Arc Generator with a Combined Filament and Hollow Cathode for Plasma Generation in a Large Volume

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Abstract – A plasma generator based on a non-self-sustained low-pressure arc discharge has been designed for finishing treatment and activation of surfaces and for plasma-assisted vacuum arc deposition of functional coatings. The generator allows treating articles of length $l \sim 50$ cm which are rotated around it with a planetary gear.

At a plasma-forming gas pressure of 0.3 Pa, a discharge current of 100 A, and an operating voltage of ~ 50 V, the generator produces plasma of density ~ 10^{10} cm^{-3} and inhomogeneity ± 15% in a vacuum volume of ~ 0.25 m^3.

In this work we study the dependence of the discharge current and operating voltage on pressure and on the filament current and also the plasma density distribution in the working chamber volume.

1. Introduction

To provide uniform vacuum ion-plasma treatment of large-dimension articles with the PINK generator [1], several plasma generators should be employed [2]. This complicates the power supply and control systems of plasma generators and necessitates special measures for improving the plasma homogeneity in the working volume. This problem can be solved by using an extended plasma generator capable of synthesizing plasma formations whose longitudinal dimensions are comparable with linear dimensions of the treated articles [3]. To use the working vacuum chamber more rationally and to increase the efficiency of the technological process, it is sometimes worthwhile to employ several extended plasma generators integrated into one unit with a common power supply.

With such a principle of generation of low-temperature gas-discharge plasmas, the problems arise with respect to the stability of the discharge into parallel working discharge cells, the uniformity of the plasma density distribution in the working volume, and to optimization of the power supply circuits of the plasma generator.

A generator of this type has been designed for treating three extended articles at a time. The articles are placed at an angle of 120° around the plasma generator which is located in the center of the vacuum chamber or are rotated around it with a planetary gear.

2. Plasma Generator Design and Power Supply Circuit

A simplified design of the plasma generator is shown in Fig. 1.

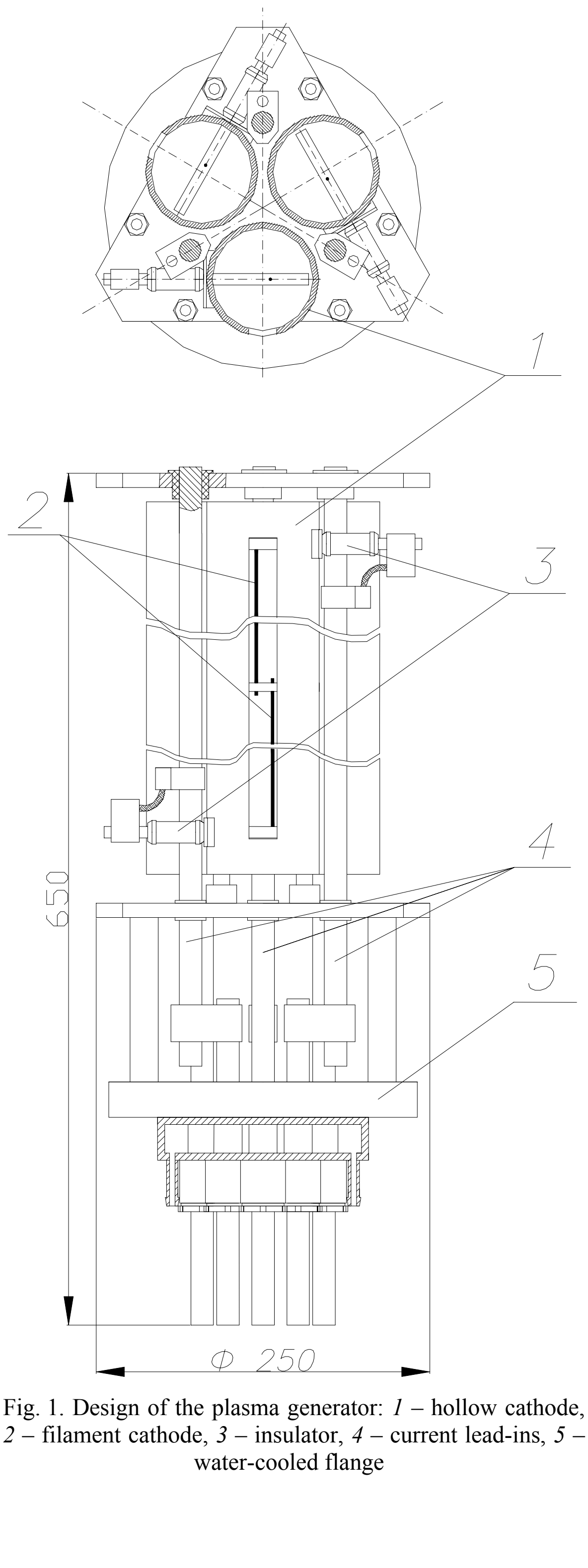

Fig. 1. Design of the plasma generator: *1* – hollow cathode, *2* – filament cathode, *3* – insulator, *4* – current lead-ins, *5* – water-cooled flange

It consists of three cylindrical hollow stainless steel cathodes *1*, each 80 mm in diameter and 440 mm in length, which are incorporated into one unit. Inside a cathode there are two filamentary tungsten cathodes *2* of diametere 0.8 mm and length 180 mm. Each filamentary cathode is fixed in cathode holders, of which one is insulated from the hollow cathode with cermet insulator *3* and the other is in direct electric contact with it. Such a circuit has made it possible to decrease the filament voltage of the tungsten wires by decreasing their length and to reduce substantially the effect of heating on deformation of the cathode filaments.

Fig. 2. Photo of the plasma generator

At the surface of each hollow cathode there is a longitudinal window of dimensions 20×400 mm which couple the cathode and anode regions of the arc discharge. The normals to the windows are at an angle of 120°. The role of the hollow anode of the discharge system is played by the internal walls of the working vacuum chamber. The plasma generator is fixed at the bottom of the vacuum chamber with water-cooled flange *5*.

Water-cooled copper current lead-ins *4* are used to power the plasma generator.

The design of the developed plasma generator allows for an increase in its total length by integrating several plasma generators into one extended unit.

The working gas (Ar) is supplied into the vacuum chamber of the setup with an automatic system of the type SNA-2. The circuit for powering the plasma generator is shown in Fig. 3. The filaments of the cathodes are powered by a three-phase a.c. transformer which is connected according to the circuit with an insulated neutral terminal and provides current of up to 100 A in the circuit of each cathode at a voltage of 30 V. A three-phase welding rectifier VD 306 U with a no-load voltage of 70 V and a load current of up to 300 A at a load voltage of ~ 20–30 V is used to power the arc discharge.

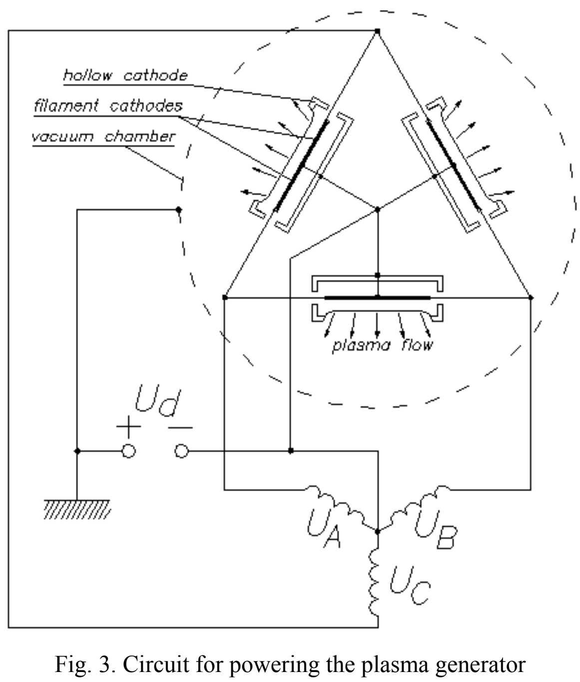

Fig. 3. Circuit for powering the plasma generator

The arc discharge initiated in the plasma generator is non-self-sustained, i.e., its parameters are effectively controlled by the filament cathode emission current. The electrons emitted by the filament cathode initiates primary ionization of the gas that is required for the initiation and operation of the discharge. When applying voltage from the welding rectifier, a non-self-sustained arc discharge is ignited between the hollow anode (the vacuum chamber) and the cathode cavities.

The combined filament-hollow cathode makes it possible to increase several times the discharge current, as compared to the discharge system with a filament cathode only.

One of the main peculiarities of the discharge system of this plasma generator is the use of three combined cathodes (discharge cells), which have a common power supply system, and one common hollow anode. Experiments have shown that in this system stable operation of the discharge in all discharge cells at a time is possible.

In the nominal mode of the operation of the plasma generator the discharge operates without formation of cathode and anode spots, but on first triggering or in the conditions of long service interruptions associated with depressurization of the vacuum chamber the discharge may change over to the modes with the formation of a cathode spot. Upon cleaning the surface, these changeovers are hardly observed. However, during the operation one should use an arc extinction system in the discharge circuit, since in the mode with a cathode spot the discharge operates in vapors of the cathode material that may cause "contamination" of the insulators of the plasma generator with products of erosion of the hollow cathodes. Moreover the formation of a cathode spot on the filament cathodes may lead to their burnout.

The discharge power is ~ 4–5 kW and therefore there is a need for intense cooling of the vacuum chamber and plasma generator.

In the developed experimental version of the plasma generator, water cooling is provided for the flange which mounts the plasma generator to the vacuum chamber and for current lead-ins of the filaments that ensures the operation of the plasma generator in steady-state conditions.

3. Experimental Results and Discussion

The plasma generator was tested experimentally in a vacuum chamber of dimensions 650×650×750 mm which was evacuated to a limiting pressure of ~ 10^{-3} Pa by a turbomolecular pump. The working gas was argon. Fig. 4 shows the operating voltage U_d and the discharge current I_d versus the filament current I_f, at an operating pressure p_{Ar} = 0.3 Pa. For stable initiation of the discharge, the filament currents of the cathodes I_f in the circuit of each filament should be 65–70 A.

At filament currents higher 100 A, the lifetime of the filaments, which makes u_p ~ 20 h in nominal conditions, is greatly decreased.

It has been found that increasing the filament current causes a decrease in the pressure at which the discharge is initiated. So, with a filament current I_f = 90 A, the discharge is initiated at a pressure of $7 \bullet 10^{-2}$ Pa and with I_f = 70 A it is ignited at ~ 0.3 Pa.
The main parameters of the discharge depend rather markedly on pressure. Fig. 5 shows the dependence of the operating voltage U_d and discharge current I_d on the pressure of the working gas at a filament current I_f = 90 A. The lower limit is governed by the pressure at which stable initiation of the discharge takes place. Increasing the pressure causes a decrease in operating voltage and an increase in discharge current that provides additional possibilities of controlling the discharge parameters.

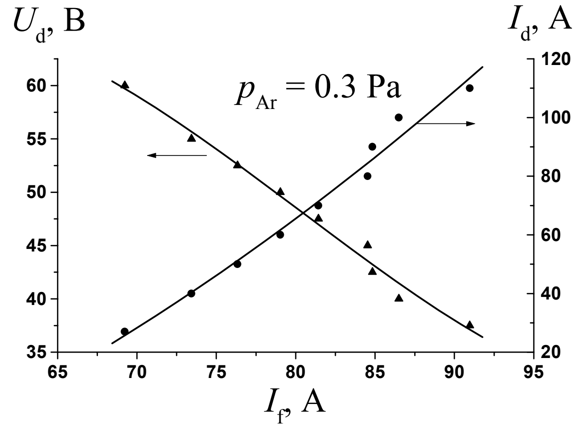

Fig. 4. Discharge operating voltage and the discharge current versus the filament current

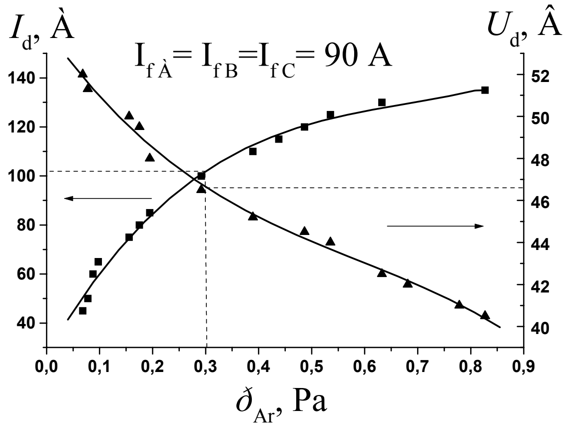

Fig. 5. Discharge operating voltage and the discharge current versus the pressure of the working gas

The main parameters of the plasma produced by the generator in the working area 10 cm away from the hollow cathodes and the saturation ion current density distribution were measured with the use of many-probe system which consisted of seven thin cylindrical tungsten probes of diameter 0.8. They were located along the axes of the hollow cathodes with a probe separation of 55 mm. To measure the saturation ion current, a negative potential of up to –50 V was applied to the probes.

The results of measurements have shown that the nonuniformity of the saturation ion current distribution along the axes of the hollow cathodes is less than ± 4% and crosswise the cathode axes it is ± 15% of the average value. The saturation ion currents of the probes for different cavities differ on average by no more than 4%. The average plasma density is ~ 10^{10} cm^{-3} and the electron temperature is ~ 4 eV.

4. Conclusion

A plasma generator has been designed which produces plasma of density $\sim 10^{10}$ cm^{-3} and inhomogeneity ± 15% in a vacuum volume of ~ 0.25 m^3.

Tests of the prototype of the developed plasma generator have revealed a possibility of stable generation of reasonably homogeneous plasma with three simultaneously operating discharge cells which have a common hollow anode and a common power supply system. This design has made it possible to simplify considerably the power supply and control systems, as compared to setups with several axially symmetric plasma generators.

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The developed plasma generator can be used for finishing treatment and activation of surfaces and for production of extended nitrided layers and plasma-assisted deposition of functional coatings.

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