

High Power Plasma Flow Interaction with Micro- and Nanopowders

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Abstract: The paper presents the study of high power Ablation-fed Pulsed Plasma Thruster (APPT) application for material processing. Plasma flow, having power density, which can exceed 10^8 W/cm² is formed in high power APPT. The pulse duration can be changed from microseconds to several milliseconds. Parameters of the plasma flow in the area of a sample may vary over a wide range. The velocity of the plasma flow reaches 10^7 cm/s, the efficiency of conversion of electrical energy into kinetic energy of plasma flow is about 40%, into thermal energy exceeds 60%. Material processing by means of fluorocarbon plasma produced in APPT is of very limited interest. So, introduction of impurities is produced to enrich the plasma flow with elements required for material processing. The materials having high evaporation temperature are attractive for applications and can be evaporated in considered plasma flow due to its high power density. For these purposes special schema, based on the impact of a plasma flow with pellets, which are distributed in space in the form of dust-like structure is used. Pellet dimensions are in a range of 0.1 – 70 μ m. Tungsten and tungsten carbide powders are mainly used in our experiments. Throughout this process the plasma flow is enriched with impurities. Then this resulting flow interacts with the surface of metal sample. Thermal behavior of pellets was analysed on the base of analytical model. The results of the experiments on the interaction of high power pulsed plasma flow with micro- and nanopowders as well as data of samples processing presented. The results of the study are discussed.

I. Introduction

ABLATIVE pulsed plasma thrusters (APPT) are well-known variety of electric propulsion devices. APPTs have a successful spaceflight heritage and were the first tested in space. APPTs have exhibited a renewed interest for use in satellite station keeping, drag makeup, and orbit raising¹⁻³ due to miniaturization of space hardware and decreasing of spacecrafts mass. Space APPT applications use thrusters having capacitor up to several hundred joules. Higher energy APPTs could have applications in technology fields. Such high energy and high discharge power devices, work usually in electrodynamic mode of operation^{4,5}. This acceleration mechanism allows for high efficient power source energy transfer to plasma directed motion energy. Efficiency of working process in these is a desirable example for conventional APPT. Fig. 1 shows impulse bit – bank energy dependences for experimental and space APPT. High power APPT having kilojoules bank energy characterized by high power MPD discharge with expressed electrodynamic mode of plasma acceleration. The difference of high power APPTs and corresponding space devices is considerable. Nevertheless, physical processes in APPTs in wide range of bank energy are similar. Acceleration of the plasma produced as a result of pulsed evaporation of a solid propellant

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(usually Teflon), when a high current discharge is initiated along its surface, is its distinctive feature of APPT. The similar technique automatically provided the matching of a propellant feed with the APPT discharge parameters and allows one to produce relatively-effective plasma acceleration. This makes it possible to realize a sufficiently high conversion efficiency of the energy stored in the power supply into kinetic energy of the plasma^{1,6}. High power APPTs produce plasma flow with duration from microseconds to milliseconds, with minimal diameter of ≈ 1 cm, the flow of particles to 10^{26} cm²/s and velocities up to $\approx 10^7$ cm/sec.

Gasdynamic and electrodynamic acceleration of plasma can be realized with the choice of geometric parameters and the parameters of APPT electric circuit. In the electrodynamic mode of plasma acceleration magnetic pressure exceeds the gas-kinetic one, and plasma is accelerated mainly due to the Lorentz force.

The maximum plasma density reaches 10^{18} cm⁻³. Plasma flow expands with velocity of about 10^6 cm/s. Interacting with the surface of the material, such flows can change its surface properties without affecting the sample as a whole. APPTs offer several advantages associated with their relatively simple structure in comparison with other plasma sources. These have no vent valves, switching devices and have the possibility of increasing the pulse duration up to milliseconds etc. Moreover, the accelerated plasma flow may have advantages over the laser and a number of chemical methods because of its low cost. Other important factors are the ability to process large surfaces and relatively high energy of particles are additional important factors. Typical ions energy is (1-3) keV, the energy density of plasma flow is from 0.1 to 100 J/cm².

Earlier, a number of successful attempts to apply plasma propulsion techniques for surface processing were completed. In⁷⁻⁸ the RF-ion thruster was proposed and tested for material processing with reactive gases. Thruster has been operated with 15 different gases, e.g. Ar, O₂, N₂ etc. The ability of the RF-ion thruster for material processing has been demonstrated. Presented results show the possibility to produce thin films and modified surfaces. In^{9,10} the MPD arcjet generators were used for coating. MPD arcjets can produce higher-velocity, higher-temperature, higher-density and larger-area plasmas than those of conventional plasma sources in MW-class input power repetitive pulsed operations. So, the discharge plasmas are expected to be utilized for various material manufacturing processes. Two types of MPD arcjet generators were developed for applications of them to ceramic spray coatings. The former was operated with Ar for Mullite or Zirconia coating due to ablation of the cathode cover and the latter with N₂ for titanium nitride coating due to reactive process between ablated titanium particles and nitrogen plasma. Coating characteristics showed that the MPD arcjet generators had high potentials for ceramic spray coatings. Successful results on tungsten carbide-cobalt coatings by the water-stabilized plasma gun with stationary power of 150 kW is presented in¹¹.

Compare to MPD arcjet generators high power APPTs is high efficiency GW-class input power device, that could cover some other possibilities of material processing. Accordingly, one can wait more intensive interaction APPT plasma flow with samples, melting and implantation can be reached.

The paper describes the experimental setup based on APPT with bank energy of 10 kJ/pulse, which is designed to study the interaction of high power pulsed plasma flow with the surface of metals and with micro- and nanopowders. Metal surface processing results are given and discussed.

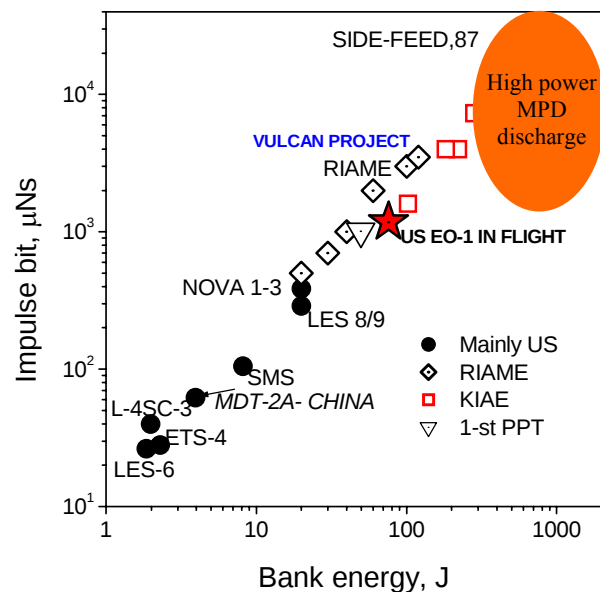


Figure 1. Impulse bit – bank energy dependences for experimental and space APPT.

II. Experimental Setup and Techniques

The quasi-steady APPT stand is written in more detail in⁹. We reiterate the most important characteristics. The pulsed power supply was assembled of 16 capacitors with the total capacitance up to 128.5 μF . Maximal initial voltage is up to 15 kV. The capacitor bank is connected with the feeder through the low inductive cable bridge composed of 48 high current coaxial cables. The estimated cable bridge inductance is $3 \cdot 10^{-9}$ H. The inductance of vacuum feeder is 10^{-8} H.

The thruster consists of a cylindrical copper anode and a tungsten cathode. The accelerating coaxial channel is near 9 cm long and 10 cm and 2 cm in diameter respectively. Outer electrode is anode. Teflon is the solid propellant. The main high current discharge in accelerating coaxial channel is triggering by low power breakdown plasma moving through the holes in the inner electrode to the outer electrode. The maximal charging voltage at plasma source in the absence of commutation devices



Figure 2. Experimental facility. 1-cable bridge, 2- vacuum feeder, 3 - vacuum chamber.

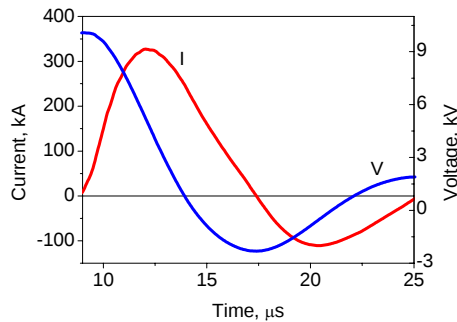


Figure 3. Input voltage, V and discharge current, I. Initial voltage is equal 10 kV.

Table 1. High power APPT discharge characteristics

V ₀ , kV	W _{bat} , J	Thermal eff.	P _{bit} , mNs	Isp, s	Mass bit, mg
3,5	557	0,85	16.7	2700	0.61
4	728	0,87	21.8	2800	0.79
4,5	921	0,81	26.4	2700	0.99
10	6000	0.7	100	5000	2.2

is determined by the surface breakdown voltage of the working insulator. For the Teflon used in the device under consideration the breakdown voltage is equal 22 kV/cm. Such materials as Teflon, porcelain, acrylic plastic, BNC etc. may be used as propellants. High voltage tests of the plasma source

were performed at the capacitor bank voltage equal up to 15 kV. APPT is housed in a rectangular stainless steel tank of volume near 1.2 m³. Prior to thruster ignition, the tank is evacuated down to approximately 3×10^{-5} torr. Experimental facility photo is given in Fig. 2.

Electrical measurements include the discharge current, voltage and the magnetic field measurements. The discharge current was measured by the Rogowski coil connected to low inductance and low resistance shunt. The voltage across the capacitor bank and at other points was measured by capacitive voltage dividers. Energy fluxes dissipated in sample and calorimetric measurements used low dimension (1 mm scale) thermistors.

A. Original Plasma Flow Parameters

Plasma flows having relatively high range of parameters can be generated in APPT under consideration. The operation modes having high reliability have been chosen for technology demonstration. Main plasma shot characteristics are given in Table 1.

After triggering for a few tens on nanoseconds the main discharge resistance decreases to 0.1- 1 mOhm. Then the discharge current in the plasma source circuit is determined by the wave impedance of the power supply and by the resistance related with

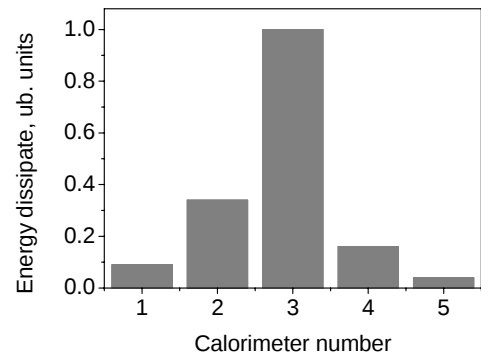


Figure 4. Results of calorimetric measurements of a plasma flow energy, 20 cm from outlet. Distance between the centers of calorimeters is equal of 40 mm. Sensor #3 placed in the axis of a plasma flow.

the plasma acceleration. As a rule, the electric surface breakdown in a vacuum ($P < 10^{-3}$ Torr) is realized in the form of a thin channel that expand with a thermal velocity corresponding to the plasma temperature (~ 3 eV). The focused pulsed plasma flow is formed at the accelerating channel outlet. Discharge characteristics – input voltage and discharge current are given in Fig.3. The outlet velocity of a plasma flow was measured in several ways. First, average velocity was determined from impulse bit P and evaporating mass m_0 , $v_1 = P/m_0$. These estimations decrease average velocity due to late time ablation effect¹.

Plasma acceleration takes place mainly within 1-3 cm from insulator surface. The measurements have shown that the distribution of accelerated mass with respect to the plasma particle velocities during the first current half-period is rather compact: at $W_0 > 5$ kJ, the average plasma velocity is $(7-9) \cdot 10^6$ cm/s. The interferometric measurements show⁶ that the plasma acceleration is actually a 2 dimensional one and the plasma flow with the minimal diameter close to the diameter of a central electrode is formed at the output of the acceleration channel. Maximal electron density in a plasma flow is 10^{18} cm^{-3} (at the distance of 4 cm from the output). Minimal diameter of a flow is realized at a distance 2-3 cm from the thruster outlet. Then flow expands with a velocity approximately corresponding to plasma temperature of about 3 eV. Energy of plasma flow after outlet of accelerating channel was determined with plasma trap. High sensitive thermo-resistors were soldered in four points of the trap. Energy distribution in a plasma flow has been determined by means of a set of calorimeters at the distance from 10 to 50 cm long from the acceleration channel. Radial distribution of energy absorbed in the calorimeters in a distance of 20 cm from the plasma source is given in Fig. 4. Energy absorbed by the sample located on the axis, in dependence on the distance to the outlet of the APPT acceleration channel is shown in Fig. 5. For example, thermal measurement give energy dissipation equal 16 J/cm^2 , if sample placed in the axis, 20 cm from outlet and for bank energy equal 3 kJ. Sample position was determined by the size of the exposed area, which increases with distance from the outlet, and energy flux. Original distance to the outlet of the accelerator channel chosen from the condition of sample heating. It was proposed that sample should accept an energy bit necessary for heating up to the melting point temperature. In general, these experiments outlined possible areas of plasma flow interaction with the samples and with powders.

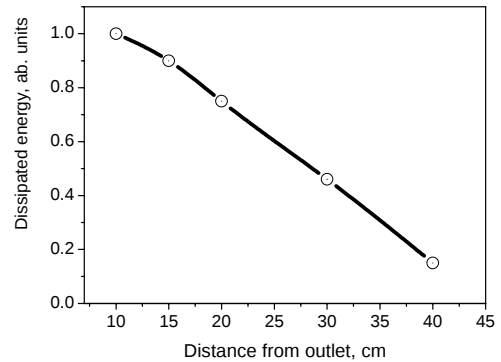


Figure 5. Energy dissipated in the samples, placed in the axis of plasma flow in dependence of distance from the outlet of accelerating channel. Diameter of the sample is 30 mm.

B. Impurity Introduction

APPT produces CF_2 plasma flow. Real technologies ask for a variety of materials for implantation, etching, etc. For this reason it is necessary to introduce impurity materials into plasma before the interaction with sample. The lifetime of the plasma flow is a few microseconds, so that the active introduction of impurities into plasma flow requires the injection velocities comparable or greater than the thermal velocity of plasma. Pellets acceleration up to velocities of $\sim 10^6$ cm/s represents a separate complicated problem. Therefore it was proposed method of plasma flow collision with a cloud of impurity pellets having a speed close to zero. Vibratory mesh, which allows to create a given density and length of the cloud of pellets was used. Mesh size, as well as amplitude and frequency of its vibrations controlled mass flow rate of powder (pellets). Photos of the cloud of molybdenum micropowder with an average particle size of 70 microns, is shown in Fig. 6.

Successful results were obtained with impurity mass in plasma flow cross section being order or smaller of plasma flow rate bit per one shot.. Initial plasma flow parameters in the pellets cloud boundary were: plasma density $10^{17} - 10^{18} \text{ cm}^{-3}$, velocity of plasma $\approx 5 \cdot 10^6$ cm/s, plasma flow cross section $\approx 50 \text{ cm}^2$. At higher density of pellet cloud initial plasma flow do not penetrates trough pellets cloud volume. The distance between pellets cloud and sample can be varied in a range 10 - 30 cm.



Figure 6. A Cloud of molybdenum micropowder. The average size of particles, 70 microns.

III. Results and discussion

A run of experiments with the introduction of powders to plasma flow have been performed. Molybdenum powder with particle dimension of 70 μm , tungsten carbide and tungsten powders with particle dimension in the range of 100 nm were used. The impact of the plasma flow occurred with the cloud of pellets having length of 1-2 cm and mass about 1 mg in the interaction cross section. Photo of high power plasma flow interaction with micropowder and then with the steel sample is given in Fig. 7. Increasing the density of pellets leads to the reflection of the flow. The study of samples surface after pulsed plasma treatment was performed on the scanning electron microscope with a resolution of 10 nm. Images of the sample surface at different magnifications were obtained using secondary electron detector. Elemental analysis was performed with use of energy dispersive microanalysis system, which is equipped with a scanning electron microscope. Fig. 8 shows the energy spectrum, obtained after processing the sample surface by plasma flow, enriched by tungsten carbide impurity.

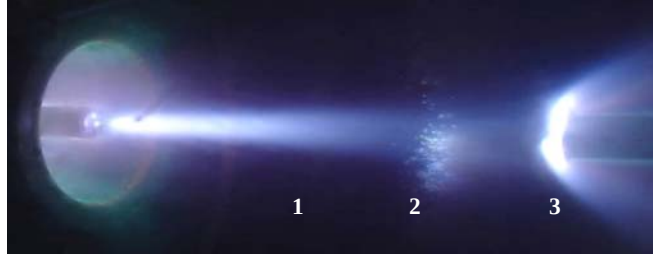


Figure 7. High power plasma flow interaction with micropowder and then with a sample. Pellets average dimension is 30 microns. Sample material is stainless steel. 1 – Initial plasma flow, 2 - pellets cloud, 3 – sample.

Scanning electron image of the sample surface after the treatment by fluorine-carbon plasma flow with WC nanopowder impurity is given in Fig.9. The electron microscope studies of treated surface shows that the plasma processing resulted in a extremely-strong reduction in the size of grains in the sample material. If the grain size in the initial state was ~20 μm , after the plasma processing it decreased to the level of 0.1 μm .

If the energy flux density is high enough, the density of thermal energy in the surface layer reaches the energy sublimation of sample material and material begins evaporation. If you do not consider the energy transfer process, the evaporation behavior under the influence of plasma flow is similar to ablation caused by irradiation of material with power laser radiation. A similar approach can be used to solve the problem of evaporation of the working fluid in APPT. With increasing energy flux density on the surface, gas-dynamic expansion of vapors significantly influenced on process.

When the plasma flow impact with the surface of pellets, boundary layer of dense plasma is formed near the sample surface. Part of the energy of the boundary layer is transferred to the sample surface. Evaporation of pellet in plasma was also studied in numerous works, devoted thermonuclear plasma^{11,12}. Simple estimates can be produced in the base of expression¹²:

$$\dot{N} = \delta \sqrt{\frac{8\pi}{m_e} \frac{n_e T_e^{3/2} r_p^2}{\varepsilon}}, \quad \text{Eq.(1)}$$

where N , n_e , T_e , r_p , and m_e , are the number of particles in a pellet, the electron density, electron temperature, pellet radial size, and electron mass, respectively. δ is the decreasing coefficient accounting energy loss in neutral or partially ionized cloud formed around pellet, ε - sublimation energy of pellet material. Accounting of pellet mass flow rate according (1) for $\delta=1$,

$n_e=10^{17} \text{ cm}^{-3}$, $T_e=3 \text{ eV}$, $r_p=1 \mu\text{m}$ gives for tungsten pellet $\dot{N} = 10^{13}$

atoms per microsecond, or $\dot{N}/N=1.5 \text{ \%}/\mu\text{s}$. So, the time necessary to evaporate $1 \mu\text{m}$ tungsten pellet in considered plasma flow is order of $100 \mu\text{s}$. Really, plasma density increased significantly due to impact of initial plasma flow with pellet.

Together with this effect $\dot{N}/N$ can be also increased with

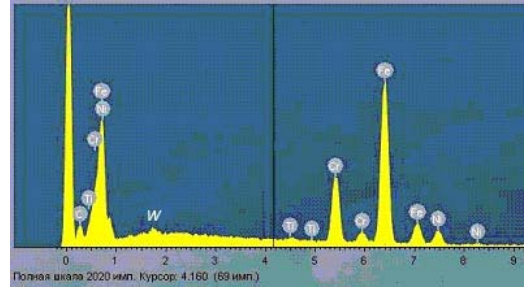


Figure 8. The results of surface microanalysis of the sample #3. Energy spectrum.

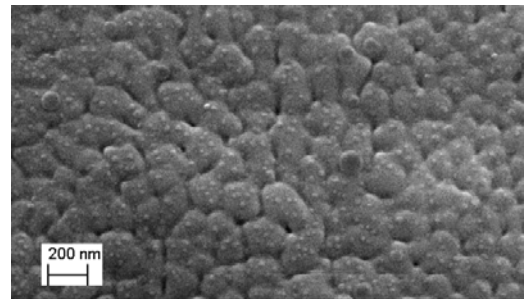


Figure 9. Scanning electron image of the sample surface after the treatment by fluorine-carbon plasma flow with WC nanopowder impurity.

decreasing of pellet size. But in any case, a complete evaporation of pellets with high evaporation temperature and high sublimation energy (W , WC) is doubtful if pellet size exceeds several tens microns.

The main interest for technological applications present modes with thin boundary layer and evaporating small masses, when the particles have a dimension lower than the depth of the thermal skin - layer corresponding to the pulse duration of the plasma flow. In this case it is natural to expect the destruction and evaporation of particles in the plasma flow.

An analysis of the first experiments can show that increasing of the impurity concentration of tungsten (in the form of plasma or gas) in the flow is possible with some decreasing pellets dimension.

IV. Conclusion

Experimental equipment for plasma flow interaction with micro- and nanopowders based on high power APPT with bank energy up to 10 kJ and necessary diagnostics have been prepared and tested. Plasma flows having velocity $7\text{--}9 \cdot 10^6 \text{ cm/s}$ and a maximum concentration of about 10^{18} cm^{-3} obtained. The distribution of energy in the plasma flow has been studied.

Technique of nanopowder introducing into plasma flow has been prepared and tested.

Estimates of plasma flow interaction with nano- and micropowders and experiments have shown that high melting and evaporation temperature pellets (W , WC) can evaporate in considered plasma flow.

The electron microscope studies of treated samples show significant change in the structure of a surface of the samples and noticeable appearance of impurity in surface layer.

Further work is necessary to optimize modes of interaction of plasma flow with nanopowders and then with samples.

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