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Ablation rate estimation of inertial fusion reactor candidate material with intense ion beam and X-ray

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Abstract

Various candidate materials were collected from many sources. Some of them were irradiated with intense proton beams at Yokohama campus of Tokyo Institute of Technology (TITech), and some others were irradiated with intense nitrogen beams at Albuquerque site of Sandia National Laboratories (SNL). Intense X-rays of SNL were also used to irradiate other materials including the above collected ones. A series of numerical calculations of X-ray ablations was additionally performed at TITech, which results were compared with the experimental ones. Our aims were to supply necessary data for the future design of inertial fusion reactor chambers. One of the key issues in this field was the ablation thickness of the various chamber wall materials with typical inertial fusion reactions. We measured the ablation thickness of various samples, and we also observed the surface conditions of the samples before and after the irradiations with a microscope and an X-ray luminescence composition analyzer.
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1. Introduction

To design an advanced version of inertial fusion (IF) reactor, we still need lots of data to be gathered into our databases. One of these is the reactor wall surface thickness which is ablated with the intense radiation (X-ray, neutron and ion) originated from the IF processes. Examples of their flux under typical IF reactions are described in [1–3]. With our present-day technology, we can produce similar orders of these fluxes, in some cases. As we could produce intense proton beams with our pulsed power machines, and as we could ask the collaborators to irradiate sample targets with the strongest X-ray in the world, we investigated target ablations with ions and X-ray both with experiments and calculations.

2. Sample targets collected for beam exposure

The sample targets were collected from many places, including TITech, SNL, ILE-Osaka University (Norimatsu), IAE-Kyoto University (Kohyama and Katoh), Tokai Konetsu Co. (Satoh) and Atago Bussan Co. (Ebara). Only a part of these samples (which are listed below) could be irradiated in our experiments. The descriptions in the list are the group number/material/size (vertical × horizontal × thickness, or diameter × thickness), all in mm/supplier/remarks.

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1-a/LiPb/16 × 19 × 1/ILE/manufactured in Ar environment, melting temperature of 233 °C (peak)/
1-b/SiC/18 × 23 × 1 etc./ILE/
4-b/Carbon G650S/30dia × 5*t*(1)/TITech/product of Nilaco Co. Ltd./
6-a/SiC/ 100dia × 2/Tokaikonetsu/product of Tokaikonetsu, normal pressure baked, both surface ground/
6-b/SiC–Si/235 × 235 × 5/Tokaikonetsu/product of Tokaikonetsu, RS420/
6-c/Al_2O_3/135 × 125 × 5/Tokaikonetsu/SSA-M, product of Nihonkagakutohgyoh, normal pressure baked/

3. Ablation experiments with intense pulsed ion beams

The initial temperature of all targets was room temperature in the following experiments. We assumed that there was no charge-up of the targets during the beam irradiation. This was normal and the reason was the ion beams were charge and current neutralized with the comoving electrons with the same speed.

3.1. Ablation experiments with proton beams

We used a pulsed ion beam generator (PICA-4) at Yokohama [4]. The target chamber was evacuated by both of a turbo-molecular pump system and a cryogenic pump system. The pulsed power apparatus supplied pulsed high voltage to the anode of the diode. When we used hydrocarbon as the anode plasma source, proton beam was extracted in a ring shape and geometrically focused at a focal point of 23 cm from the anode surface. Examples of the proton energy, the pulse width and the peak current were 200–240 keV, 100 ns and 1.6 kA. The typical diameter of the beam was 23 mm at the focal point. The beam dose was about 10 J/cm^2, which was high enough to ablate most of the targets with only one beam irradiation.

Sample targets were placed at the beam focal point, normal to the beam axis. The half surfaces of the targets were covered with masks for the targets not to be irradiated. The target surfaces were polished and cleaned before the beam irradiation. The beam dose was changed with the change of the supplied voltage with the pulsed power. The ablation thickness was measured with a laser displacement diagnostic tool. A series of beam irradiation with three different target materials (carbon, LiPb and SiC/4-b, 1-a and 1-b in Section 2) was tried, which results are shown in Fig. 1.

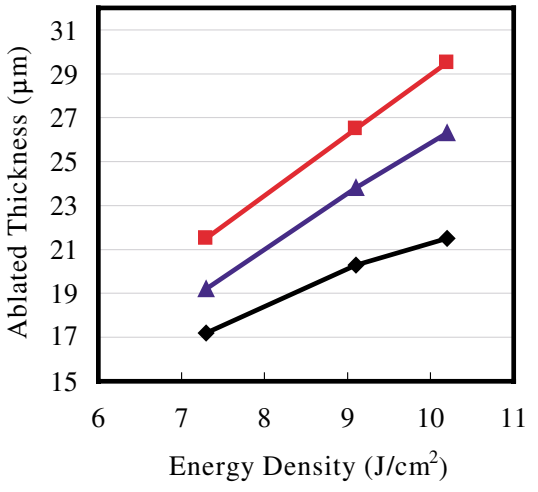

Fig. 1. Ablation thickness vs. energy density of pulsed proton beam for three different materials (SiC, LiPb and carbon, from top to down) measured with a laser displacement thickness meter. This is a case under proton beam irradiation with 100–200 keV (energy), 1.6 kA (peak current) and 100 ns (time duration).

3.2. Ablation experiments with nitrogen beams

A similar pulsed power machine (RHEPP-1) at Albuquerque was used to irradiate different sample targets (SiC and Al_2O_3/6-a and 6-c in Section 2) with nitrogen ions. As the beam focus diameter was larger than the proton beam case, we could separately observe the different dose places on the same (larger) targets. We placed four Faraday cups along the beam diameter from the center to the outer radius. With the total number of consecutive 50 shots, the beam dose was 3.9, 3.2, 2.2 and 1.6 J/cm^2. The beam was also focused on the target, and the beam energy was about 500 keV.

Two kinds of diagnostic methods were chosen to observe the target surfaces. One was a laser reflection microscope method, and the other was X-ray luminescence composition analysis method. We asked the Center for Advanced Material Analysis in the Tokyo campus of TITech to use these diagnostic tools.

Fig. 2 shows an example of the microscope image of SiC surface. The left half is the region with the mask, while the right half is the region with the beam irradiation. With the multiple beam irradiations, the surface condition is changed drastically from the original condition. The geometrical structure along the depth of the surface could be also observed with this microscope. A profile was obtained along the top horizontal line in the figure. The distance between the two other horizontal lines was 6.4 μm, while the distance between the two vertical lines was 597 μm. The former was the mean surface ablation thickness near to the edge of the mask, while the latter was the rough sample size of the microscope view. The beam irradiated surface looks like to have a structure after re-crystallization. On the contrary, in the case of Al_2O_3, there was no observable ablation thickness with the same diagnostic method.

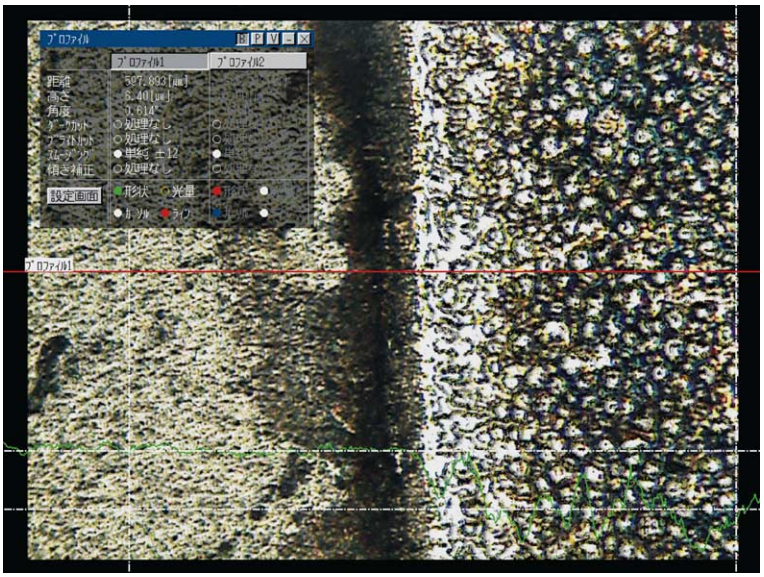

Fig. 2. Laser microscope image of SiC surface with and without nitrogen ion irradiation.

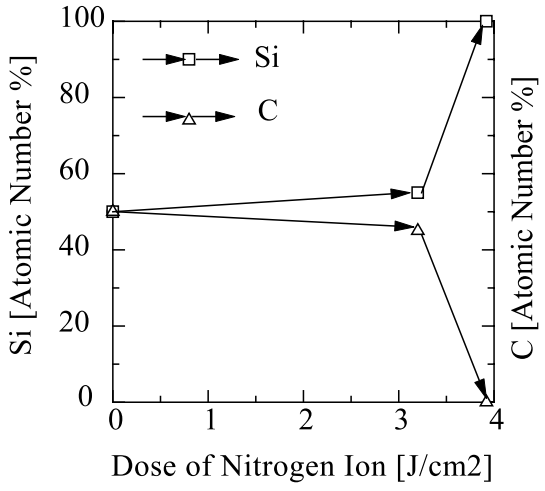

Fig. 3. Change of SiC surface composition with different dose of nitrogen ion irradiation, measured with X-ray luminescence analysis.

Fig. 3 shows the result of the X-ray luminescence analysis of SiC. The change of surface composition is shown as a function of the ion dose. With the highest dose, the carbon is lost completely from the surface after the beam irradiation. Together with the above microscope image and the luminescence result, the re-crystallized structure seems to be Si. On the contrary, in the case of Al_2O_3, there was no observable composition change with the same diagnostic method.

4. Ablation estimation with intense X-ray

4.1. Calculation of ablated thickness

The ablation rates with intense pulsed X-rays with the spectrum and energy level of the Z-machine at SNL were numerically estimated with a simple model [5,6]. The ablation rate was 1–7 μm in the case of C, while the thickness was 0.1–1.5 μm in the case of LiF. The maximum C ablation was obtained with the X-ray temperature of 50–200 eV, while the maximum LiF ablation was obtained with the X-ray temperature of 200–600 eV.

Under the conservation of total X-ray energy of 1 MJ, we could plot the Planck's radiation law with different black body temperature of 100, 300 and 500 eV. The ordinate was the X-ray intensity, while the abscissa was the photon energy. The spectral intensity of X-ray was calculated with the Planck's equation with the above plot.

We chose two kinds of materials (C and LiF) to calculate the ablated depth with X-ray. The respective mass absorption coefficient for C and LiF is shown in [5] as a function of photon energy. To calculate X-ray absorptions with wall materials, the wall thickness was sliced into very thin layers with same thickness, and the X-ray absorption and transmittance were calculated, layer by layer. We assumed that the layer was ablated if the absorbed energy was larger than the total energy for the layer temperature to become higher than the sublimation temperature of C, or the vaporization temperature of LiF.

We calculated the sublimation depth of C as a function of the black body temperature of X-ray under

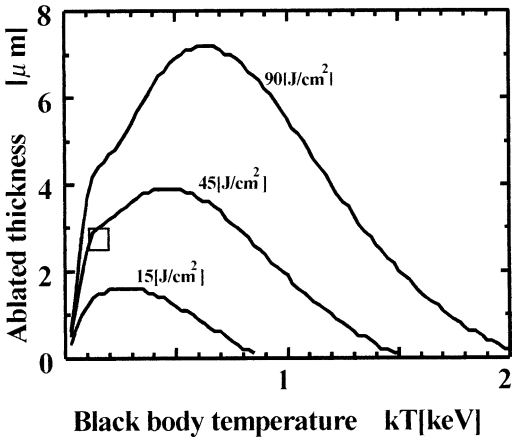

Fig. 4. Comparison of numerical (90, 45 and 15 J/cm^2 dose) and experimental (40 J/cm^2 dose) cases for ablated thickness with X-ray. This is a case of LiF with (experimental) X-ray source temperature of 100–200 eV.

different X-ray dose (90, 45 and 15 J/cm^2), which result is shown in [5]. The similar result for LiF is shown in Fig. 4.

4.2. Ablation experiments with X-ray

The X-ray irradiation of a LiF sample (prepared by SNL) was measured experimentally with the SNL Z-machine. The measured ablation was about 3 μm from a single Z shot with an estimated X-ray dose of 40 J/cm^2. SiC/Si (an example of composite material) and SiC (6-a and 6-b in Section 2) was irradiated with X-ray of 7 J/cm^2 dose. The measured ablation depth for SiC/Si was about 0.5 μm, while no discernible ablation was measured for SiC. The experimental result in the case of LiF is also shown with a small white box in Fig. 4 to compare with the numerical results. The black body temperature of X-ray (corresponded to the experiment) is about 100–200 eV. Similar experiments with various materials and different X-ray dose are scheduled in the near future.

5. Conclusion

Under the proton beam irradiation with the dose of about 10 J/cm^2 per shot, the ablated rates were up to 20 μm for carbon, and 26 μm for LiPb and SiC. The change of the rate was investigated with the change of the dose. Under the nitrogen beam irradiation with the dose of 4 J/cm^2, the ablated thickness of up to 6 μm was observed for SiC, while no remarkable ablation was observed for Al_2O_3. Surface conditions before and after the nitrogen beam irradiation was investigated with a microscope and X-ray fluorescence analysis. SiC surface turned into Si surface, while no discernible change was seen for Al_2O_3. Under the X-ray irradiation of LiF, SiC/Si and SiC, the ablation thickness of 3, 0.5 and 0 μm was observed under the dose of 40, 7 and 7 J/cm^2. More experiments and calculations with more advanced methods are scheduled in the near future.

The most recent review concerning the various aspects of IFE reactor design is shown in [2,8]. The energy and species of the ions, and the X-ray spectrum are shown in the same reference. Comparing these with the parameters shown in this paper, the importance of our current results in this paper can be well understood.

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