ELSEVIER

Journal of Nuclear Materials 313–316 (2003) 465–468

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Influence of high-power plasma streams irradiation on surface erosion behavior of reversible hydrogen getters

V.N. Borisko [a,*], I.E. Garkusha [b], V.V. Chebotarev [b], M.V. Lototsky [c], J. Langner [d], M.J. Sadowski [d], V.I. Tereshin [b], Yu.F. Shmal'ko [c]

[a] Kharkov National University, Svobody sq. 4, 61077 Kharkov, Ukraine
[b] Institute of Plasma Physics of the NSC KIPT, Kharkov, Ukraine
[c] Institute of Mechanical Engineering Problems, Kharkov, Ukraine
[d] The Andrzej Soltan Institute for Nuclear Studies, Swierk, Poland

Abstract

The paper presents results of investigations of the shielding effect observed at the interaction of pulsed plasma streams with metal-hydrides on the base of $Zr_{55}V_{40}Fe_5$ alloys. A reversible hydrogen getter tablet was initially saturated with pure hydrogen and then irradiated with pulsed plasma beams. The total content of accumulated hydrogen was 2 dm^3 (under normal conditions). The plasma irradiation induced desorption of accumulated hydrogen, due to the high-speed heating and the formation of gas shield layer in front of the tablet surface. That layer decreased considerably the value of an energy density, which was delivered to the sample surface. The energy densities delivered to the sample and mass losses of material have been determined as a function of a number of pulses. It was found that hydrogen buildup promotes an increase of the shielding effect.

PACS: 52.40.Hf
Keywords: Plasma-wall interactions; Metal-hydride; Hydrogen getter; Gas shield

1. Introduction

At present, hydride-forming materials (getters) are considered as rather prospective ones for the improvement of cathodes to be used in gas discharge systems [1]. In fusion devices such getters can be used for the creation of a controlled flow of hydrogen isotopes from the material surfaces to be exposed to hot plasma. As the working gases in fusion devices the hydrogen isotopes are usually in use. Therefore, their additional flow, which should be matched with a pumping system, is ideal from the point of view of the providing the low-Z impurities, forming the shielding layer. So, this additional flow from constructional elements does not lead to any complication of the fusion reactor operation. From the other side, it promotes the creation of a shielding gas target, which considerably screens the plasma energy delivered to the material surface. One of the advantages of such a protection is that the shielding target is formed by hydrogen (not by material of eroded target) and not permanently, but by the self-consistent way, i.e. only during periods when plasma contacts with the getter material surface. The use of the hydride-forming materials is prospective for the formation of such shielding targets. Utilizing the effect of a hydrogen counter-current flow formation (from the metal-hydride divertor plates) allows to control effectively the operation regimes of divertors in the toroidal magnetic traps. This also leads to an improvement of the plasma confinement within the working volume of the trap. The main aim of

* Corresponding author. Address: Physics and Technical Department, Kharkov National University, 31 Kurchatov Av., 61108 Kharkov, Ukraine. Tel./fax: +38-0572 35 0525.
E-mail address: borisko@pht.univer.kharkov.ua (V.N. Borisko).

0022-3115/03/$ - see front matter © 2003 Elsevier Science B.V. All rights reserved.
PII: S0022-3115(02)01366-1

this work is to investigate shielding properties of reversible hydrogen getters under irradiation of getters with high-power plasma streams.

2. Experimental setup

Tablets of the $Zr_{55}V_{40}Fe_5$ getter (of 20 mm in diameter and 8 mm in thickness) were manufactured by their pressing with an additional binding-dopant (copper powder) [2]. Afterwards they were saturated with pure hydrogen. The total quantity of hydrogen accumulated in the material was 2 dm^3 (under the atmosphere pressure). For a comparison, a copper sample of the same diameter was also investigated.

The experiments were carried out within the IBIS facility [3]. That rod-type plasma injector was described elsewhere [4]. Pulsed plasma streams were generated as a result of low-pressure high-current discharges performed between two coaxial sets of the multi-rod electrodes. The working gas was pure hydrogen. Typical operational parameters were as follows: the initial charging (supply) voltage was 30 kV, a delay time of the high-voltage pulse in relation to the injection of hydrogen into the interelectrode volume was 160 μs, and a distance between the electrode and the investigated target was 300 mm. Energy density in plasma stream was 14 J/cm^2, mean energy of ions up to 10 keV, pulse duration $\sim$1 μs. The plasma stream energy density and that delivered to the metal-hydride and copper samples surfaces were measured with a miniature copper-calorimeter. A scheme of the calorimetric measurements was similar to that described in [3].

For comparative analysis of structural changes in surface layer one getter tablet was irradiated with nitrogen plasma streams generated by coaxial plasma accelerator 'Prosvet' [5]. The time duration of the plasma generation is 3–6 μs. The accelerator generates plasma streams with ion energy up to 2 keV, plasma density 2×10^{14} cm^{-3} and an energy density of the plasma stream 25 J/cm^2.

3. Results of experiments

Fig. 1 shows the energy density delivered to the sample surface in IBIS facility, as a function of the number of pulses delivered to the hydrogen getter and a copper sample of the same diameter. It follows from Fig. 1 that in the case of the copper target about 78% of the plasma stream energy is delivered to the target surface. This value remains unchanged with an increase the number of pulses. It should be noted that some melting of the copper surface was observed as result of the copper surface – plasma stream interaction. For the getter target, only 32% of the plasma energy density is transferred

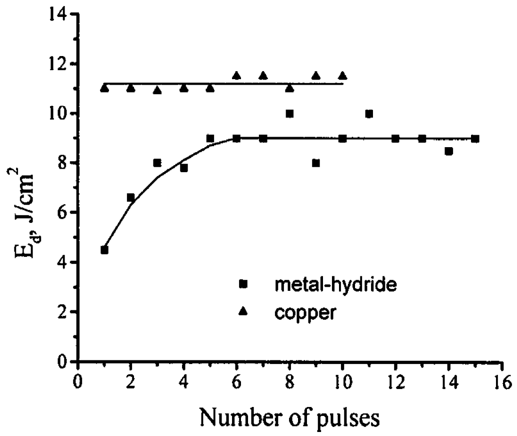

Fig. 1. Energy density delivered to the samples surface versus the number of plasma pulses.

to the target surface during the first pulse. In this case the value of the delivered energy density increases with an increase in the number of plasma pulses. The saturation, which is visible on the curve for getter, was achieved after five plasma pulses, but even in that case the value of delivered energy is about 60% of plasma energy (i.e. lower than for the copper target). Such behavior of the delivered energy curve for the hydrogen getter can be explained by the decomposition of hydride phases in a near surface layer of the sample. It could be a result of the pulsed heating of the surface up to a high temperature, and the formation of a shielding layer of hydrogen stored initially in the surface layer. Since the following pulses lead to the heating of the same thin layer (if one does not take into account some heating of the sample as a result of the previous plasma pulses), this provides the saturation of curve in Fig. 1. The fact that the delivered energy value over the plateau is still lower than that for the copper sample, can be explained by the influence of the process of hydrogen doping (reverse process) into the melted layer from a plasma stream during the pulse end phase. So, one can observe contributions of two competitive processes: the hydrogen doping by the plasma stream and hydrogen desorption from the surface. The obtained plateau of the energy curve with a lower value of the energy density is an evidence of some balance between these processes.

Mass losses of the getter sample are presented in Fig. 2. After the first pulse the mass losses are maximal, and they rapidly decrease with following pulses. The plateau is achieved after the irradiation with five pulses. Rather high values of mass losses are due both to fragments weakly connected and escaping away from the material surface, as well as to the hydrides decomposition accompanied by the hydrogen desorption. Since the getter material is prepared of pressed powder, the decreased heat conductivity between grains can lead to the

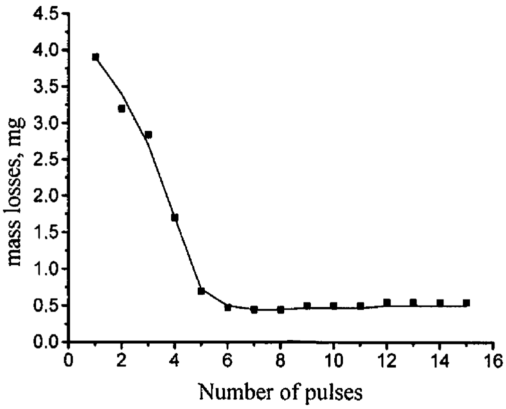

Fig. 2. Mass losses of the metal-hydride samples versus the number of plasma pulses.

evaporation of the material, and it can be another reason of additional mass losses. The observed decrease in the mass losses, with simultaneously increase in the delivered energy value, indicates that desorbed hydrogen plays the essential role in dynamics of the shielding layer formation. Otherwise, in the case when shielding layer is formed from the eroded target material and a plasma stream stopped upon the surface, the higher delivered energy value should lead to an increase in the mass losses, as a result of the target erosion.

A typical image of the getter surface after the plasma irradiation is shown in Fig. 3. According to the SEM pictures, the irradiated getter sample was subject to some melting with the gas bubbling through the melted surface [6]. An analysis of the metal-hydride surface after the plasma beam irradiation has shown that a structure of the getter surface and its color were considerably changed as a result of the plasma interaction. More detailed information about the structure and the phase composition was obtained with an X-ray diffraction analysis. As a result of the plasma treatment, there were found some changes in the phase content. Apart from phases of Cu, λ_2-$Zr(V,Fe)_2H_x$, ε-ZrH_x, and η-$Zr_3(V,Fe)_3OH_x$, existing in the initial surface, an intermetallic phase of $ZrCu_5$ with an increased lattice parameter was formed. The most probable explanation of this effect is the interaction (during the plasma treatment pulse) of the zirconium hydride (whose fraction in the composite was considerably decreased under the treatment) with the melted copper. The irradiated sample is characterized by a noticeable broadening of lines in the difractogram, and a simultaneous decrease in their absolute intensities. It testifies that the irradiated surface of the sample has a fine-crystalline or apparently amorphous-like structure.

Similar fine-crystalline surface layer of several tens of micrometers in depth was obtained for getter irradiation with nitrogen plasma streams. But in this case, in contrast to hydrogen plasma, an increase of copper crystal lattice period was registered. This result can be explained by effective implantation of nitrogen in surface layer. Interaction of getter alloy with hydrogen plasma stream did not result in changes of copper lattice period because a copper did not form stable hydrides.

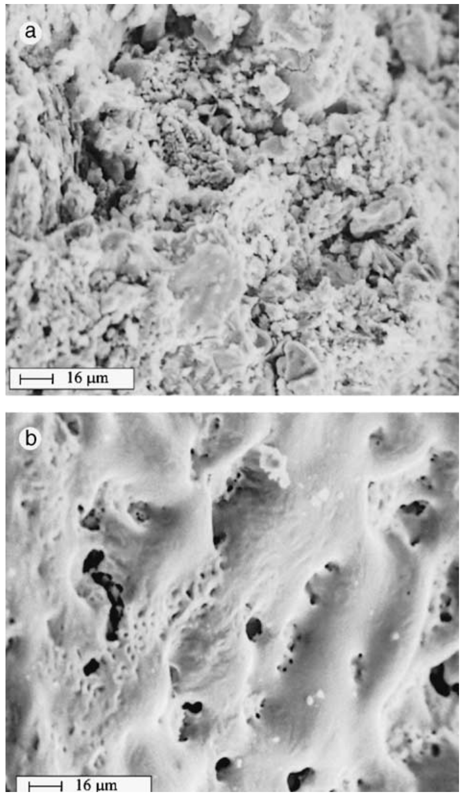

Fig. 3. SEM images of the getter surface: (a) before treatment and (b) after the treatment.

An element content distribution along the sample surface, as measured before and after the treatment, is shown in Fig. 4. Irradiated surface is characterized by essential modulation of the copper content from 20% to 80% with a period of about 0.4 mm. It should be noted, that behavior of Cu and Zr are quite opposite, i.e. a decrease in the Cu content accompanied by an increase in Zr. The periodical structure is difficult to explain. Possibly, it arises due to some gas bubbling during the surface melting. An average content of the main elements along the scanning trace was as follows: Cu – 56.7%, Fe – 0.7%, V – 17.1%, Zr – 25.5% before the irradiation, and Cu – 32.6%, Fe – 0.8%, V – 19.1%, Zr – 47.5% after the treatment. The obtained decrease in the average Cu content could not be explained by the selective evaporation of Cu (because Cu content in the maximum points is still high), and it is probably explained by high modulation of Cu content (Fig. 4(b)).

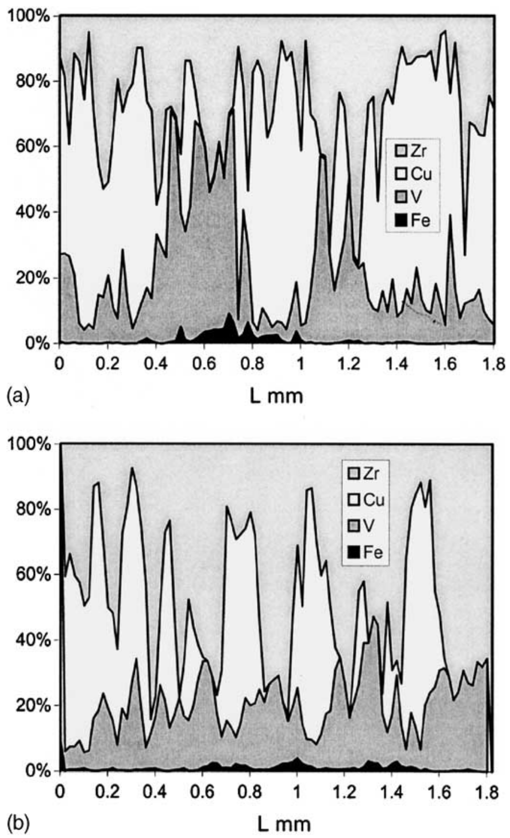

Fig. 4. Elements profiles along the getter surface: (a) before treatment and (b) after the treatment.

More likely, this is peculiarity of the ultra-speed melting, when Zr melt covers the surface of sample with breaks in points of gas bubbling and material pores. Therefore, the sample surface obtains white color after the treatment.

4. Conclusions

The obtained results have shown a possibility of the effective shielding of material surfaces by desorbed hydrogen. It was found that the hydrogen buildup promotes a considerable increase in the shielding coefficient. Temperatures of the hydrides destruction in the getter material are in interval of 150–500 °C. Therefore, hydrogen is desorbed not only from a melted layer but also from a layer thicker than 10 μm, which is heated up to such temperatures. The desorption above 2×10^{19} particles/cm^2 can be achieved. This leads to the shielding layer formation with density higher than 10^{17} cm^{-3} (close to the sample surface) during parts of microsecond. As it was shown in our previous experiment [3], the thickness of the shielding layer is about 1 cm. A considerable modulation of copper surface content is observed with a spatial period of about 0.4 mm. Behavior of the Cu and Zr distributions along the surface are quite different. The X-ray analysis has shown that the intermetallic phase of $ZrCu_5$ is formed during the crystallization. The irradiated surfaces of the sample have a fine-crystalline or amorphous-like structure. Power flux of the plasma stream used in our experiments was about 14 MW/cm^2, and similar one can be expected for off-normal events in ITER-like tokamaks. The pulse duration of order 1 μs is of course essentially shorter than at tokamak conditions. However, the first instants of the interaction are most important for an energy transfer to the material surface, because (due to the shielding) rather small part of plasma energy is delivered later [7]. Moreover, an increase in the pulse duration may lead to hydrogen diffusion from deeper material layers, what will additionally increase the material surface shielding.

Acknowledgement

This work was partly performed with financial support by STCU Project # 959.

References

[1] V. Bastiev, M.A. Obolenskij, V.V. Solovej, Aktivaciya vodoroda i vodorodosoderjaschih energonositelej, Naukova dumka, Kiev, 1993, 162 p (in Russian).
[2] P. Della Porta, C. Pizani, SAES getters, Techical Reports, No. 8–16, Milano, Italy, 1969.
[3] V.V. Chebotarev, I.E. Garkusha, J. Langner, M. Sadowski, V.I. Tereshin, J. Tech. Phys. 40 (1999) 469.
[4] J. Piekoszewski et al., Nucl. Instrum. and Meth. B 53 (1991) 148.
[5] V.F. Zelenskij et al., J. Nucl. Mater. 178 (1991) 99.
[6] V.N. Borisko, V.V. Bobkov, et al., Probl. At. Sci. Technol. 6 (2000) 166.
[7] V.V. Chebotarev, I.E. Garkusha, V.V. Garkusha, et al., J. Nucl. Mater. 233–237 (1996) 736.