HIGH-PRODUCTIVE SOURCE OF THE CATHODIC VACUUM-ARC PLASMA WITH THE RECTILINEAR FILTER

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The design and performance of high productive cathodic vacuum arc plasma source with rectilinear "magnetic island" filter, which is suitable for industrial applications, are briefly described. The device is characterized by achievable output ion current up to 4 A at an arc current of 100 A, Ti coating deposition rate at a distance of 150 mm from the outlet is 20 micron/hour within the circle of 180 mm diameter. In terms of productivity and quality of plasma purification from particulates the developed plasma source is superior to world analogues by 1.5...2 times.

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INTRODUCTION

The vacuum-arc method of coating deposition has received wide industrial application in almost all branches of engineering for the hardening of cutting tools and machine parts. The main drawback of the method is the generating droplet phase of the cathode spot of a vacuum arc. This leads to deterioration of the deposited coatings. A radical solution to this problem is the use of filtering systems to clean the plasma flows of droplets and particulates. However, existing filtering systems inefficient, which hampers their use in industrial applications.

Currently, in the NSC KIPT the high-performance source of cathodic vacuum arc plasma with rectilinear filter, which includes so called "magnetic island", developed and manufactured, the design suitable for industrial applications.

The magnetic island (MI) filters originate from 80-th of 20 century, when the first design was patented by KIPT inventors [1]. Plasma generated on the cathode surface propagates along the straight tube with longitudinal magnetic field like in a straight filter, but there is a shield with the magnetic structure on the axis and there is no line-of-sight between the cathode and substrate. The MI magnetic field directed opposite to that created by external coils. The resulting lines configuration allows plasma stream round the MI and pass the plasma-guide with minimal losses whereas the macroparticles trapped by the shield and walls.

In the first design there was electromagnetic coil placed inside the MI. Later the constant magnet was applied in the MI in addition to the magnetic coil for creating the same configuration of the magnetic force lines [2]. Another arrangement realized in [3] where a shield plate of non-magnetic stainless steel placed between the cathode and the substrate, and the magnetic field focused using a permanent magnet, positioned behind the substrate, that produced a field of around 300mT on the substrate. In this apparatus the deposition of TiN was studied.

Comparison of the toroidal filter and MI one in Al_2O_3 coating deposition was done in [4]. The deposition rates achieved applying the toroidal filter were a factor of 5 higher (approx. 2 $nm{\cdot}s^{-1}$) than the deposition rates with the MI, but the surface area available for homogeneous deposition was much smaller with the toroidal filter (approx. 30 mm in diameter). Initial tests for the deposition of Al_2O_3 without particle filter showed that the droplet coverage of the coated surface is close to 100%. Applying the toroidal filter and the shield/magnetic island filter, strong reductions of the droplet coverage of the coated surfaces were obtained.

The MI filters are the objects of interest to present day. The authors of [5] compared the efficiency of MI filters working with DC and pulse vacuum-arc sources. Applying the magnetic island filter it can be seen (with 500x magnification of Ti coatings) that practically no macroparticles were visible for both arcs (pulse and DC). For DC arc 125 A the measured deposition rate at distance 5,5 cm behind MI was of $r = 4.5$ nm/s at B_{ext} = 6 mT and B_{MI} = 36 mT (r =19 nm/s without MI). Here B_{ext} and B_{MI} are the values of the magnetic field created by the external coils and MI structure respectively. The 'system efficiency' of the plasma source with the magnetic island filter was not evaluated.

None design described before in the literature was industrially suitable because of low deposition rate or/and small deposition area. The goal of the present publication is brief description of the design and performance of cathodic vacuum arc plasma source with rectilinear filter, which is suitable for industrial applications.

EXPERIMENTAL DEVICE DESCRIPTION

Vacuum-arc plasma is created and transported to the substrate in a plasma-optical system with the rectilinear filter shown in Fig. 1 [6].

This system includes a cathode 1, an anode 2, and a plasma guide with electromagnetic coils encircling the aforementioned elements. The plasma guide includes two parts: the inlet part. 4 and the outlet part 5; these parts are electrically insulated from each other and from the anode. The system further includes an arc power supply source 15 and macroparticle reflectors 3. The system also includes an electromagnetic deflection coil 12 placed inside an electroconductive tube case 11 (magnetic island) coaxially placed inside the anode, electrically connected thereto, and screened on the cathode side.

In a plasma-optical system a transporting magnetic field has a constant time component which is created by two electromagnetic coils 9 and 10. Besides the transported plasma flow is exposed to additional magnetic fields, whose intensities are varied proportional to electric currents running through the follows structural elements (anode 2, magnetic island 11 and output section 5 of plasma guide) of the plasma-optical system. This is a subject of IP [6]. The additional magnetic fields inside the anode are created with an electromagnetic coil 16 encircling the anode and an electromagnetic deflection coil 12 coaxially placed inside the anode. A positive terminal of the arc power supply source is electrically connected to the anode through an electromagnetic coil 16 encircling it and connected to the case of the MI through a coil 12. Arc electric current flows through the coils. When the plasma flow approaches the surface of some structural element, the intensity of corresponding additional magnetic field is increased proportional to an intensity of the electric current running through this element.

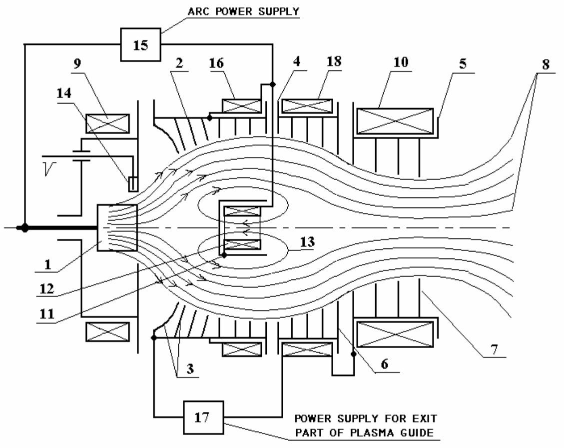

Fig. 1. Scheme of the vacuum-arc system. The arrows on the magnetic field lines indicate the direction of the magnetic field

The main parameters of the design are follows. The diameter of the cylindrical cathode is 60 mm. The inner diameter of the output flange is 180 mm. The overall length of the device is 800 mm. Arc current up to 150 A. Arc voltage drop is in the range of 30…40 V (Ti-cathode) or 40…70 V (graphite cathode). Power consume of the electromagnetic coils is less than 1.5 kW. Achievable output ion current is 4 A when an arc current is of 100 A. It is necessary to use argon for stable arc operation with graphite cathode. The physical configuration of the vacuum arc source with the MI filter is shown in Fig. 2.

TRANSPORTING AND FILTERING PROPERTIES OF THE FILTER

The magnetic field distribution in the plasma guide channel strongly influences the transport properties of the plasma-optical system. Instantaneous distribution of the magnetic field lines is shown in Fig. 1. The direction of the magnetic field created by outer coils is opposite to that of the MI coil and magnetic field lines distort. Therefore the charged components of the plasma started on the cathode surface flows along the curved magnetic field lines and pass around the case of the magnetic island, whereas the macroparticles go along straight lines and stop on the surfaces of the MI case and reflectors placed on the inner sides of the anode and plasma guide. The additional magnetic fields, created by the fraction of the arc current flow through the electromagnetic coil 16 encircling the anode and an electromagnetic deflection coil 12 coaxially placed inside the anode, adjust the radial position of the plasma stream and promote the increase in output ion current.

Fig. 2. Plasma coating setup with the vacuum arc source and MI filter

The "system efficiency" ε of the plasma source with the MI filter was evaluated using the ratio of the ion current I_i collected by a circular plate collector of 8 cm in radius, placed at the output of the filter, to the arc discharge current I_{arc}, i.e. $\varepsilon = I_i/I_{arc}$. Its value amounts to 4%, that is 1.5…2 times greater than superior world analogues. Output ion current I_i is determined by the arc current I_{arc} and magnetic system properties. The plot I_i versus I_{arc} is shown in Fig. 3. The output ion current nearly linearly grows with the arc one.

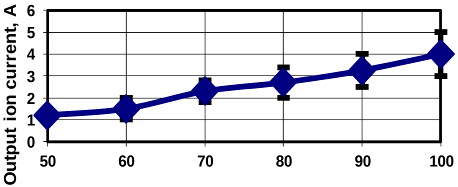

Fig. 3. Output ion current I_i versus the arc current I_{arc} (Ti-cathode)

Proper directions of currents in the magnetic coils are crucial for the system operation. Wrong commutation can cause the damage of the design. To obtain the maximum output ion current I_i value, the magnetic system should be optimized. A constant time component of the transporting magnetic field is created by two electromagnetic coils: 9 and 10. Coil 9 ("cathode coil") sets also the regime of operation of vacuum arc evaporator. The dependence of the I_i on I_9 (the current in coil 9) is shown in Fig. 4.

Quality of plasma filtration was verified by examining the surface of Ti-coating deposited on polished monocrystal Si during 30 min. The Si specimens were placed at a distance of 150 mm from the output flange of the filter. In Figs. 5a, 5b the appearance of the region (marked with the scratch) of the surface of uncoated and Ti coated specimen disposed at 50 mm from the axis is shown. The small number of the introduced defects confirms the good filtering properties of the developed device.

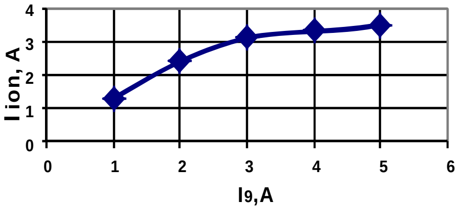

Fig. 4. Dependence of the output ion current on the current in the "cathode coil". I_{arc} = 100 A

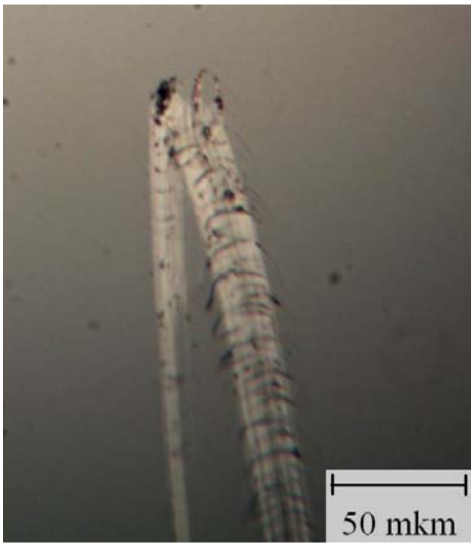

Fig. 5a. The appearance of the initial surface of Si sample with the scratched mark on it

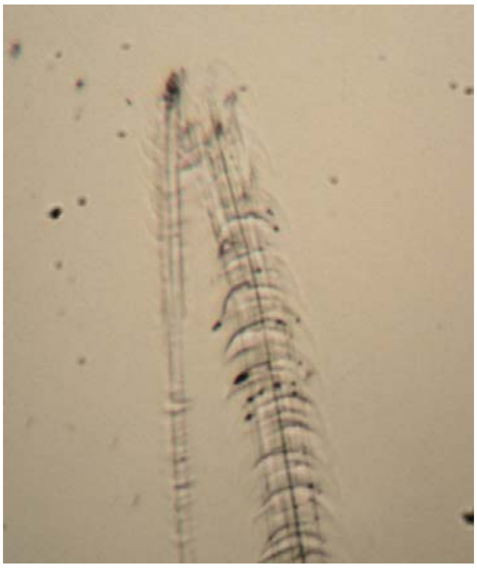

Fig. 5b. The appearance of the same region of the surface coated with Ti (30 min deposition duration)

EXAMPLES OF SOURCE USE FOR DEPOSITION THE FUNCTIONAL COATINGS

The hard nitride and DLC coatings were deposited on the setup described in [7]. Arc supply source with the open circuit voltage of 150 V was used for stable arc operation with the graphite cathode. Focusing of the plasma flow in the vacuum chamber with the additional magnetic coil placed behind the substrate ensured a high deposition rate of Ti-coatings of 20 μm/h at the arc current of 100 A, uniform over the area of ~ 18 cm in diameter. For DLC coatings the rate is of 4 μm/h at the arc current of 70 A over the same diameter (Fig. 6).

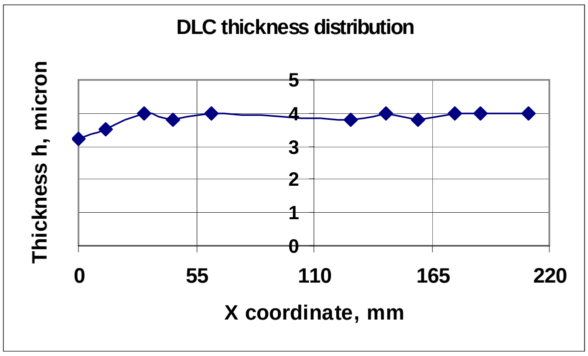

Fig. 6. Distribution of DLC film's thickness h(x). X coordinate of axis is 110 mm

The mechanical properties of the nitride TiN, TiAlN, TiAlYN coatings, manufactured by PIII&D method using new high-performance source of cathodic vacuum arc plasma with MI filter, are listed in the Table.

Mechanical properties of the nitride PIII&D coatings

Coating composition	TiN	$(Ti_{0.5}Al_{0.5})N$	$Ti_{0.5-x}Al_{0.5}Y_xN$ ($x \leq 0.01$)
Thickness, μm	7…10	5…6	5…7
Hardness, GPa	32…36	30…35	30…35
Residual stress, GPa	4…5	3…4	3…4

The erosion rate under the action of cavitation in distilled water at room temperature was studied on the facility with an ultrasonic vibrator. Cavitation durability of the produced coatings illustrates Fig. 7.

Incorporation of small amount of yttrium in PIII&D (Ti, Al)N coatings led to increase in their wear resistance. Nanostructured hard (Ti, Al)N+1 at.%Y coatings with high oxidation resistance showed the best characteristics during cavitation tests [8]. The average rate of the cavitation and abrasion wear of (Ti, Al)N + 1 at.%Y coatings is 3 to 5 times less than that of the (Ti, Al)N coating and is 10 times less than that of the TiN coating deposited under the same conditions.

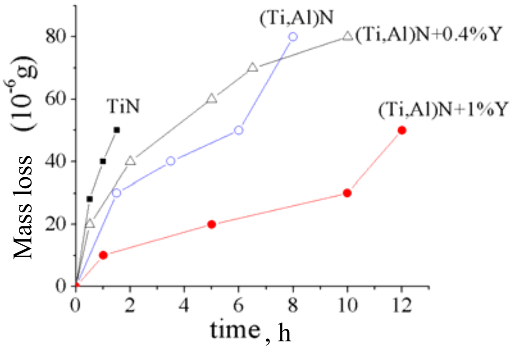

Fig. 7. Kinetic curves of cavitation wear of the stainless steel specimens with the nitride coatings of various compositions [8]

CONCLUSIONS

New high-performance source of cathodic vacuum arc plasma with “magnetic island” rectilinear filter has been developed and manufactured in the NSC KIPT, the design suitable for industrial applications. Features of the manufactured source:

– achievable output ion current up to 4 A when an arc current of 100 A;

– the diameter of the applied coating with the thickness deviation ± 5% – 180 mm;

– Ti coating deposition rate at a distance of 150 mm from the outlet – 20 micron/hour.

In terms of productivity and degree of plasma purification from particulates the developed plasma source is superior to world analogues by 1.5...2 times. The source can be used successfully for the deposition of high-quality functional coatings on various substrates.

REFERENCES

1. U.S. Pat. N 4,452,686. *Arc plasma generator and a plasma arc apparatus for treating the surfaces of work-pieces, incorporating the same arc plasma generator* / I.I. Aksenov, V.A. Belous, V.M. Khoroshikh, V.G. Padalka. 1984.
2. A. Kleiman, A. Marquez, and R.L. Boxman. Performance of a magnetic island macroparticle filter in a titanium vacuum arc // *Plasma Sources Sci. Technol.* 2008, v. 17, p. 015008.
3. H. Takikawa, M. Nagayama, R. Miyano, and T. Sakakibara. Enhancement of shielded cathodic arc deposition // *Surf. Coat. Technol.* 2003, v. 169-170, p. 49-52
4. H. Bolt, F. Koch, J.L. Rodet, D. Karpov, and S. Menzel. Al_2O_3 coatings deposited by filtered vacuum arc – characterization of high temperature properties // *Surf. Coat. Technol.* 1999, v. 116-119, p. 956-62.
5. A. Duran, M. Fazio, A. Kleiman, et al. Study of the efficiency of magnetic island macroparticle filters for different vacuum arc configurations // *Journal of Physics: Conference Series.* 2012, v. 370, p. 012016.
6. PCT patent application, WO 2012/064311 A1, 18.05.2012. *Method and device for transporting vacuum arc plasma* / V.V. Vasyliev, V.E. Strelnytskij.
7. V.A. Belous, V.V. Vasyliev, V.S. Goltvyanytsya, et al. Structure and properties of Ti-Al-Y-N coatings deposited from filtered vacuum-arc plasma // *Surface & Coatings Technology.* 2011, v. 206, p. 1720-1726.
8. V. Belous, V. Vasyliev, A. Luchaninov, et al. Cavitation and abrasion resistance of Ti-Al-Y-N coatings prepared by the PIII&D technique from filtered vacuum-arc plasma // *Surface & Coatings Technology.* 2013, v. 223, p. 68-74.

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ВЫСОКОПРОИЗВОДИТЕЛЬНЫЙ ВАКУУМНО-ДУГОВОЙ ИСТОЧНИК ПЛАЗМЫ С ПРЯМОЛИНЕЙНЫМ ФИЛЬТРОМ

В.В. Васильев, А.А. Лучанинов, В.Е. Стрельницкий

Приведено краткое описание конструкции и характеристик высокопроизводительного, пригодного для промышленного применения, вакуумно-дугового источника плазмы с прямолинейным фильтром типа «магнитный остров». Достижимый выходной ионный ток источника – 4 А при токе дуги 100 А. Скорость осаждения Ti-покрытия на расстоянии 150 мм…20 мкм/ч в пределах круга диаметром 180 мм. По производительности и качеству очистки от макрочастиц разработанное устройство превосходит мировые аналоги в 1,5…2 раза.

ВИСОКОПРОДУКТИВНЕ ВАКУУМНО-ДУГОВЕ ДЖЕРЕЛО ПЛАЗМИ З ПРЯМОЛІНІЙНИМ ФІЛЬТРОМ

В.В. Васильєв, О.А. Лучанінов, В.Є. Стрельницький

Наведено скорочений опис конструкції та характеристики високопродуктивного, придатного для промислового застосування, вакуумно-дугового джерела плазми з прямолінійним фільтром типу «магнітний острів». Досяжний вихідний іонний струм джерела – 4 А при струмі дуги 100 А. Швидкість осадження Ti-покриття на відстані 150 мм…20 мкм/год у межах кола з діаметром 180 мм. За продуктивністю та якістю очищення від макрочасток розроблений пристрій перевершує світові аналоги в 1,5…2 рази.