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Study of Material Destruction During Powerful Plasma Exposure

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Results of experimental research during the interaction of powerful plasma flow with aluminum and graphite targets are presented. The experiments were carried out at plasma energy density of up to 5 MJ/m^2 and time duration of up to 600 μs. Strong damage of target materials was observed as a result of the plasma flow interaction as well as the formation and the ejection of macroscopic particles from the target surface. The ejected particle size and spatial distribution were measured as well as the velocity of these particles during the experiments. The method of laser scattering was applied for these measurements.

1. Introduction

It was shown experimentally and predicted by theory that macroscopic destruction of plasma-facing materials can occur during disruptive heat load. This can be a key factor in limiting the lifetime of these components. Several models of brittle destruction of carbon-based materials as well as melt-layer splashing of metallic materials have recently been developed [1]. The study of the characteristics and dynamics of erosion products formed as a result of plasma surface interaction is described in this work to better understand the real nature of the resulting damage.

2. The experimental procedure

Experiments were performed at the quasi-stationary plasma accelerator (QSPA) device [2-3] which generates a high-energy hydrogen plasma flow. Graphite and aluminum were both used as

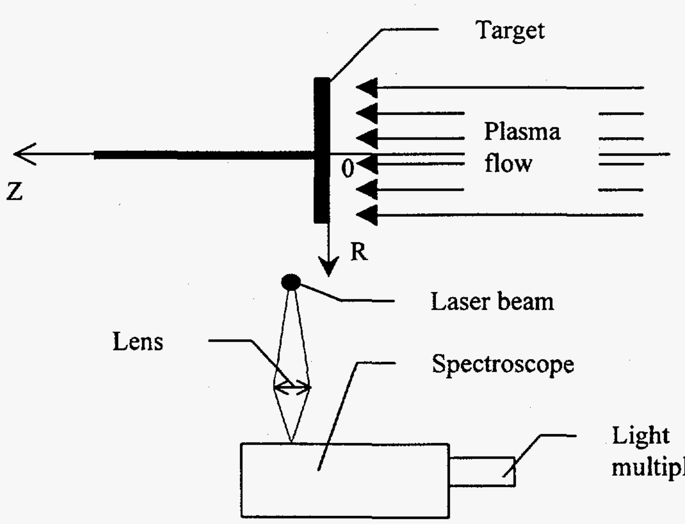

Fig. 1. Schematic illustration of the experimental setup

target materials. Target samples of 30 and 80 mm diameters (for aluminum targets) and 20 mm diameter (for graphite targets) were used to study in detail the characteristics of the erosion products. The samples were installed on a special holder in order to enable the target motion along both the radius and the Z-axis of the chamber. The samples were placed perpendicular to the magnetic field lines in the central part of the flow that possesses the highest energy density. The experiments were made for magnetized plasma flows in a field strength of $B = 1T$. The parameters of the plasma flow in the target area were the following: time duration $\approx$ 600 μs, power density $\approx$ 10 GW/m^2, energy density $\approx$ 5 MJ/m^2, plasma density $\approx 10^{16}$ cm^{-3}, and flow diameter $\approx$ 4 cm.

Figure 1 shows a schematic illustration of the experimental setup. The size and velocity of the particles flying-off the surface of the exposed target were measured in these experiments. The measurement of particle parameters was carried out using laser scattering methods. For measurements, the helium-neon stationary laser by potency 2 W and $\lambda = 5145\ \mathring{A}$ was used. The laser beam is located at the surface of the target with the scattered light measured at an angle of 90^0. The size of the laser beam area where the light is scattered has a height of $\approx$ 2cm and a width of $\approx$ 10 microns. Moving the laser beam on R and Z coordinates has enabled us to measure the spatial distribution of the flying-off particles from the surface. The method of sedimentation of particles on the specially prepared target surfaces was also applied in these experiments.

3. The experimental results

Intense plasma flow on target surfaces usually results in the formation of a shielding layer [4]. The dense plasma layer with $n > 10^{17}$ cm^{-3} creates high intensive radiation in the visible range of light. For this reason the registration of the unexpected light was made through 1-1.5 ms after termination of the plasma flow. Because of this fact it was not possible to investigate areas that were closer than 1 cm from the edge of the target Three types of samples were experimentally studied: aluminum targets with 3 and 8 cm diameters and graphite targets with 8 cm diameter (with heated area $\approx$ 2 cm diameter).

The surface of the aluminum target during the plasma flow is melted up to a depth >100 micron with distinctive microscopic structure. Surface analysis of the target shows two different characteristic areas, i.e., a central area of diameter < 4 cm and a peripheral area of diameter > 4 cm.

The central part (shown in Fig. 2a) is exposed to the most intensive part of the flow and has the

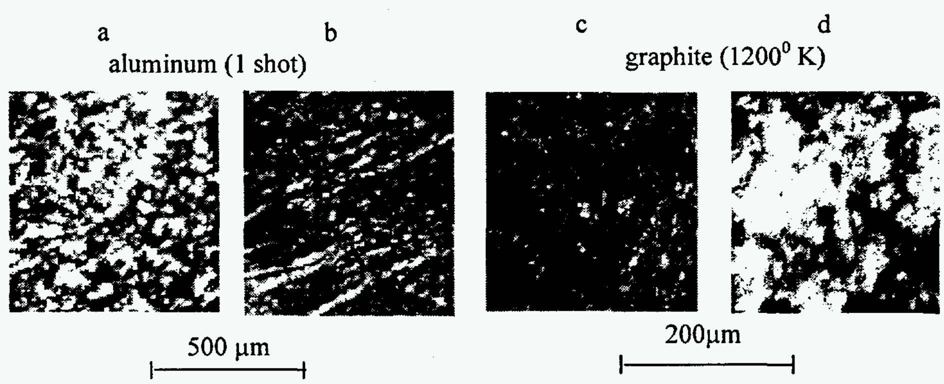

Fig. 2. Top view of the different exposed targets.
a) central area; b) peripheral area; c) before experiment; d) after 3 shots;

characteristic view of a solidified surface. This part of the target is covered by plenty of bubbles and droplets with diameters up to 0.2 mm. Traces of these droplets moving from the center to the edge of the target on the peripheral area are shown in Fig. 2b. On the smaller samples (diameter = 3 cm) such tracks are not observed since the plasma flow covers the whole surface of the target. However, many of the aluminum droplets were observed on the lateral part as well as on the back side of the samples. The splashed metal droplets from the surface, however, were found on the diagnostic windows of the vacuum chamber!

The graphite targets were made of MPG-8 type-graphite. Before installation in the vacuum chamber the targets were polished. Plasma flow interaction with carbon targets were exposed to both cold ($T = 300^0$ K) and hot ($T = 1200^0$ K) targets. The microscopic photos of the target before the influence of plasma flow are shown in Fig. 2c, while the surface of the target after 3 shots is shown in Fig. 2d. From detail analysis one can see that it distinctly demonstrates the macroscopic destruction nature with characteristic particle sizes exceeding 100 microns and up to depth of 1-2 microns.

4. Discussion

The analysis of experimental data shows that mechanisms of target destruction largely depend on target material and its physical properties. The mass loss of an aluminum target, for example, can not only be explained by surface vaporization. The destruction and erosion of metallic targets depend largely on melt-layer splashing under action of various forces including the pressure gradient of the incident plasma flow. During the plasma flow interaction with melted-target surface hydrodynamic instabilities (such as Rayleigh-Taylor, Kelvin-Helmholtz, etc.) as well as bubble boiling will cause large surface protuberances. Because of the pressure-gradient of the incident plasma these protuberances are broken causing the formation of droplets which are accelerated along the surface of the target. Formation and motion of droplets along the surface of the target are demonstrated in Figs. 2a-b. Traces of droplets are shown in the radial direction along surfaces of a target. The analysis of the spatial distribution of particles flying-off the target surface confirms this mechanism of destruction. Figure 3 shows the distribution of the ejected

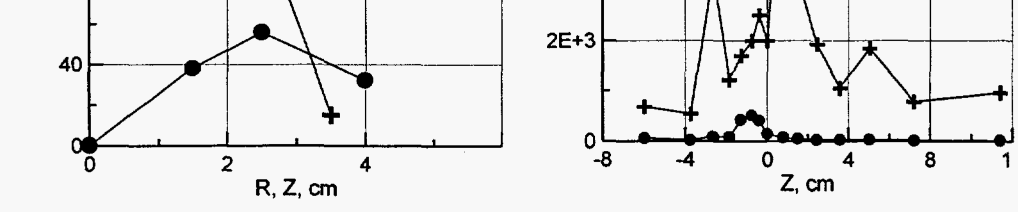

Fig. 3. Particles distribution of aluminum targets in R and Z direction.
a) target diameter 3 cm, b) target diameter 8 cm (z=6.5 cm)

particles along axes R and Z (Fig. 1). For targets with diameter less than the diameter of plasma flow, the droplets are removed from the area of the target. For targets of a diameter 8 cm large droplets > 10 microns are registered mainly in area Z=0 (plane of target). Fine particles with D < 10 microns have much larger density and have wider spatial distribution. In front of the target (r = 0) particles were not found in all experiments. The measured velocities of the ejected particles were in the range of 7-10 m/s. Microscopic analysis shows that these particles have a spherical form.

Surface analysis of graphite targets shows that carbon destruction has a different nature. The erosion occurs as a result of a brittle destruction of the material without the melting phase. On the target surface (Fig. 2d) it was possible to see craters with rough edges of depth up to 1-2 microns. The characteristics of the destruction of hot (1200^0) and cold (300^0) targets is practically similar. This shows that heating targets up to 1200^0 does not result in significant growth of erosion under the conditions studied in this work.

5. Conclusions

Based on the presented experimental results the following conclusive remarks can be made:

1. The destruction of an aluminum target occurs not only at the expense of evaporation but also as a result of melt-layer splashing under the action of existing forces and the pressure gradient of the incident plasma flow. As a result of the splashing, droplets of spherical form of sizes of 1 micron and higher are formed. The velocity of the splashed particles was as high as 10 m/s.
2. The spatial distribution of the flying-off particles depends on the relationship of the size of the target and the plasma flow.
3. The erosion of a graphite target occurs due to brittle destruction of a superficial layer without any phase change.

6. Acknowledgment

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