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Influence of the vacuum-arc source configuration and arc discharge parameters on the evolution and location of arc spots on the cathode surface

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ABSTRACT

Purpose: The paper presents investigations of the evolution, structure and location of arc spots on the cathode frontal surfaces of two types of industrial arc sources.

Design/methodology/approach: The temporal behaviour of cathode spots was recorded with the use of a fast CCD camera. The experiments were performed at four values of arc current, nine compositions of the process atmosphere N_2+C_2H_2 and three pressure ranges of the process atmosphere.

Findings: The analysis of the recorded pictures revealed the fine structure of the arc discharge for the investigated range of process conditions. Both temporal and spatial behaviour of cathode spots were different for both investigated arc sources. The correspondence between radial distributions of the cathode spots on the cathode surface and radial distribution of plasma flow elements analysed in the volume of the vacuum chamber was revealed.

Research limitations/implications: The paper show experimental methodology that can be used for the research of the specificity of cathode spots movement on the cathodes made from different materials.

Originality/value: The originality of the research presented in the paper consists in assigning overall correlation between vacuum-arc source configuration and parameters of vacuum-arc discharge – on the one hand, and space-time behaviour of the arc spots during their movement on the circular cathode surface and radial distribution of excited and ionized atoms of the cathode material in the deposition chamber – on the other.

Keywords: Thin and thick coatings; Arc evaporation; Titanium; Cathode spots behaviour

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1. Introduction

Vacuum-arc PVD technology is at present commonly used for deposition of simple and complex (gradient, multicomponent and multilayer) antiwear coatings [1-4]. Arc discharge characteristics and cathode spots localization as well as structure of generated plasma flow are determined by the magnetic field configuration in the cathode vicinity and within interelectrode area [5, 6].

The cathode spot movement is influenced by both external magnetic field created by the arc source magnetic system, and internal magnetic field created by the current that comes out of the cathode spot. According to the mechanism proposed by H.O. Schrade the cathode spots movement is stimulated by instabilities of emitted plasma flows, which undergo buckling and initiate new spots locations [7]. A. E. Robson [8] M.G. Drouet [9] and I. G. Kiesaiev [10] investigated cathode spots movement in different configurations of the magnetic field near the cathode surface. When magnetic field lines are parallel to the cathode surface the cathode spots move in the direction perpendicular to magnetic field lines. In homogeneous magnetic field, directed perpendicularly to the cathode surface the cathode spots move chaotically, while in non- homogeneous perpendicular magnetic field they move towards the area of maximum magnetic flux density. When magnetic field lines are inclined to the cathode surface at some acute angle, the direction of the cathode spots trajectories is inclined to the plane of constant magnetic induction at nearly the same angle – the so called "acute angles law" [8, 9].

Mutual locations of the cathode spots are determined by magnetic field configuration as well as by the value and the change rapidity of the arc current. At high dynamics of the arc current increase cathode spots are located most distantly from each other. I. G. Kiesaiev ascribes this phenomenon to general tendency of the cathode spots movement towards the area of maximum magnetic flux density – total magnetic inductance generated by two current channels that come out of two neighbouring cathode spots is higher outside them than in between [10].

The paper presents investigations aimed at assigning correlation between parameters of vacuum-arc discharge and space-time behaviour of the random arc spots during their movement on the cathode surface, i.e. their evolution, structure and location. The investigations were performed with two constructions of arc sources, considerably different in their ignition systems, cathode spot localization systems, cathode shapes and cathode cooling systems.

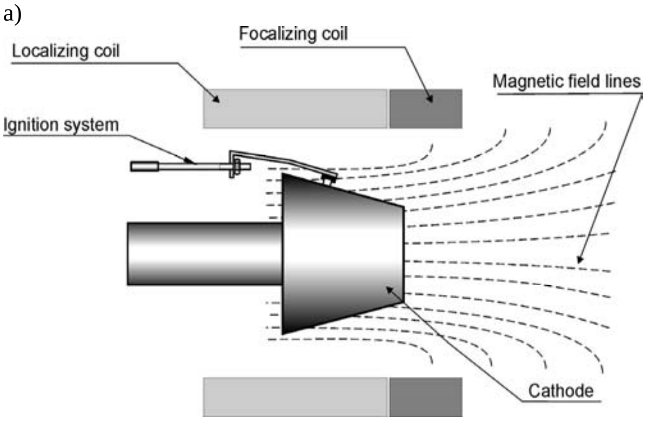
2. Experimental

The investigations were performed in two industrial multi-source vacuum-arc devices equipped with sources of significantly different constructions: nine-source device CDS manufactured by the Institute for Sustainable Technologies - National Research Institute in Radom and eight-source device MZ 383 manufactured by Metaplas Ionon, Bergisch Gladbach. Schematic diagrams of both sources are presented in Fig. 1 and their main technical parameters are given in Table 1.

Table 1.
Parameters of investigated arc sources CDS and MZ 383

Parameter	CDS source	MZ 383 source
Cathode material	Ti	Ti
Cathode diameter (mm)	79	63
Cathode thickness (mm)	35	33
Magnetic induction at the cathode surface (mT)	7 - 12	3
Arc current (A)	45, 60, 80, 100	45, 60, 80, 100

a)



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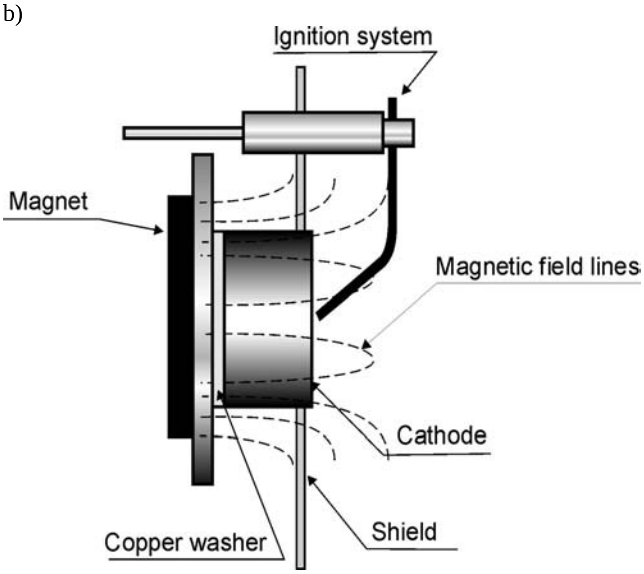


Fig. 1. Schematic diagrams of investigated arc sources: a) the source of the CDS device; b) the source of the MZ 383 device

The first investigated arc source was equipped with a high-voltage discharge ignition system and a directly cooled cathode in the shape of a truncated cone. The discharge, which was ignited at the lateral inclined cathode surface, was localized on the cathode frontal surface by a double-coil magnetic system utilizing Robson's acute angles law. Two coils created strong axial magnetic field. The second investigated source was equipped with a mechanical discharge ignition system and an indirectly cooled cathode in the shape of a cylinder. The discharge was ignited at the cathode frontal surface, by touching it with a molybdenum starting electrode, and was localized by electrostatic shield. Localization of the discharge was supported by a weak axial magnetic field created by a permanent magnet.

The investigations of the arc discharge changes on the cathodes of both sources were carried out with the use of fast CCD video camera SVS084-F manufactured by SVS-Vistek (Germany) with software Video Acquisition System manufactured by Hard Soft Kraków. The camera was equipped with the objective TV Zoom Lens manufactured by Computar (Japan). The applied recording parameters are given in Table 2. The investigations of the cathode spots structure and locations were performed at the same process parameters as applied earlier in the investigations of spatial distribution of plasma flow elements inside the deposition chamber [11]. The distribution of the cathode spots location was analysed in seven concentric circular zones of equal width fixed at the cathode surface. This enabled authors to correlate the spatial structure of arc discharge at the cathode surface with determined spatial structure of plasma flow within the deposition chamber [11].

Table 2.
Recording parameters

Recording parameters	
Focal distance	50 mm
Distance from the objective to the cathode	1.5 m
Exposure time	21 µs / 10505 µs
Number of frames in one sequence	100
Duration of one sequence	4 sec.

Table 3.
Experimental conditions of investigated processes of arc evaporation

Arc current [A]	Atmosphere pressure [mbar]	Atmosphere composition	BIAS [V]
45, 60, 80, 100	1.0×10^{-4}	100% Ar	–200
	1.2×10^{-2}	100% N_2	
	2.0×10^{-3}	70% N_2 + 30% C_2H_2	
		100% C_2H_2	
	8.0×10^{-3}	95% N_2 + 5% C_2H_2 + Ar	
		90% N_2 + 10% C_2H_2 + Ar	
		85% N_2 + 15% C_2H_2 + Ar	
		80% N_2 + 20% C_2H_2 + Ar	
		75% N_2 + 25% C_2H_2 + Ar	

The four-second sequences of 100 frames recorded at two exposure times (21 µs and 10505 µs) were analysed frame by frame for each of 36 sets of experimental conditions (Table 3). The applied analysing procedure enabled to determine:

- cathode spots multiplicity – the number of cathode spots recorded on each frame,
- quantitative (percentage) share of cathode spots of specific multiplicity – total number (percentage) of frames in each sequence with the same recorded number of spots,
- radial distribution of cathode spots location on the cathode surface – the total number of frames in each sequence with cathode spots located in individual concentric zones of equal width determined on the cathode frontal surfaces (N = 1 – zone at the cathode edge, N = 7 – zone at the cathode axis).

3. Results and discussion

Structures of arc discharge operating on titanium cathodes, typical for investigated sources, recorded at different exposure times in the same process conditions (I_{ARC} = 100 A, p = 8.0×10^{-3} mbar, 90%N_2 + 10%C_2H_2) are shown in Fig. 2. At the exposure times applied in the experiments (21 µs and 10505 µs) cathode spots of the Type 2 [5] were recorded (with average lifetime of 0.5 – 1.5 ms).

In the CDS source the discharge ignition takes place on the cathode lateral surface and under the influence of axial magnetic field cathode spots are pushed towards the cathode frontal surface. The cathode spot traces have a tree-like form and are localized within a relatively narrow area moving around the cathode surface (Fig. 2a), but multiple spots occurring at high arc currents are distinctly separated from each other (Fig. 2b). In the MZ 383 source arc ignition occurs in the place where the starting electrode strikes on the cathode frontal surface, and then under the influence of magnetron-like shaped magnetic field cathode spot traces are stretched circularly around the cathode (Fig. 2c). The occurrence of the magnetic field component parallel to the cathode surface causes that the discharge traces cover bigger cathode surface in comparison to the CDS source. However, because of lower magnetic inductance value and its magnetron-like configuration multiple spots are concentrated close to each other (Fig. 2d). Five types of the cathode spot arrangements were identified in both sources - from single- to quintuple-spot systems. At low arc currents (I_{ARC} = 45 A), comparable to the critical value defined for titanium cathodes as 30 - 70 A [12, 13], single cathode spots were observed. Increase of discharge current caused increase of cathode spots multiplicity to quintuple spots at 100 A. However the discharge structure, in terms of the number of simultaneously existing cathode spots, was unstable – the multiplicity of cathode spots was changing dynamically even at constant discharge conditions.

The influence of the process atmosphere composition on the multiplicity and space-time structure of cathode spots is discussed in detail in three following paragraphs.

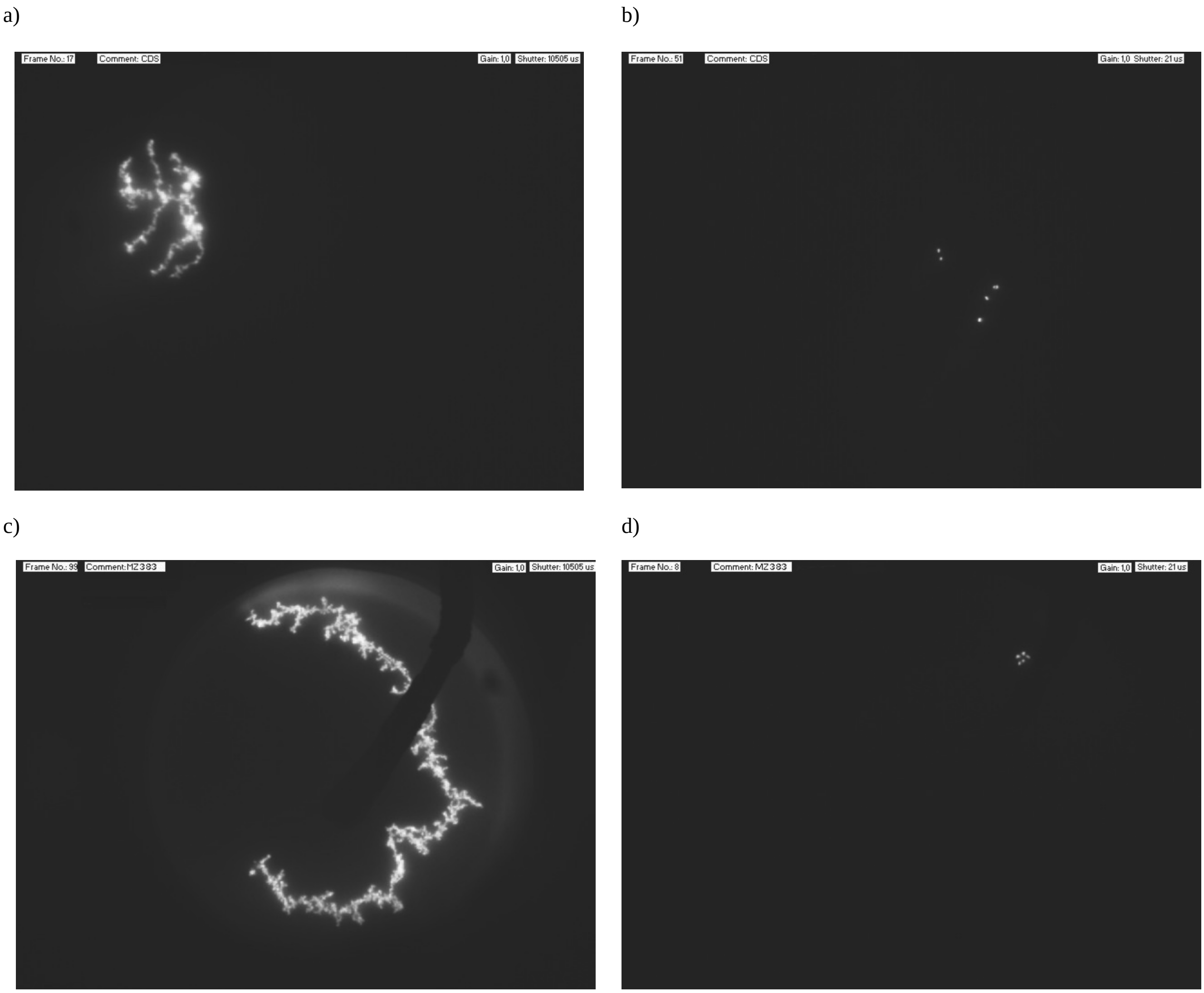


Fig. 2. Structures of arc discharge operating on titanium cathodes recorded at different exposure times: a) CDS source - 10505 μs, b) CDS source - 21 μs, c) MZ 383 source - 10505 μs, d) MZ 383 source - 21 μs

3.1. Influence of the process atmosphere composition on the cathode spots multiplicity

Strong influence of the process atmosphere chemical composition on the multiplicity of cathode spots was observed for the CDS source. As it can be seen in Fig. 3a in processes carried out at arc current of 100 A for acetylene amount of 10 – 20% in N_2+C_2H_2 mixture anomalous change of cathode spot multiplicities occurs. For this range of the process atmosphere composition local increase in the number of single and double cathode spots, at the expense of number of spots of the highest multiplicities, is clearly visible. Local extrema, however not so distinct, are also visible for the same range of gas composition in the discharge structure behaviour revealed in the MZ 383 source (Fig. 3b).

The changes in the cathode spot multiplicities observed with increasing amount of acetylene in $N_2 + C_2H_2$ mixture seem to confirm special properties of atmospheres composed of nitrogen and hydrogen-containing gas in plasma enhanced reactive processes of surface engineering. Such special properties were also revealed in investigations of crystallization conditions of $Ti(C_x,N_{1-x})$ coatings in the large-scale multi-source arc device [11] and in investigations of plasma nitriding processes [14].

3.2. Temporal stability of the arc discharge structure

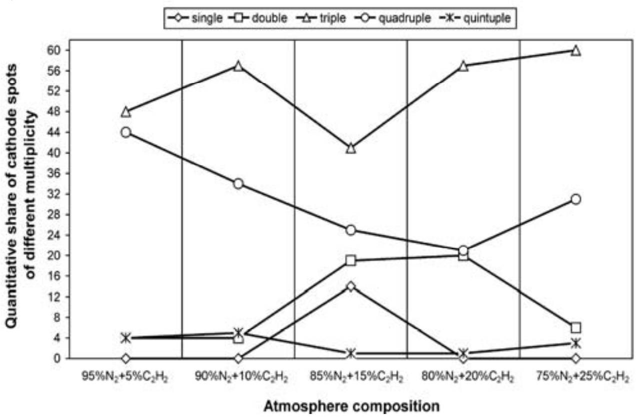
Temporal stability of the arc discharge structure in argon atmosphere under high vacuum and in $N_2 + C_2H_2$ mixture under pressure typical for deposition processes of Ti(C,N) coatings is shown for both sources in Fig. 4.

In the CDS source at low pressure of argon atmosphere ($p = 1.0{\times}10^{-4}$ mbar) discharge is very stable in terms of cathode spots multiplicity – for most of the recorded time period distinct domination of triple cathode spots is visible (Fig. 4a). Double and quadruple spots appear only temporarily. In reactive atmosphere 90% N_2 + 10% C_2H_2 at the pressure of $p = 8.0{\times}10^{-3}$ mbar the stability of the discharge structure is lower – continuous changes of the cathode spots multiplicity from double to triple and vice versa take place. Other multiplicities appear only incidentally (Fig. 4b).

The stability of the arc discharge structure observed in the MZ 383 source in both atmospheres is lower than in the CDS source (Figs. 4c and 4d). In both processes the cathode spots multiplicities change continuously: triple – double in high vacuum argon atmosphere, and in a very wide range single – quintuple in reactive atmosphere at $p = 8.0{\times}10^{-3}$ mbar.

On the basis of carried out analysis of the arc discharge structure one may say that in general the cathode spots multiplicity in the investigated sources changes with increased arc current according to the diagram developed by B. E. Diakov and R. Holmes [15], however maximum multiplicities are much higher than those pointed out by the diagram. The ranges of cathode spots multiplicity changes, at fixed process parameters, are also higher.

a)



b)

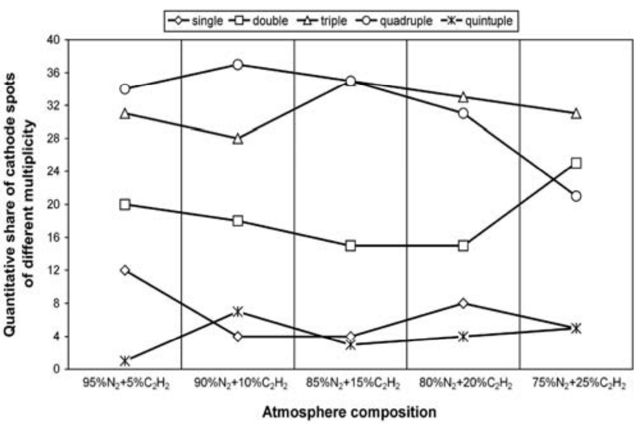
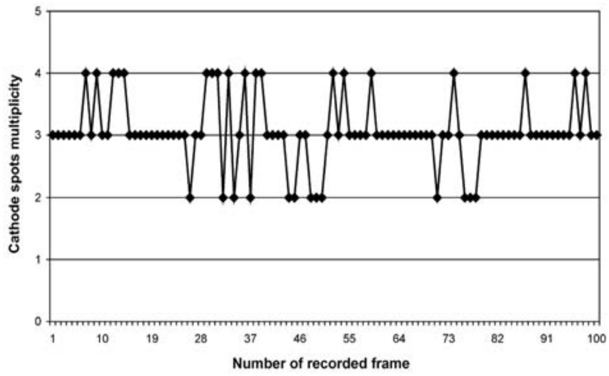


Fig. 3. Influence of the process atmosphere composition on the cathode spots multiplicity at arc current of 100 A and atmosphere pressure of $8{,}0{\times}10^{-3}$mbar: a) in the source of the CDS device, b) in the source of the MZ 383 device

a)



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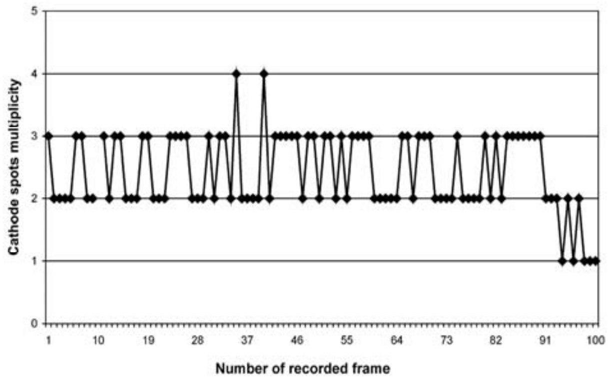


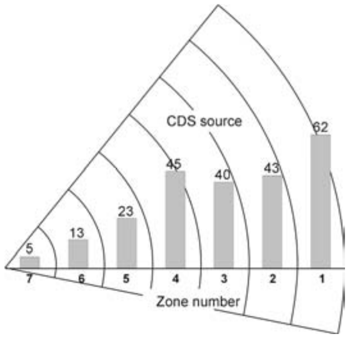
Fig. 4.Temporal stability of the arc discharge structure: a) CDS source: 100% Ar, $p = 1.0{\times}10^{-4}$ mbar, I = 100 A, b) CDS source: 90% N_2 + 10% C_2H_2, $p = 8.0{\times}10^{-3}$ mbar, I = 80 A, c) MZ 383 source: 100% Ar, $p = 1.0{\times}10^{-4}$ mbar, I = 100 A, d) MZ 383 source: 90% N_2 + 10% C_2H_2, $p = 8.0{\times}10^{-3}$ mbar, I = 80 A

3.3. Radial distributions of cathode spots locations

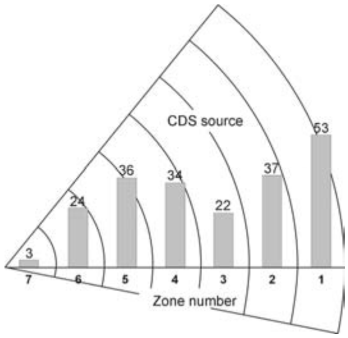
Radial distributions of cathode spots on the cathodes of the CDS and MZ 383 sources are shown in Fig. 5.

The shape of radial distribution of cathode spots locations reconstructed on the cathode of the CDS source for discharge operating in high vacuum of the order of 10^{-4} mbar at arc current of 80 A (Fig. 5a) points to occurrence of two privileged areas of the arc residing – in the edge (N = 1) and middle (N = 4) zones of the cathode. Such distribution of the cathode spots location corresponds to radial distribution of titanium emitters concentration reconstructed within the deposition chamber for the same process conditions [11]. This correlation confirms the hypothesis formulated on the basis of spectral investigation results about dominating role of electrons emitted from cathode spots in the processes of excitation and ionization of titanium atoms evaporated in such conditions. In the conditions of deposition process, i.e. in reactive nitrogen atmosphere at the pressure of $1.2{\times}10^{-2}$ mbar, the shape of radial distribution of cathode spots location is retained (Fig. 5b).

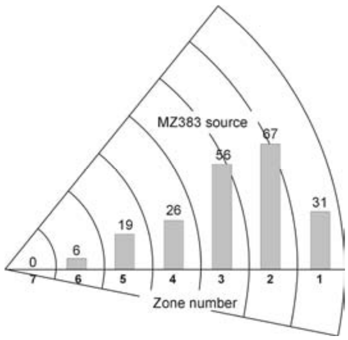
a)



b)



c)



d)

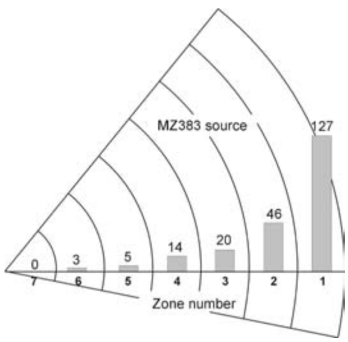


Fig. 5. Radial distributions of cathode spots locations: a) CDS source: 100% Ar, p = 1.0×10^{-4} mbar, I = 80 A, b) CDS source: 100% N_2, p = 1.2×10^{-2} mbar, I = 80 A, c) MZ 383 source: 100% Ar, p = 1.0×10^{-4} mbar, I = 80 A, d) MZ 383 source: 100% N_2, p = 1.2×10^{-2} mbar, I = 80 A

Radial distributions of the cathode spots location reconstructed for the MZ 383 source differ significantly from those reconstructed for the CDS source. In both analysed processes one maximum of the cathode spots location occurred in the edge zone of the cathode (Fig. 5b and 5d). Such shape of the cathode spots location is caused by magnetron-like configuration of the magnetic field, which forces the cathode spots to move circularly around the cathode centre. The lack of the spots in the axial zone (N = 7) of the cathode in both processes confirms such statement.

4. Conclusions

- The configuration of the magnetic field at the cathode surface and the value of magnetic inductance determine first of all the shape of cathode spots trajectories and their mutual locations. In strong axial magnetic field cathode spot traces are localized within a relatively narrow area moving around the cathode surface, but multiple spots are distinctly separated from each other. In weak magnetic field of "magnetron" configuration discharge traces are stretched circularly around the cathode, however multiple spots are concentrated close to each other.
- Also radial distribution of the cathode spots locations and temporal stability of the discharge is strongly influenced by the magnetic field parameters. Better temporal stability of the discharge was observed for the source with strong axial magnetic field. In such conditions cathode spots are located mainly in two zones of the cathode frontal surface, the configuration of which correspond to radial distribution of titanium excited and ionized atoms in the deposition chamber, reconstructed by the authors for CDS source [11]. This observation confirms hypothesis about occurrence of two zones of electron emission at the cathode surface in such sources.
- The cathode spots multiplicity distribution is distinctly influenced by the process atmosphere composition. In reactive atmospheres, especially those composed of nitrogen and hydrogen-containing gas, the temporal stability of the multiplicity distribution is lower than in inert atmosphere. Stronger influence was observed for the arc source with weak magnetron-like magnetic field.

Acknowledgements

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