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Journal of Nuclear Materials 363–365 (2007) 1304–1308

journal of nuclear materials

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Particle reflections of low energy light ions from a vanadium alloy (V–4Cr–4Ti)

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Abstract

The angular distributions and energy spectra of positive and negative ions reflected from a vanadium alloy (V–4Cr–4Ti) bombarded by beams of low energy (1–2 keV) ions of H, He, and O were measured. The intensities of H^+ or H^- produced from reflection of 2 keV H^+ beam at the surface of vanadium alloy showed the maxima at the angles closer to the surface normal from the mirror reflection angle, compared with Mo and W samples. The time dependence of the angular distributions of the reflected H^+ or H^- ions measured at the sample temperature of about 240–260 °C showed a shift of the peak in the angular distribution to the mirror reflection angle.

PACS: 68.49.Sf; 52.40.Hf; 52.40.Mj

Keywords: First wall; Ion–surface interactions; Vanadium; Edge plasma; Hydrogen inventory

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1. Introduction

Vanadium alloys have favorable characteristics as materials for fusion reactors. Their high strength at elevated temperature, low-activation properties and good resistance against neutron irradiation make the alloys the most promising candidates for the blanket structure and first wall materials [1,2]. Recycling materials and minimizing radio active wastes from fusion reactors attract particular attention to the low activation property of vanadium alloys. The reference vanadium alloys for fusion reactor with 92 wt% V, 4 wt% Cr and 4 wt% Ti (wt%: weight percent) are produced as NIFS-HEATs and have tested its properties [2].

Vanadium is also known as a hydrogen absorbing material. The character of hydrogen absorption of the vanadium compounds makes the alloys an efficient hydrogen storage material for clean and highly efficient energy combustion systems. In an ideal case, approximately 3.5 wt% of hydrogen is absorbed in the vanadium compound, which corresponds to the

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doi:10.1016/j.jnucmat.2007.01.183

volume of hydrogen 1000 times larger than the volume of the compound. Conversely, rapid release and/or absorption of hydrogen absorbed in the vanadium compound can strongly affect the boundary plasma in a fusion reactor system when vanadium compounds are used as plasma-facing materials. The release and absorption of hydrogen from the vanadium compound at given temperature, hydrogen flux and heat loads change the plasma density and temperature in the boundary, and finally the plasma confinement. However, the interaction of the vanadium compounds with plasma particles has not been investigated.

We have been developing an experimental system to study interactions of beams with solid surfaces. The system has successfully produced ion spectra reflected from Mo, carbon coated Mo, and W targets [3–6]. In this paper we report the first results of the study on particle reflections from the NIFS-HEATs vanadium alloy bombarded by low energy (1–2 keV) hydrogen ions. Results of He and O ion reflections from the vanadium alloy are also presented for comparison.

2. Experimental setup

The detail of the experimental system has already been reported elsewhere [5,6]. Several improvements have been made to study hydrogen-absorbing characteristic of vanadium alloys. First, we have added an electrostatic focusing system with a beam steering system in the beam downstream of the mass selector magnet to enhance the signal to noise ratio so as to detect small ion flux due to hydrogen absorption on the target. Second, an infrared target heating system was installed to study the effect upon ion reflections due to the target temperature. Other components of the system were tuned to minimize the time to record the energy spectrum of the reflected ions obtained by the magnetic momentum analyzer.

The analyzer angle against the incident beam was calibrated by directly injecting the weak primary beam from the ion source to the analyzer. Both the positive and negative ions in the reflected beam were analyzed by a single sweep of the analyzer magnetic field to reduce the measurement time. The correlation between the beam energy and the induction current of the magnetic momentum analyzer was carefully calibrated by directly injecting low intensity positive and negative ion beams. The sample temperature was measured by the thermocouple and correlated to the heating power of the infrared target heater. It reaches to approximately 240–260 °C within 10–15 min after the start of heating outside the vacuum.

The incident beam intensity was varied from a few to a few tens nA. In the following results, intensities of the reflected beams are normalized to the target currents. We did not apply any potential for suppression of secondary electrons from the target to avoid any deflection of the beam prior to the entrance into the magnet analyzer. Therefore, there can be subtle differences between the real and used values of the target currents as one compares the intensities of the reflected beams depending upon the different beam injection energy and/or geometries. However we can still compare the results for the normalized intensities in the corresponding experimental conditions. Besides, the beam current on the target was kept constant during the experiments.

3. Results and discussion

Fig. 1 shows examples of the energy and angular resolved intensity contour map of H^+ and H^- ions at the incident angle of 20° at room temperature, reflected from (a) Mo, (b) carbon on Mo, (c) W and (d) Vanadium alloy targets, respectively. We observe similar trends for all targets [5,6]. We always observe the positive and negative ion reflections for both cases of the positive and negative hydrogen ion injections. In the H^+ beam injection the intensities of the reflected positive ions are usually higher than those of the negative ions in this energy range. The normalized intensities of the reflected ions for the vanadium target are the same order as those for W and Mo [5,6]. The energy spectra of the reflected ions from the vanadium target depend upon the reflection angle β more strongly than other targets. This result suggests the possibility that the incident H^+ ions interact with the vanadium alloy in the way different from other materials. Vanadium is known to absorb hydrogen atoms in the bcc lattice. The absorption and the release of hydrogen atoms depend on the sample temperature and the equilibrium hydrogen surface density is to be determined at a given temperature after the surface is saturated with hydrogen atoms by the incident beam. Thus, the hydrogen–vanadium interaction can show a very slow time dependence, which was not confirmed in this experiment.

When the oxygen beam was injected onto the vanadium alloy, we observed the reflected ion intensity

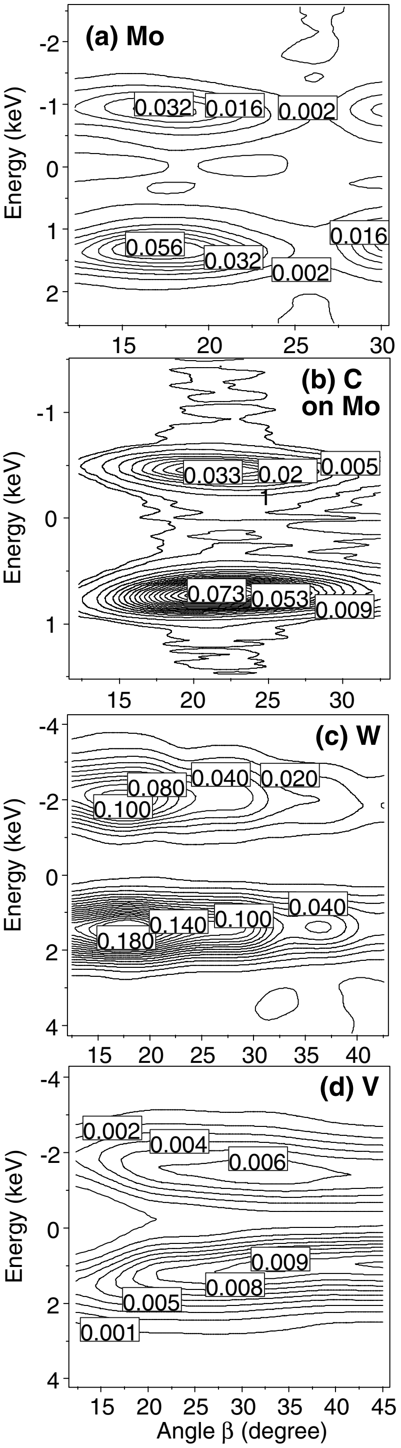

Fig. 1. Contour intensity plots of energy and angular resolved intensity profiles of positive and negative ions reflected from vanadium alloy surface at the incident angle of 20° for H^+ beam injection; (a) Mo target for 1.76 keV beam, (b) C on Mo target for 1.65 keV beam, (c) W target for 2 keV beam, and (d) V target for 2 keV beam. The intensities are normalized by the target currents and are arbitrary units.

only in the negative ion side and there were no positive ions, while very weak O^+ ions were observed from a W target [6]. Compared with the cases of Mo and W targets, energies at which the energy distributions of reflected ions from vanadium take their maxima show stronger angle dependence for both cases of hydrogen and oxygen beam injections. Similar dependence of the energy spectra of reflected ions upon angle had been observed in other measurements [7–9]. Possible reasons for observing the angular dependence are elastic scattering, electron transfer from the surface to the incident atoms and multiple scattering [10]. As our samples are polycrystalline there can be other reasons causing the angular dependence.

Fig. 2 shows angular distribution of the reflected positive and negative ion intensities for (a) 2 keV H^+ beam, (b) 2 keV He^+ beam and (c) 0.7 keV O^+ beam for the vanadium target. In Fig. 2 horizontal and vertical axes correspond to the projections of the intensity (I) to each axis, $I\cos\theta$ or x axis and $I\sin\theta$ for y axis. Note that the axis scales of O^+ beam injection at the incident angle more than $\alpha = 40°$ are 10 times as large as the case at the angle less than $\alpha = 30°$. Mirror reflections ($\alpha = \beta$) are shown by the solid lines. For H^+ beam injection the deviation from the mirror reflection seems to be large at lower incident angle less than $\alpha = 30°$ even if we take the error of the target angle ±3° into account. In the He^+ beam injection, the reflected He^+ ion intensity normalized by the target current is one order of magnitude smaller compared to the intensities of reflected hydrogen and oxygen ions. It is considered that the injected ions on the surface are firstly neutralized by the Auger process. Then secondly, they loose or capture electrons near the surface. The intensity of reflected He^+ ions should become small as the ionization potential of 24.6 eV of neutral He atoms are substantially higher than those of H and O atoms.

Some inter-metallic compounds including vanadium are known as a material to absorb hydrogen and oxygen. We expected the characteristics of the ion reflection would differ from those of other materials depending on the sample temperature and the time to bake out the surface. Fig. 3 shows the changes observed at certain times after the target temperature was increased from the room temperature to 240–260 °C with the angle α kept at 10°. Fig. 3(a) shows the angular distributions and (b) shows the intensity of the reflected H^+ ions for H^+ beam injection, while (c) shows the angular

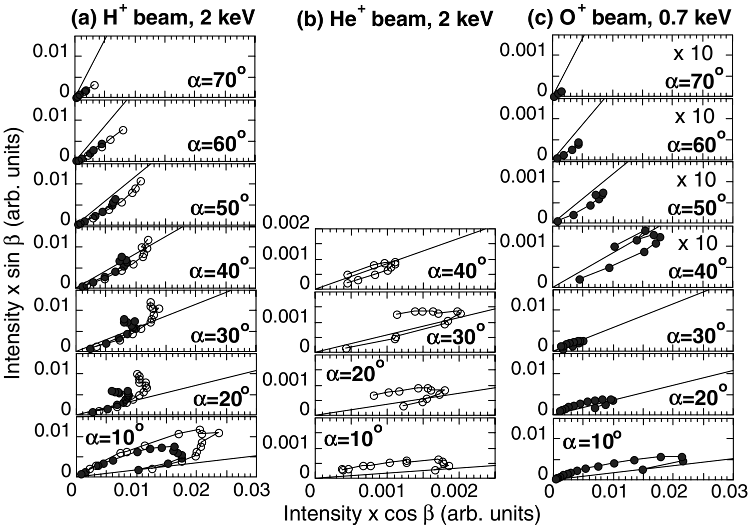

Fig. 2. Angular distribution of the intensity of reflected positive and negative ions from the vanadium alloy target for (a) H^+ beam of 2.0 keV, (b) He^+ beam of 2.0 keV and (c) O^+ beam of 0.7 keV. Open and closed circles correspond positive and negative ions, respectively.

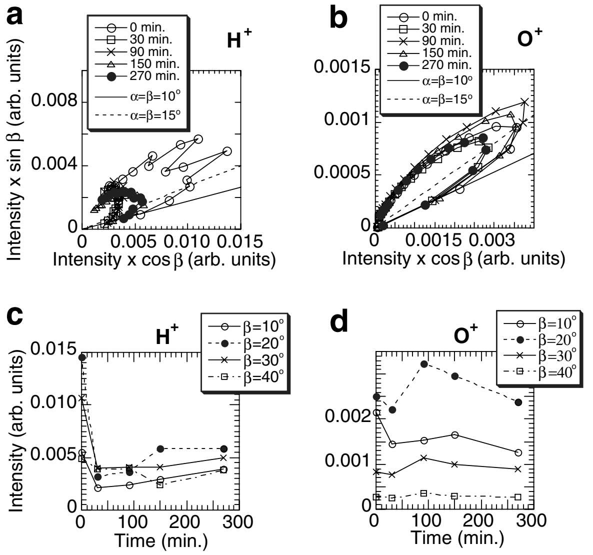

Fig. 3. Time dependence of the angular distributions and intensities for the vanadium alloy target at $\alpha = 10°$ at 240–260 °C. (a) and (b); the reflected H^+ ions for 2 keV H^+ beam injection and (c) and (d); O^- ions for 0.7 keV O^+ beam injections.

distributions and (d) shows the intensity of the reflected O^- ions for O^+ beam injection. During the experiment, the sample temperature was kept constant. In Fig. 3, data of 0 min correspond to those taken without any surface treatment after the evacuation. Before any heating, the intensity of the reflected H^+ beam was relatively large, probably due to the hydrogen or water adsorption on the sample surface. After heating the sample at 240–260 °C for 30 min, the reflected H^+ intensity decreased drastically and then took the minimum values. It recovered slightly after 270 min. As time passes, the angular dependence of the reflected H^+ intensity became closer to mirror reflection. For the case of O^+ beam injection, the intensities of the reflected O^- ions were not as affected as the case of H^+ emission as shown in Fig. 3(b).

In the vanadium compounds, normally the number of absorbed hydrogen atoms decreases by increasing the sample temperature, known as the Arrhenius plot, showing the relation between the equilibrium hydrogen pressure (number of hydrogen atoms in the material) and sample temperature. Here we only took the data set at one sample temperature. It is important to measure the temperature dependence of the reflected ions, particularly at a higher temperature to use the data for actual fusion reactor designs. We also consider that much higher incident beam intensity is required to realize surface condition of the vanadium alloy to be closer to that in an actual fusion reactor environment. Extension of the research to tungsten-coated vanadium alloys is also necessary as it is proposed as the fast wall material for it is high heat load resistant [11].

4. Summary

We have studied low energy beam interaction with the vanadium alloy. This sample shows interesting behavior compared to the plasma-facing material candidates of W, Mo and C [5,6]. The vanadium alloy surface shows a characteristic reflection angle dependence of the reflected ion energy with the time-dependent change at a constant temperature. Further study on the temperature dependence and flux dependence of the angle resolved energy spectrum are necessary to clarify the hydrogen ion beam interaction with vanadium alloys.

Acknowledgement

We thank Dr T. Nagasaka in NIFS, kindly giving us the vanadium alloy target. We appreciate Y. Aoyama in Tohoku University for his help in the experiment. This work was performed under the collaboration program of NIFS (2005&2006).

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