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STUDY OF HIGH DENSITY PLASMA SPRAY PARAMETERS USING PLASMA COAXIAL ACCELERATOR

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Plasma accelerator was used for the deposition of a material powder placed at a breach. A capacitor bank of 46.26 μF charged to 3 kV (208.17 J) gave a peak current of 8.8 kA after 15 μs. Plasma inductance varied between 3 μH and 1.5 μH while the plasma resistance varied between 5 mΩ and 300 mΩ within one shot, while the electron temperature and plasma density near the substrate measured with a double electric probe was about 3 eV and 2.7×10^{13} cm^{-3}, respectively. Carbon plasma velocity at the muzzle was 6.0 cm/μs which agrees with calculations. The deposited graphite powder showed mostly a homogeneous distribution of clusters. The total efficiency of the system, considering both the internal and kinetic energy, was found to be 10.9 %.

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1. *Introduction*

Plasma-enhanced chemical vapour deposition (PECVD) was used to deposit transition metals and transition-metal silicides. Plasma enhanced CVD of inorganic dielectrics was also used for the reactive glow discharge film formation in microelectronic applications. It was found that the structural and electrical properties of the deposited films depend on the variation of the reactant gases [1].

Coaxial accelerators have recently been used in several applications such as surface nitriding [2], material-testing [3] and impulse plasma deposition (IPD) [4]. Studies of the pulsed high-energy deposition by plasma gun (PHEDP), using coaxial accelerators, have been carried out by using the electrodes as the source of deposited materials [5] or the reactive plasma materials [6]. The coaxial accelerator efficiency depends on the transfered part of the discharge energy to the plasma either for kinetic motion or plasma heating.

Marshall and Henins [7] studied the fast plasma from a coaxial gun and found that the amount and energy of the fast plasma produced at the gun muzzle apparently depends on the gas density distribution in this region at the gun firing time. The streaming velocity of the plasma should everywhere be in the $\boldsymbol{E} \times \boldsymbol{B}$ direction.

Lindberg and Jacobsen [8] found that the plasma expelled from a coaxial plasma gun had a conical shape with a central axial pinch. When a radial magnetic field is applied at the muzzle of the gun, magnetized plasma rings are formed.

The study of the breakdown phase in plasma coaxial gun showed that the optimum start and operation conditions appeared to be strongly dependent on the material and length of the cylindrical insulator [9].

A modified coaxial plasma gun in high density regime was investigated experimentally and theoretically by Schaer [10]. Further improvement has been achieved by the use of a magnetic nozzle [11].

The aim of the present work is to study the plasma parameters (e.g. plasma electron temperature and density, plasma inductance and plasma resistance) of the plasma coaxial accelerator under different experimental conditions. The deposition process is studied for graphite powder placed at the breach of the coaxial accelerator head under various conditions of the charging voltage, number of shots and the initial gas pressure.

2. *Experimental setup*

Figure 1 shows a schematic diagram of the experimental setup. The plasma coaxial tube consists of two hollow cylindrical coaxial steel electrodes. The inner electrode is 14.8 cm long and 5.2 cm in diameter while the outer electrode is 16.2 cm long and 8.4 cm in diameter. The two electrodes are isolated from each other by a teflon disc. A rectangular glass substrate placed at the muzzle is used for the deposition of evaporated particles. The plasma coaxial tube is fixed in the vertical position. The formed plasma sheath moves upwards.

The coaxial tube is powered by capacitor bank consisting of six capacitors, each of 7.71 μF, connected in parallel, and a spark-gap switch. The potential difference between the two electrodes is measured by a capacitive divider (designed and developed in our laboratory). Magnetic probes and pick-up coils are used to measure the plasma sheath velocity. The electron temperature and the plasma density are measured using double electric probe.

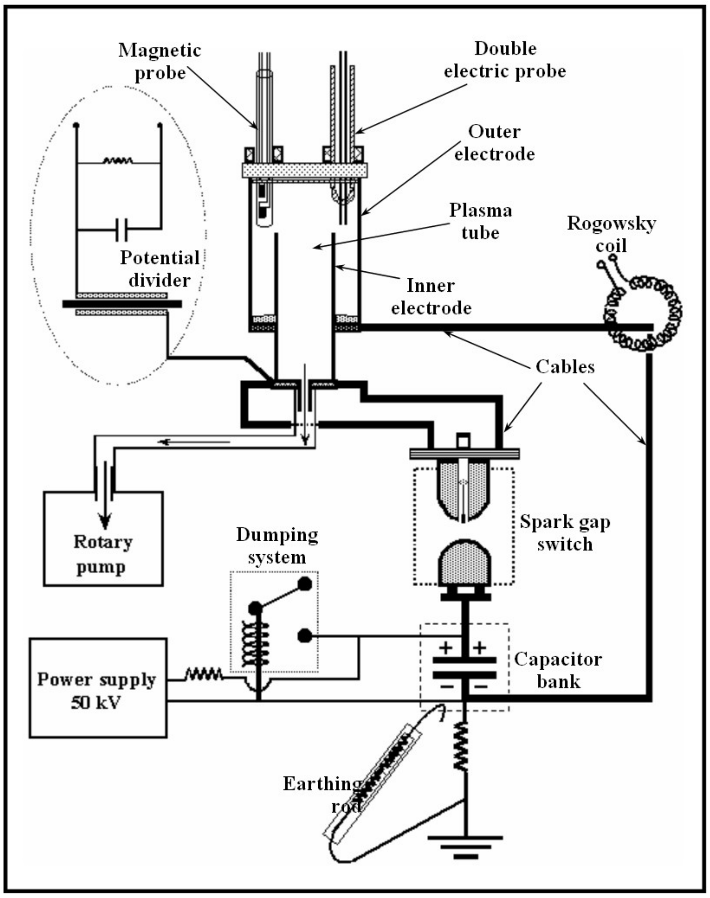

Fig. 1. A schematic diagram of the experimental setup.

3. Results and discussion

Figure 2 shows the variation of the discharge current and voltage across the coaxial accelerator with time. The discharge current and voltage showed that the current sheath reached 8.8 kA after 15 μs from the start of the discharge.

The plasma inductance showed that it has a peak values of 2.82 μH, 2.74 μH, 2.59 μH and 2.22 μH at discharge times of 12 μs, 44 μs, 76 μs and 104 μs, respectively, as shown in Fig. 3. These represent the times at which the plasma current sheath reached the muzzle at each half cycle of the discharge current.

It has been observed that the plasma resistance has a minimum values of 12.05 mΩ, 19.77 mΩ, 3.98 mΩ and 1.22 mΩ at discharge times of 28 μs, 56 μs, 96 μs

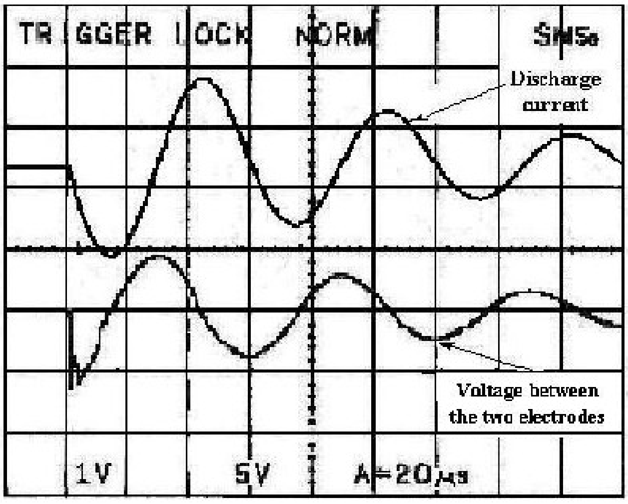

Fig. 2. The current and voltage signals at 3 kV *charging voltage and at 25* Pa *pressure.*

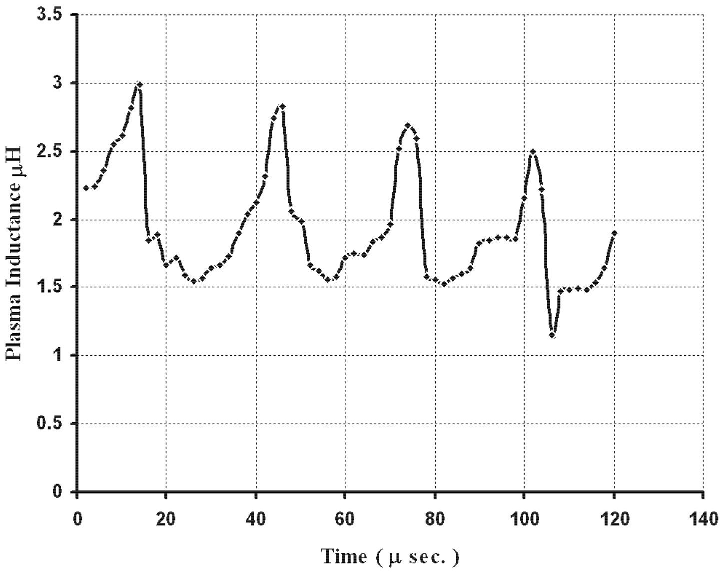

Fig. 3. The discharge time to plasma inductance relation curve at 3 kV *charging voltage and 25* Pa *pressure.*

and 112 μs, respectively, as shown in Fig. 4. These minimum values represent the complete formation of the plasma sheath current at these times.

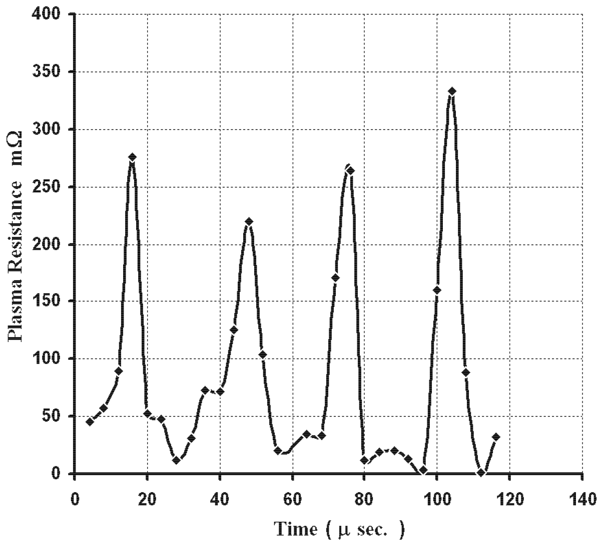

Fig. 4. The discharge time to plasma resistance relation curve at 3 kV *charging voltage and 25* Pa *pressure.*

Double electric probe results showed that the electron temperature and density at the substrate were around 3 eV and 2×10^{13} cm^{-3}, respectively, for the first, second and third half cycle of the discharge signal, as shown in Table 1.

TABLE 1. Results of the double electric probe.

Peak No.	Saturation current (mA)	Electron temperature (eV)	Ion density$\times 10^{13}$ (cm^{-3})
1st	39	3.05	2.692
2nd	33.5	2.95	2.351
3rd	17	2.8	1.225

Pick up coils wound around the outer diameter of the system did not detect any formation of the axial magnetic field. Two magnetic probes are used to determine the plasma sheath velocity. Fig. 5 shows the variation of the ejected plasma sheath velocity with the position above the muzzle. The extrapolation of the curve of the first current peak curve showed that the plasma reaches the muzzle end with a velocity of about 6.0 cm/μs. A decrease of the axial plasma velocity up to 3 cm from the muzzle, followed by an increase after that position, has been observed. The main reason for this variation is due to the electromagnetic lens which causes

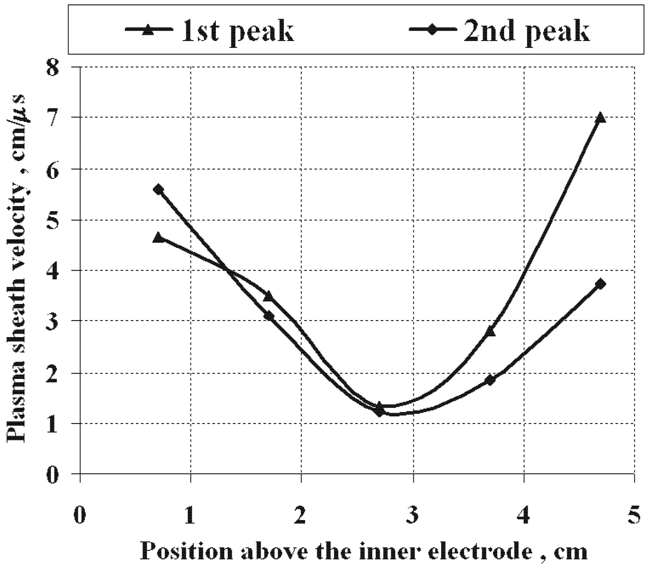

Fig. 5. The position above the inner electrode to plasma velocity relation curve at 3 kV *charging voltage and 25* Pa *pressure.*

a transfer of the axial kinetic energy to radial one in the region from the muzzle up to 3 cm, and further on it reverses its direction.

In a theoretical simulation, the axial velocity v_z and the distance traversed by the plasma sheath z after time t have been calculated. The force acting on the plasma sheath is equal to the rate of the momentum variation and is given by [12]

$$\frac{\mathrm{d}(m\boldsymbol{v}_z)}{\mathrm{d}t} = \int (\boldsymbol{J}\times\boldsymbol{B})\,\mathrm{d}V, \tag{1}$$

where $\boldsymbol{J}\times\boldsymbol{B}$ is the Lorentz force, $\boldsymbol{J}$ is the current density, $\boldsymbol{B}$ is the magnetic field, m is the carbon-particle sheath mass, and $\mathrm{d}V$ is the elementary sheath volume. For a constant mass m, one can consider a constant volume V, so the Eq. (1) can be written as

$$m\frac{\mathrm{d}\boldsymbol{v}_z}{\mathrm{d}t} = (\boldsymbol{J}\times\boldsymbol{B})\,V. \tag{2}$$

By integrating Eq. (2), the axial velocity and position can be obtained as a function of the time t

$$v_z = K\left(t - \frac{\sin 2\omega t}{2\omega}\right), \tag{3}$$

$$z = \frac{K}{2}\left(t^2 - \frac{\sin^2 \omega t}{\omega^2}\right), \tag{4}$$

where K is given by

$$K = \frac{J_0 B_0}{2m} = \frac{\mu_0 I_0^2}{2\pi^2 (a+b)^2 \delta \rho}\,, \tag{5}$$

where ω is the angular frequency, J_0 is the peak current density, B_0 is the peak magnetic field, I_0 is the peak discharge current, $a = 2.6$ cm is the inner electrode radius, $b = 4.2$ cm is the outer electrode radius, μ_0 is the permeability of vacuum ($4\pi \times 10^{-7}$ W/Am), δ is the sheath thickness, and ρ is the average plasma density that can be written as

$$\rho = \text{ion density} \times \text{carbon atom mass}. \tag{6}$$

The calculated relation between position and velocity is shown in Fig. 6. From this figure, one can see that the plasma reaches the muzzle (which is at the distance of 7.7 cm from the breach) with a velocity of 5.5 cm/μs. This result is in a good agreement with our experimental result of 6.0 cm/μs.

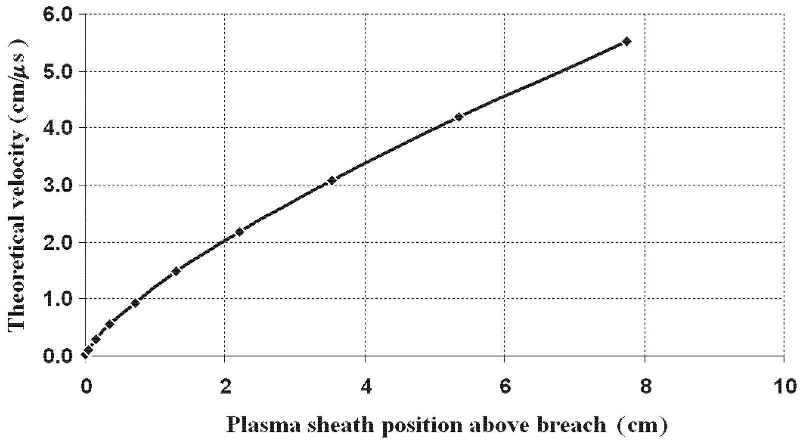

Fig. 6. Theoretical relation between the position above the breaching end and velocity at 3 kV *charging voltage and 25* Pa *pressure.*

The used energy of the system, E_u, has been calculated using the following formula,

$$E_\mathrm{u} = \int P \, \mathrm{d}t \tag{7}$$

where P is the discharge power flow through the coaxial electrodes. The calculation showed that $E_\mathrm{u} = 107.5$ J.

The kinetic energy has been calculated from the relation

$$KE = \frac{1}{2} m v_z^2, \tag{8}$$

where m is the plasma sheath mass which is given by $m = \rho V$, V is the volume of the carbon plasma sheath which is given by $V = \pi(b^2 - a^2)\delta$, and v_z is the plasma sheath velocity due to the particle motion measured at the muzzle end. The kinetic energy is calculated for each half cycle and the total kinetic energy is then equal to the summation of the kinetic energies for all half cycles. For the 3 kV charging voltage and at 25 Pa (0.19 Torr; 1 Torr=133.3 Pa) initial pressure one gets, $KE \approx 10.98$ J, hence, the kinetic efficiency $KE/E_{\mathrm{u}} = 10.2\,\%$.

The internal energy is the plasma thermal energy calculated from the relation

$$IE = \sum (NkT_{\mathrm{e}} + N\varepsilon) \approx 0.156 + 0.590 = 0.746 \text{ J}, \tag{9}$$

where T_{e} is the plasma electron temperature, ε is the ionization energy (1086 kJ/mole for carbon) and N is the total number of the particles in the sheath, given by

$$N = n_i V, \tag{10}$$

where n_i is the plasma density. Hence, the internal efficiency $IE/E_{\mathrm{u}} = 0.69\,\%$. Thus, the ratio between the total energy gained by the plasma to the electric discharge energy gave the total efficiency of 10.9 %.

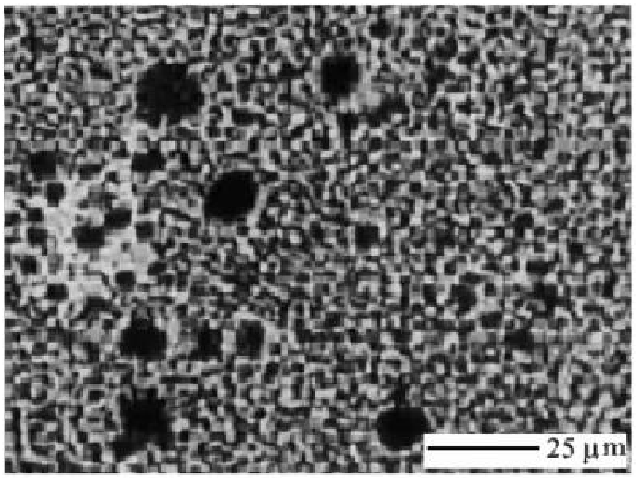

Fig. 7. Surface morphology of a micrograph obtained by scanning electron microscope (SEM) of thin graphite film on glass substrate produced in 100 pulses at 3 kV.

The deposited carbon structure at the substrate, using scanning electron microscope (SEM), for 100 discharge pulses at 3 kV charging voltage, is a homogeneous layer as shown in Fig. 7 for an area of 4 cm diameter. The grain size of the graphite powder is about 2 μm and its heap thickness is about 0.5 cm. The estimated quantity of deposited carbon per discharge was 0.3 mg (from thin film thickness measurements by laser interferometry).

The presented results show a successful deposition of graphite powder, for the first time by pulsed discharge, onto the insulator between the two electrodes at the breach. There were clusters of the graphite that deposited on the glass substrate, which became larger when increasing the charging voltage and the number of pulses. At first sight, these clusters consisted of carbon atoms, but by SEM investigations, little shining clusters were observed, which means that apparently diamond-like carbon films were created. These homogeneous layers of the graphite, which were deposited on the glass substrate, grew thicker when increasing the charging voltage and/or the number of pulses (shots).

4. Conclusion

Plasma coaxial accelerator is used for the deposition using powder of the test material at the breach.

The discharge current and voltage were measured; the first peak current of about 8.8 kA occurs after 15 μs at 3 kV charging voltage. The electron temperature and density, measured by double electric probe, were 3 eV and 2.25×10^{13} ion cm^{-3}, respectively. Plasma inductance varies between 3 μH and 1.5 μH and plasma resistance varies between 5 mΩ and 300 mΩ within one shot.

The estimated velocity of the plasma sheath at the muzzle was about 6.0 cm/μs, which is in agreement with the theoretical calculation which gives 5.5 cm/μs. The variation of the ejected plasma sheath velocity with position may be due to the electromagnetic lens occurring at the muzzle, which transfers part of the axial velocity to the radial one, up to a distance of 3 cm, then the process is reversed.

The calculated efficiency of the system for energy transfer to the carbon plasma from the coaxial discharge is 10.2 % for transfer to kinetic energy and 0.69 % for transfer to internal energy.

SEM studies have shown that the deposited carbon structure after 100 discharge shots is mainly a homogeneous layer.

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PROUČAVANJE PARAMETARA RASPRAŠIVANJA PLAZMOM VELIKE GUSTOĆE U KOAKSIJALNOM UBRZIVAČU PLAZME

Rabili smo ubrzivač plazme za naparavanje praha postavljenog na otvoru za snop. Sklop kapacitora od 46.26 μF nabijen na 3 kV (208.2 J) davao je vršnu struju 8.8 kA nakon 15 μs. Indukcija plazme mijenjala se između 3 i 1.5 μH, a otpor plazme između 5 i 300 mΩ tijekom pojedinog palenja. Elektronska temperatura i gustoća plazme u blizini podloge, koje smo mjerili dvostrukom električnom sondom, iznose oko 3 eV odn. 2.7×10^{13} cm^{-3}. Brzina ugljične plazme kod otvora iznosi 6.0 cm/μs, u skladu s izračunatom vrijednošću. Naparen grafitni prah pokazuje većma jednoličnu raspodjelu nakupina. Ukupna učinkovitost sustava, ubrajajući unutarnju i kinetičku energiju, iznosi 10.9 %.