368.
7. I. Bizyukov, J.W. Davis, A.A. Haasz, P. Brodersen. CD₄ production from mixed W-C-D surface during simultaneous ir-radiation of W with C⁺ and D⁺ // *J. Nucl. Mater.* 2009, v. 391, p. 925-928.
8. B.V. Mech, A.A. Haasz, J.W. Davis. Isotopic effects in hydrocarbon formation due to low-energy H⁺/D⁺ impact on graphite // *J. Nucl. Mater.* 1998, v. 255, p. 153-164.
9. I. Bizyukov, J.W. Davis, A.A. Haasz, P. Brodersen. C and D reemission from mixed W-C-D layers during single-species and simultaneous irradiations of W with C⁺ and D⁺ // *J. Nucl. Mater.* 2010, v. 400, p. 245-250.
10. V. Philipps, E. Vietzke, R.P. Schorn, H. Trinkaus. Flux dependence of radiation induced sublimation of graphite at elevated temperatures // *J. Nucl. Mater.* 1988, v. 155-157, p. 319-323.

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КЛЮЧЕВЫЕ СВОЙСТВА СМЕШАННОЙ W-C-D ПОВЕРХНОСТИ, ВЛИЯЮЩИЕ НА ЭРОЗИЮ ВОЛЬФРАМА

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Распыление поверхности вольфрама, облучаемого смешанным потоком частиц углерода и дейтерия, находится под влиянием нескольких факторов. Основным фактором является формирование смешанной W-C-D поверхности, что уменьшает количество атомов вольфрама в приповерхностной области, откуда они распыляются. Другие факторы, такие как химическое распыление и радиационно-усиленная сублимация, влияют на концентрацию углерода на поверхности и связаны с ее повышенной температурой.

КЛЮЧОВІ ВЛАСТИВОСТІ ЗМІШАНОЇ W-C-D ПОВЕРХНІ, ЯКІ ВПЛИВАЮТЬ НА ЕРОЗІЮ ВОЛЬФРАМУ

І.О. Бізюков

Розпилення поверхні вольфраму, опромінюваної змішаним потоком частинок вуглецю й дейтерію, знаходиться під впливом кількох факторів. Основним фактором є формування змішаної W-C-D поверхні, що зменшує кількість атомів вольфраму у приповерхневій області, звідкіля вони розпилюються. Інші фактори, такі як хімічне розпилення та радіаційно-посилена сублимація, впливають на концентрацію вуглецю на поверхні і пов'язані з її підвищеною температурою.