Plasma diagnostics in a pulsed accelerator used for material processing

A Zhukeshov

Science Research Institute of Experimental and Theoretical Physics, al-Farabi Kazakh National University, 96a Tole bi str., 050012 Almaty Kazakhstan

E-mail: zhukeshov@physics.kz

Abstract. Results of research work of a pulsed plasma accelerator, designed as diagnostic and material science stands in SRIETP are presented. We present results on the development of electric and magnetic probes used for measurement of plasma parameters. The physical properties and changes in structure of vanadium alloy, common quality carbon and stainless steels have been investigated as well.

1. Introduction

The pulsed plasma accelerators (PPA) are used for obtaining powerful concentrated fluxes. The features of accelerator’s construction allow obtaining plasma flows in a wide range of ion component energy – from several to hundreds keV. This gives the possibility to use them for a wide range of applications in various fields of plasma physics and material science. Therefore for many applications it is necessary to determine parameters of plasma flow – temperature and particle number densities as well as their velocity.

Operation of the facility is based on the acceleration of plasma formed in the inter-electrode space by its own magnetic field under electric discharge. In order to create the above conditions a high voltage is applied to the electrodes and vacuum sufficient for discharge breakdown. The main elements of the accelerator are the working chamber with two coaxial electrodes and the accumulating capacitors. The task to control the facility means to fulfill Pashen condition for the gas under which practically all working substance will be ionized. In case of impulse injection of a working gas it is necessary to coordinate the time of gas injection into the inter-electrode space with the voltage pulse. For this purpose a special pulse generator is used. In case of continuous filling, the chamber is first filled with a gas to the pressure at which discharge may occur and the dependence of discharge current on pressure is studied. In the last case the continuous mode of accelerator work has been realized.

The present paper presents the results of investigation of accelerator operation in continuous mode carried out with the help of probe techniques. The detailed description of this device has been given in [1]. The accelerator has two cylindrical electrodes with diameters of 90 mm (external) and 24 mm (internal). The energy of the capacitor bank is 32 kJ. The voltage is 10 – 30 kV. The discharge current represents a harmonically decreasing signal with period of 14 µs. First we studied features of accelerator operation at different input pressures. The tests demonstrated that the accelerator may work in the continuous mode in a rather wide range of working pressures (~10⁻³–10² Torr). The maximum power density and, hence, efficient acceleration of the plasma flow was obtained at a pressure of about 10⁻¹ Torr and was equal to 45 Joule/cm² at a discharge voltage of 25 kV.
2. Plasma diagnostics in continuous mode of operation

At the beginning of this part we present the results of investigations of the structure of current layers formed between coaxial electrodes of plasma accelerator by means of an array of 15 coils. Each coil was made of 0.13 mm-wire wound on a frame of 1.5 mm in diameter. The coil was attached at the end of tightly interweaved conductor which was placed in a quartz tube of 4 mm in diameter and 60 cm long. The probe was placed on a special support and connected to a measuring oscilloscope through a 50 Ohm coaxial cable. The equivalent coil cross-section was 0.26 cm$^2$ and inductivity $\mu H$. The time constant $L/R_0$ was about 2 ns, i.e. very short for the experiment under consideration.

It is known, that the signal from a magnetic probe is proportional to the speed of change of the magnetic field. For integration of the probe signal we used a passive $RC$ circuit. The integrator output voltage is equal to

$$V_0 = \frac{1}{C} \int Idt = \frac{1}{RC} \int (V_i - V_0)dt,$$

where $V_i$ is the input voltage of the circuit. When the $RC$ constant it is larger than the integration time, the voltage $V_0$ is sufficiently small compared to $V_i$ and the size $RCV_0$ gives a good conformity of integral from $V_i$ [2]. The integration error can be estimated by the formula

$$V_0 = V_i(1 - e^{-t/RC}) = V_i \left[ \frac{t}{RC} - \frac{t^2}{2RC^2} + \ldots \right].$$

The first term in right part is the true value of the integral, while the second gives an estimate of the first order error. As the characteristic time of the magnetic field variations is about 7 µs, a passive integrating circuit with $RC = 50 \text{ Ohm} \times 1.5 \mu \text{F} = 75 \mu \text{s}$ has been used. In our case, for $t/RC = 0.1$ the error is estimated as 0.5 %. Therefore, the probe sensitivity is 34 µV/G. Such sensitivity enabled to measure signals by using the oscilloscope directly, without additional amplifiers, with an acceptable signal-to-noise ratio. Using the probe array we can measure $B_\phi(t)$ for various positions of the probe.

In these experiments the maximum value of the magnetic field measured was about $4 \times 10^3 \text{ T}$. The results demonstrated a high signal reproducibility for different discharge conditions. Analysis of experimental data shows that the magnetic field moves along the axial direction and that the front speed of magnetic field equals about 50 km/s at pressure of 0.1 Torr. At this speed a current layer has thickness in axial direction of about 10 cm.

To measure parameters of particles (temperature, particle number density) in a pulsed plasma flow, a single Langmuir probe was used. The probe represents a cylindrical steel electrode, 19 cm long and 1.8 mm in diameter. The actual collecting area of the probe is about 60% of the geometric one. The potential difference $U_p$ between the probe and the grounded outer PPA casing was changed on the shot-to shot basis and the temporal evolution of the probe current was measured. Examples of the probe current evolution are shown in figure 1 (a, b, c). The current-voltage characteristics were constructed from the experimental data for different time moments of the discharge. The I-V characteristic of probe is show in the figure 2. The electron temperature was determined by fitting the experimental I-V characteristics to the formula

$$\frac{dV}{d \ln I} = \frac{kT_e}{e} = T_A[eV],$$

where $V$ is the voltage applied to the probe, $I$ is the probe current. The electron temperature $T_e[eV] = 67 \pm 5 \text{ eV}$. Let us note that the measurements of temperature in such a way are possible for electron plasma components only, because the directed speed of ions is larger than their thermal speed. In the latter case, the classical theory of probes is not applicable.

The electron number density is calculated by using the formula
where \( I_{\text{sat}} \) is the experimental value of the electron saturation current (820 mA), while \( S \) is the probe area. The thermal electron velocity \( \bar{\nu}_e \) equals

\[
\bar{\nu}_e = \sqrt{\frac{8kT_e}{\pi m_e}}.
\]

The typical value of the electron density is \( n_e = 2 \times 10^{12} \text{ cm}^{-3} \).

Figure 1.

Horizontal (time) scale, 5 \( \mu \text{s} / \text{div} \); vertical (current) scale, 200 mA/div.

Figure 2.

It should be noted that operation of a pulsed plasma accelerator in the continuous mode of filling does not differ considerably from the pulsed mode. However, in the latter case it is possible to carry out smooth regulation of plasma parameters in a wider range as the energy of the flow is affected both by the working gas pressure and the applied voltage.

3. Material processing

The next purpose of the research was a study on the influence of pulsed plasma flows on durability superficial properties (in particular, microhardness of a surface) of metal alloys used as material for controlled thermonuclear installations and different industrial technology applications.
The technological applications of this accelerator for a semiconductors surface structure modification have been studied in [3]. The method of plasma processing is widely acceptable in order to improve the surface properties of metal alloys, such as carbon and stainless steels. This part of the work is devoted to investigation of influence of plasma flows on various constructional materials. The physical properties and changes in the structure of vanadium alloy, common quality carbon and stainless steels were investigated. The formation of a modified layer on the surface after plasma processing is typical for metals. However, the large density of energy results in formation of blisters and non-uniform relief of the surface. This undesirable phenomenon can be avoided if one uses a smaller energy density. In all cases when the value of melted energy achieved 15-25 J/sm², re-crystallization of the surface area and structure modification took place on a depth of 10-30 µm and more depending on the material treated. The character of structural changes in metals depends on the energy density and the introduced dose. It depends also on the working gas used and on accelerator’s operation mode. When processing vanadium alloy surface with argon and helium, two different kinds of relief are formed.

For the carbon steel with a ferrite as basic structure, the formation of improved austenitic and martensitic phases is observed after the processing. At the same time for stainless steel the formation of nitride hardening phases is usual at processing by nitric and air plasmas. The microhardness of common steels processed with plasma increases 1.5 – 4 times when one repeats the processing (figure 3). As it has been shown in [4], in pulsed plasma accelerators introduction dozes as high as $10^{16}$-$10^{17}$ per pulse are achieved. Obviously, the degree of hardening is proportional to the number of pulses. After plasma processing wear resistance of carbon steel increased up to 4 times. This parameter was determined by abrasive method for seven samples treated by different number of pulses (figure 4).

The stainless steel samples were treated by several pulses. The processing of stainless steel samples with energy density about 25-30 J/sm² at once was carried out 10, 20 and 30 times. In all cases the influence of plasma leads to surface melting and formation of a homogeneous relief with blisters. As the number of treatments increase, the number of blisters increases as well. They unite into groups and form complexes. The surface of the processed sample is not etched in usual solutions of acids. The microhardness is 3 times higher, and $H_v$ size has a directly proportional dependence on the number of pulses observed. To specify the metallographic data, a X-ray analysis of all three samples of stainless steel processed by using different number of pulses was carried out. The basic phase of an initial sample is austenitic stainless steel. With the
help of the automated program, the parameter of a austenite crystal lattice was determined and was found to be \( a = (3.58980\pm 0.0006) \) Å. The phase structure analysis of the samples shows the presence of two basic phases: iron nitride and austenite in the processed layer of the surface. For iron nitride and austenite phases the parameters of crystal lattice were determined. This parameter for nitride is \( a = (3.6104\pm 0.0011) \) Å and for austenite \( a = (3.5896\pm 0.0015) \) Å.

From the comparison of austenite phase parameters for various samples it is seen that within the experimental error this parameter remains almost the same after processing, apart from a possible weak deformation of the crystal lattice. The iron nitride structure can be expressed as \( FeN0.056 \) or \( FeN0.059 \).

References
[1] Ibraev B M 2003 J. Engineering Thermophysics 12 2–65
[2] Chen F 1965 Electric probes Plasma diagnostic techniques, eds R.D.Haddleton and S.L.Leonard (Moscow: Mir, in Russian)
[3] Baimbetov F B, Ibraev B M and Zhukeshov A M 2002 Semiconductors 36 2–197
[4] Langner J, Piekoszewski J and Stanislawski J 2000 Nukleonika 45 3–193