Electromagnetic plasma rail accelerator for surface analysis and modification in solids

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Abstract. In this study we investigate the possibility of using plasma rail accelerator as a dense plasma jet generator for scientific and technological purposes. It was found that plasma railgun can generate supersonic plasma jets, both pure and saturated with solid and liquid microparticles. Such jets can cause thermal and mechanical erosion of the target surface, sputtering material of the railgun channel and transferring it to the surface being treated. We studied working regimes of the plasma railgun. SEM and optical micrographs of the treated samples were obtained.

1. Introduction
Rail accelerator is widely used to accelerate macroscopic solid projectiles and to produce strong shock waves [1-3]. When rail accelerator works with a plasma piston, catastrophic erosion of the accelerator's working channel is observed. In this work, we consider the use of plasma rail accelerator as a generator of a high-speed dense plasma and multiphase jets. In this paper we investigate the impact of the plasma jet produced by railgun on the substrates of different materials.

2. Experimental setup
A pulsed current source is made as a pulse forming network (PFN) with lumped capacitance (K41I-7, 100μF, 5kV) and distributed inductance of a copper busbars. Line is discharged to the load by the triggered mercury valve. Adjusting the number and arrangement of capacitors we can adjust the parameters of the current pulse (amplitude, shape, duration), which is registered by oscilloscope with Rogowsky coil.

The load (railgun) is located in a vacuum chamber made of stainless steel, equipped with side windows made of polymethyl methacrylate with vacuum sealed current feedthroughs. Transparent side windows allow us to observe and conduct photo and video recording of processes, as well as spectrometric measurements in the transmission band of polymethyl methacrylate. The figure 1 show the photo of the setup and figure 2 show a schematic of experiment.
The rail accelerators we used in this paper consist of rigidly fixed copper or graphite rails with side walls made of polymethyl methacrylate or without side walls.

3. Experimental
In a railgun with side walls after electric discharge initiation in breach part formed plasma is accelerating with Ampere force to the muzzle. In a railgun with side walls after the initiation of an electric discharge in the breech part, the formed plasma formed is accelerated by the Ampere force in the direction of the muzzle. During the movement of the plasma piston, the sputtered material of the working electrodes and side walls is accumulated in plasma piston. Under certain conditions (the nature and pressure of the gas
in the chamber, the amplitude and shape of the current pulse through the railgun, the geometry of the railgun channel, the material of the electrodes), the electric explosion of the railgun electrodes surfaces results in the accumulation of dust and droplet phases in the plasma piston.

In railgun operation without side walls plasma exits the channel and expands during its movement, which effectively limits the plasma density, reduces the degree of erosion of the working electrodes and eliminates contamination caused by the ablation of the side walls. Mode detailed description of plasma jet formation can be found in [4,5]. A operation of the railgun developed at Ioffe Institute presented in [6-9].

4. Results
We found that a rail accelerator with a plasma piston is able to generate dense plasma and multiphase jets, with the jets being focused and concentrated even in the case of a railgun without sidewalls. This makes it possible to use a railgun for local processing (sputtering, plasma erosion) of materials. The jet velocities obtained in the muzzle region, measured with the schlieren method, exceed 14 km/s and depend on the gas pressure in the vacuum chamber. Figure 3 shows the dependence of muzzle velocity of plasma jet at different initial pressures in vacuum chamber.

Figure 3. Muzzle velocity of plasma jet vs Pressure at electrical discharge current of 60 kA

Figure 4. Plasma jet produced by copper railgun with side walls
After the plasma jet leaves the railgun channel it expand and flows to the target side. Figures 4 and 5 demonstrate luminosity of the plasma jet in the railgun channel and its interaction with target.

As plasma jet leaves the target there is a process of a material deposition on the plasma surface. We study the deposition process of copper on a sodium-silicate glass, and obtained ultrathin coatings with an excellent adhesion to the substrate. Figure 6 and 7 demonstrate photo and SEM picture of the coating.

When a plasma jet velocity (and impulse) become higher a quality of a coating decreases. It is due to the fact that a high-speed multiphase jet contains supersonic dust and droplets, which can seriously damage the target's material. Figure 8 shows an example of surface damage due to carbon jet interaction with target, it is clearly seen that there are some craters on the surface in size of 10-30 μm.
5. Conclusion
We discover a railgun operating mode in which it can function as a generator of dense focused plasma and multiphase jets. We investigate the speeds of a plasma jets in dependence of gas pressure in the vacuum chamber. The operational mode of a railgun with plasma piston is found, in which multiphase jet is produced. Such jets can seriously damage the surface of the solid substrates. The results obtained make it possible to use rail accelerator as a generator of a dense plasma and multiphase jets for technological and scientific purposes.

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