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OPTIMIZATION OF THE MAGNETIC SYSTEM OF A VACUUM-ARC PLASMA SOURCE WITH A STRAIGHT LINE FILTER

D.S. Aksyonov, V.V. Vasyliev, A.A. Luchaninov, V.E. Strel'nitskij

National Science Center "Kharkov Institute of Physics and Technology", Kharkiv, Ukraine

E-mail: strelnitskij@kipt.kharkov.ua

The vacuum-arc plasma source with a rectilinear filter has been optimized for deposition of coatings on large size products. The calculations of the magnetic configuration options of the system were performed by using the FEMM program. New design of the output coil of the filter allows increase by 1.3 times the efficiency of plasma transportation to the substrate with a diameter of 300 mm. Plasma instabilities are proposed for the explanation the features of the motion of vacuum-arc plasma through the regions of an inhomogeneous magnetic field in a rectilinear macroparticles filter with a "magnetic island".

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INTRODUCTION

Vacuum-arc plasma sources are widely used in industry for deposition functional coatings on parts for various purposes, from decorative products to elements of high-tech devices [1]. A significant factor limiting use of such sources is the presence of micron-sized particles in the plasma flow generated by them, the so-called macroparticles (MPs), formed during the erosion of the cathode material and deposited on the treated surfaces. The presence of MPs is insignificant for hardening coatings on the processing tool. However, many applications (such as optics, micromechanics, etc.) require optical grade quality coatings. In order to cleanse the plasma of MPs, macroparticles filters (MF) are used, in the design of which the obstacles are required, excluding the direct visibility of the processed products from any point of the cathode surface. The obstacles interrupt the path of MPs flying along rectilinear trajectories. The movement of charged plasma particles is controlled by a magnetic field, the configuration of which ensures the transfer of ionized particles of the cathode material to the surface to be coated in accordance to the plasma optics principles [2].

One of the promising option of MF is a rectilinear filter with a "magnetic island" (MI) [3-7]. In such a device, the plasma is transported along the lines of force of the main magnetic field. MI presents a structural element, the case of which contains a permanent magnet or an electromagnet, the field of which is directed oppositely to the main transporting field. The case is used as a barrier to the MPs. In an ideal magnetic configuration, the lines of force of the resulting field should bypass the case and out of the filter avoiding interruption on its structural elements.

This paper presents the results of computer calculations and optimization of the elements of the transporting magnetic system of the rectilinear filter of the vacuum-arc plasma source developed in the NSC KIPT. The source is intended for use in the modernized equipment for deposition coatings of equal thickness on products up to 300 mm in size.

1. DESIGN OF THE VACUUM-ARC PLASMA SOURCE WITH THE RECTILINEAR MI FILTER

The source of vacuum-arc plasma with a rectilinear filter [8] is one of the main elements of the experimental installation designed for deposition of carbon coatings with a uniform thickness on large products. In the vacuum chamber there are additional magnetic coils and ferromagnetic parts, which help deposit coatings of equal thickness on the surfaces of the products. The source is connected to the vacuum chamber of the installation "Bulat-6", made of ferromagnetic material (steel). In this configuration, a significant percentage of the lines of force of the magnetic field transporting the plasma are shorted to the steel walls, which leads to plasma losses and reduced productivity of the source. Experiments have shown that the size of the deposition zone of the coating of uniform thickness does not exceed 200 mm.

To solve the problem of deposition the coatings of equal thickness inside the zone with a diameter of up to 300 mm, a modified version of the device was developed. In it, the output section of the filter plasma-guide with the output coil is inserted into the steel pipe of the vacuum chamber. Due to this, the power lines enter the vacuum chamber by passing the steel walls, which significantly reduces plasma losses during transportation.

The improved rectilinear source of the filtered vacuum-arc plasma (Fig. 1) includes a vacuum-arc evaporator 1 with an expendable cathode 4, a vortex chamber 3 for inert gas supply, an auxiliary ring anode 5 with an arc-initiating electrode 6, located near the end of the cathode, electromagnetic coil 7 with a cylindrical magnetic screen 8. The anode assembly 9 comprises an electromagnetic coil 10 and a MI 11 with a deflecting electromagnetic coil 12. The MI case is electrically connected to the anode. The output plasma duct 13 of reduced diameter is connected to the vacuum chamber so that the output electromagnetic coil 14 is placed inside the steel port of the chamber. Such location leads to an increase in the percentage of magnetic field lines, transporting the plasma that gets on the surface of the substrate holder.

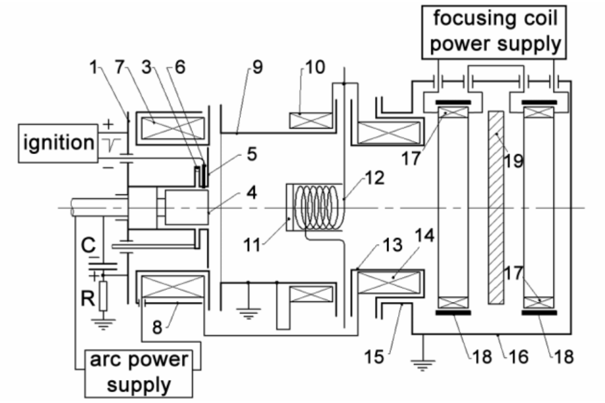

Fig. 1. Scheme of the installation with an advanced straight-line source of filtered vacuum-arc plasma

Measurements showed that the induction of magnetic field produced by the output coil is 600 G at maximum current of 200 A. With such significant design changes it was necessary to conduct research to optimize the parameters of the magnetic transportation system of vacuum-arc plasma source with a rectilinear filter, namely currents in magnetic coils and the use of additional ferromagnetic parts.

2. OPTIMIZATION OF THE TRANSPORTATION MAGNETIC SYSTEM

The elements of the transport system were optimized based on the results of computer modelling. The computer program FEMM was used to perform the calculations [9]. The calculation area included a source of vacuum-arc plasma with the MP filter and the steel vacuum chamber. The following equipment parameters were varied: currents in magnetic coils, namely anode one 10, output one 14, focusing one 17; current in coil 12 of the MI (see Fig. 1); the presence or absence of magnetic field concentrators (parts made of magnetic materials) in the calculation area.

The FEMM program allows you visualize the magnetic field lines on the coordinate plane **r**, **z** in the case of axially symmetrical coils and other structural elements (such conditions are satisfied by the equipment of the experimental setup), calculate the magnetic field induction **B** at each point of the calculation area and calculate the magnetic flux through specified surfaces.

The values of magnetic flux through the output diaphragm of the filter were calculated, as well as through the surface of the substrate holder with a diameter of 300 mm for specific combinations of equipment parameters. The results of calculations made it possible quantify the efficiency of plasma transport from the output diaphragm of the filter to the substrate holder (i. e. inside the vacuum chamber) and determine the influence of the parameters of the magnetic system components located in the chamber. As criterion for the efficiency of transportation the value of **K** was chosen, the ratio of the magnetic flux through the surface of the substrate holder with a diameter of 300 mm to that through the output diaphragm of the filter. The obtained data were compared with those calculated for the previous design of the plasma filter, in which the output electromagnetic coil is located outside the vacuum chamber.

The largest value of the coefficient of transportation efficiency for the developed structure is **K** = 0.567. In the previous design, the value of **K** did not exceed 0.422, this was achieved at maximum current of 140 A in the focusing magnetic coils (see Fig. 1). In this case, as experimental results show, the coating of uniform thickness was deposited within the plane of the circle with a diameter of 200 mm.

The use of the output coil of the developed design allows increase the efficiency of plasma transport inside the vacuum chamber from the output diaphragm of the filter to the substrate by 0.567/0.422 = 1.3 times. In addition, a more complete use of the peripheral part of the plasma flow will expand the deposition zone of the coating of equal thickness to a diameter of 300 mm. The graph in Fig. 2 shows the effect of currents in the output coil 14 and focusing one 17 on the efficiency of plasma transport.

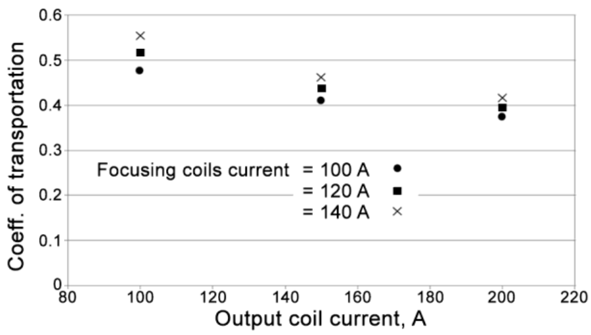

*Fig. 2. Coefficient of transport efficiency of plasma **K** inside the vacuum chamber depending on the current in the output coil 14. A magnetic concentrator is placed behind the substrate holder*

The following data allow us to estimate the magnetic concentrator effect on the value of **K**. At current in the focusing coils of 100 A: **K** = 0.449 without concentrator and 0.477 with it. That is, increase in **K** is 6%. At the current of 140 A: **K** = 0.526 without concentrator and 0.555 with it. Thus, increase in **K** is 5.4%. The magnetic concentrator plays another important role. It promotes increase in the number of magnetic field lines that get on the peripheral part of the substrate holder. This leads to increase in the plasma flow into this area, which will improve the thickness uniformity of the deposited coating at the edge of the circle zone of 300 mm diameter.

Such design changes of the output magnetic coil of the filter and its location changes affected the distribution of the magnetic field in every point of the device as a whole. Therefore, calculations and analysis of the magnetic field configuration inside the entire filter, from the cathode to the output diaphragm were performed. Among the results of calculations, according to 72 different combinations of variable parameters (currents in the coils and the presence or absence of parts made of ferromagnetic materials), we looked for such configurations of the magnetic field, the shape of which facilitates the most efficient transport of plasma from the cathode surface to the output diaphragm of the filter. According to the ideas of "plasma optics" [2], under certain conditions, the electronic and ionic components of the plasma can move together along the lines of force of the magnetic field. In ideal configuration all the magnetic field lines on their path from the cathode to the filter outlet do not interrupt on either the diaphragms of the anode or the case of the MI.

The analysis of the simulation results clearly shows the influence of the current in output coil on the magnetic configuration of the system (Figs. 3-5) and allows predict the range of currents optimal for plasma transportation. If the current is less than 20 A, all field lines from the working surface of the cathode interrupt on the diaphragms of the anode section (see Fig. 3). Here, the plasma, moving along the magnetic field lines, gets on the anode and does not pass through the filter.

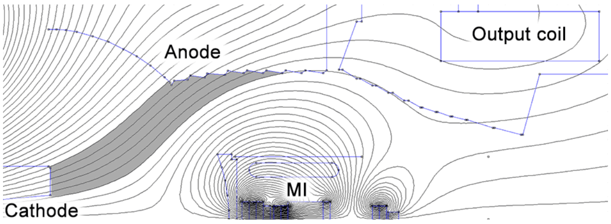

Fig. 3. Interruption of the magnetic field lines on the anode. Current in the output coil is 20 A

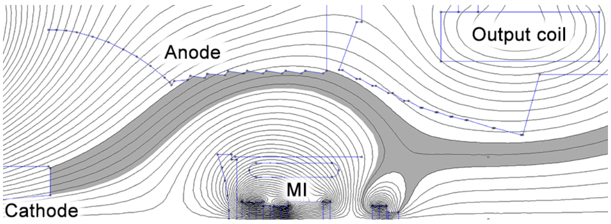

Fig. 4. Magnetic field configuration at output coil current of 80 A

As the current increases, some of the field lines that start from the working surface of the cathode pass to the vacuum chamber without touching either the anode or the MI case (see Fig. 4). Such conditions are most effective for transporting plasma through a filter. With further increase in the current of the output coil, the focusing of the plasma jet increases and the diameter of the circle within the output diaphragm of the filter, from the inner part of which the field lines get on substrate with diameter of 300 mm, decreases.

With a significant increase in the current, all field lines are shorted to the MI, and plasma jets originating from the cathode get on the case of the MI (see Fig. 5) and free plasma flow to the substrate truncates.

Only a few magnetic configurations, implemented in narrow ranges of equipment parameters, provide an unobstructed passage through the filter the field lines from a small part of the working surface of the cathode. The vast majority of magnetic field lines from the cathode surface get either on the anode diaphragms or on the case of the MI, which means that plasma on the way from cathode to out of the source should pass transversely the magnetic field lines, but it cannot be explained within the frames of plasma optics [2].

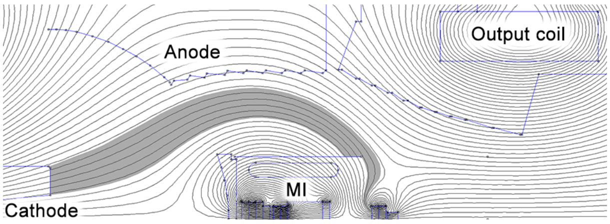

Fig. 5. Shorting the magnetic field lines on the case of the MI. Current in the output coil is 260 A

It should be noted that previously a vacuum-arc plasma source with a so-called "picket-fens" magnetic field configuration between the anode and cathode [10] was proposed and implemented. The configuration is created by input and output solenoids whose magnetic fields are opposite, resulting in a "zero **B** field" region between them. Field lines along which plasma leave the cathode oriented in the axial direction. The arc current flows through plasma jets moving along the lines of field of the input solenoid. Near the region of the "zero field" the lines bent sharply and enter the anode in the radial direction. The experiment shows that plasma passes through the region of the "zero field" and enters the lines of force of the output solenoid. The fact is not obvious from the point of view of "plasma optics", because during such transition the plasma should move transversely the field lines of transporting magnetic field.

In [11] the so-called "dome" source of plasma is presented, in the magnetic system of which there is a ring zone of weak **B** field ("x-point" zone), through which plasma is transported moving across the magnetic field lines.

The invention [6] also mentions the "Exit Null Ring" zone, which is formed between the poles of the same name of permanent magnets. Plasma follows the field lines from the cathode, around the Center Magnet, enters the "Exit Null Ring" zone transversely the field lines and then leave the source.

However, none of the publications discusses the physical mechanisms that cause such "non-classical" behaviour of plasma in the mentioned vacuum-arc sources.

The most likely cause may be the occurrence and development of plasma instabilities. Well known that non-equilibrium plasma moving in a curved magnetic field is unstable. The so-called "groove" instability leads to the movement of the plasma as a whole transversely the line of force in the direction away from the centre of curvature. This effect in devices for holding plasma (traps) in the axially symmetric "bottle-like" configuration of the magnetic field [12] leads to the expulsion of plasma onto the walls.

Instability, which negatively affects the plasma retention in the traps, plays a positive role in a rectilinear vacuum-arc plasma filter with a MI. The configuration of the filter magnetic system is such that the magnetic field lines are bent, especially strongly near the end of the magnetic island closer to the vacuum chamber. Starting from the cathode, the field line moves first in the direction of the vacuum chamber, and then bends and enters the end of the MI in almost the opposite direction. Plasma flow, which has reached a zone of significant curvature of field lines, due to instability is shifted transversely to the magnetic field line in the direction from the centre of curvature of the line, enters zone of "zero field" and further moves along the field lines of the output coil of the filter.

Indirect evidence of the proposed mechanism can be found in the literature. The process of instability proceeds in an oscillatory mode. Typical frequencies of plasma expulsion from the traps recorded in experiments [12] are of the order of tens of kilohertz. The occurrence of oscillations with frequencies of 20...80 kHz is reported by the authors of work [13], in which plasma transport through a 90-degree filter was studied. Oscillations of plasma jets with frequencies of tens of kilohertz were registered in a stationary Morozov source [14]. The experimental conditions in these references are close to those in the source under study.

Figs. 6, 7 shows the magnetic field lines and normal to them at the point of greatest curvature near the end of the MI, closer to the output diaphragm of the filter. Plasma flow, originated from cathode, is marked by shading. Due to the development of instability, plasma enters "zero field" zone. From there the plasma flow, width and average radius of localization of which depend on the magnitude of the magnetic field generated by the output coil, moves along the magnetic field lines toward the output diaphragm.

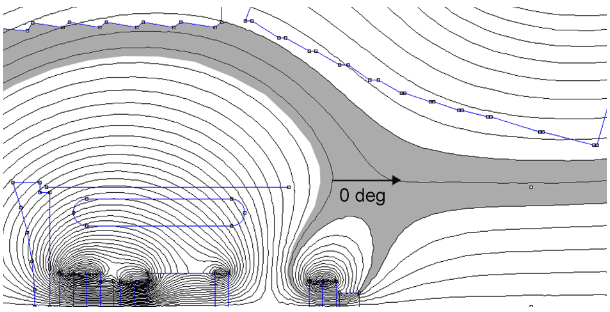

Fig. 6. Magnetic field configuration and the direction of the normal to the field line at point of its greatest curvature at output coil current of 80 A

The direction, which indicates the normal to the field line at the point of its greatest curvature and in which the displacement of the plasma flow and the movement of its centre is predicted, changes in a probabilistic way in a certain range of angles. Effective from the point of view of plasma transportation are configurations in which the angle between the direction of the flow displacement and the axis of the filter is not very large, so that as a result the plasma gets the outlet orifice of the filter.

Based on the analysis of the calculation results, we can introduce another characteristic of the filter efficiency, namely D_{useful}, the diameter of the circle within the output diaphragm of the filter, from the inner part of which plasma gets to the substrate with a diameter of 300 mm. The dependence of D_{useful} on the current in the output coil is shown in Fig. 8.

The graph shows clearly that within the current range of the output coil 40...260 A, the vacuum-arc plasma can get through the filter to the substrate with a diameter of 300 mm. As the current increases, the plasma flow is more strongly focused by the magnetic field, as a result of which the D_{useful} value decreases.

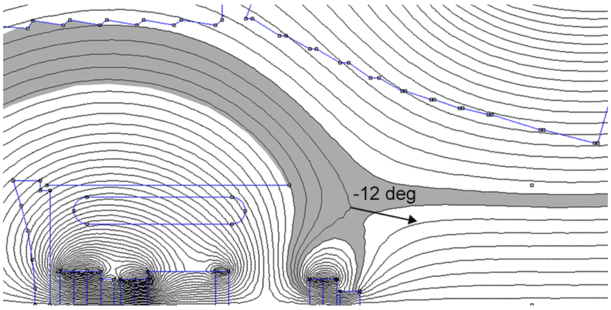

Fig. 7. Direction of the normal to the field line at point of its greatest curvature. Output coil current is 160 A

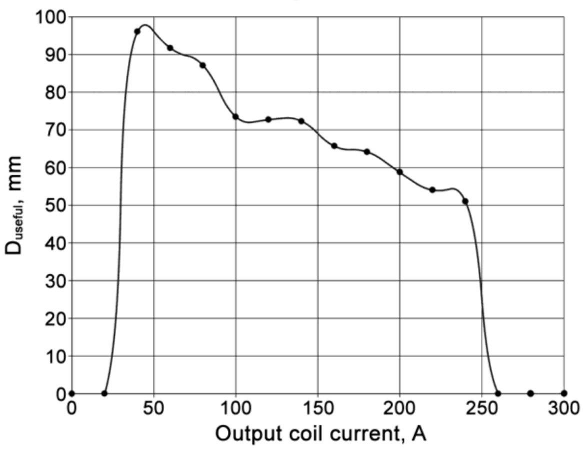

Fig. 8. Dependence of D_{useful} on the output coil current

Thus, the simulation results show that the optimal use of the cross section of the output diaphragm, which diameter is 96 mm, takes place in the output coil current range of 40...140 A at which D_{useful} = 75...96 mm (see Fig. 8).

CONCLUSIONS

Optimization of the vacuum-arc plasma source with a rectilinear filter for deposition of coatings on large size products was performed. The magnetic configuration options of the system were calculated by using the FEMM program.

Such configurations of the magnetic field were looked for, the shape of which facilitates the most efficient transport of plasma flow from the cathode surface to the output diaphragm of the filter in accordance with the "plasma optics" principles.

There were found no magnetic configurations which provide an unobstructed passage of the vacuum-arc plasma through the filter along the field lines from the whole working surface of the cathode. The vast majority of magnetic field lines from the cathode surface get either on the anode diaphragms or on the case of the MI, which means that plasma on the way from cathode to out of the source should pass transversely the magnetic field lines. We suppose the plasma instabilities cause such non-classical behaviour of the plasma flow behind the magnetic island, in the region where the magnetic field lines bent strongly.

The calculations results show the new design of the output coil of the filter be able to increase by 1.3 times the efficiency of plasma transportation to the substrate with a diameter of 300 mm. The optimal value of the output coil current is in the range of 40...140 A.

ACKNOWLEDGEMENTS

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ОПТИМИЗАЦИЯ МАГНИТНОЙ СИСТЕМЫ ВАКУУМНО-ДУГОВОГО ИСТОЧНИКА ПЛАЗМЫ С ПРЯМОЛИНЕЙНЫМ ФИЛЬТРОМ

Д.С. Аксенов, В.В. Васильев, А.А. Лучанинов, В.Е. Стрельницкий

Вакуумно-дуговой источник плазмы с прямолинейным фильтром оптимизирован для нанесения покрытий на крупногабаритные изделия. Расчеты вариантов магнитной конфигурации системы проводились с использованием программы FEMM. Новая конструкция выходной катушки фильтра позволяет в 1,3 раза увеличить эффективность транспортировки плазмы к подложке диаметром 300 мм. Особенности движения вакуумно-дуговой плазмы в прямолинейном фильтре макрочастиц с "магнитным островом" объясняются развитием плазменных неустойчивостей в областях неоднородного магнитного поля.

ОПТИМІЗАЦІЯ МАГНІТНОЇ СИСТЕМИ ВАКУУМНО-ДУГОВОГО ДЖЕРЕЛА ПЛАЗМИ З ПРЯМОЛІНІЙНИМ ФІЛЬТРОМ

Д.С. Аксьонов, В.В. Васильєв, О.А. Лучанінов, В.Є. Стрельницький

Проведено оптимізацію вакуумно-дугового джерела плазми з прямолінійним фільтром для нанесення покриттів на великогабаритні вироби. Розрахунки варіантів магнітної конфігурації системи проводилися з використанням програми FEMM. Нова конструкція вихідної котушки фільтра дозволяє в 1,3 раза збільшити ефективність транспортування плазми до підкладки діаметром 300 мм. Особливості руху вакуумно-дугової плазми в прямолінійному фільтрі макрочасток з "магнітним островом" пояснюються розвитком плазмових нестійкостей в областях неоднорідного магнітного поля.