EFRE 2020 | 7th International Congress on ENERGY FLUXES AND RADIATION EFFECTS — ONLINE

C1-O-054401

BEAM-PLASMA FORMATIONS IN A HOLLOW CATHODE OF A NON-SELF-SUSTAINED GLOW DISCHARGE FOR TECHNOLOGICAL APPLICATIONS

Vladimir V. Denisov, N.N. Koval, Yu.A. Denisova, E.V. Ostroverkhov, S.S. Kovalsky, V.V. Yakovlev

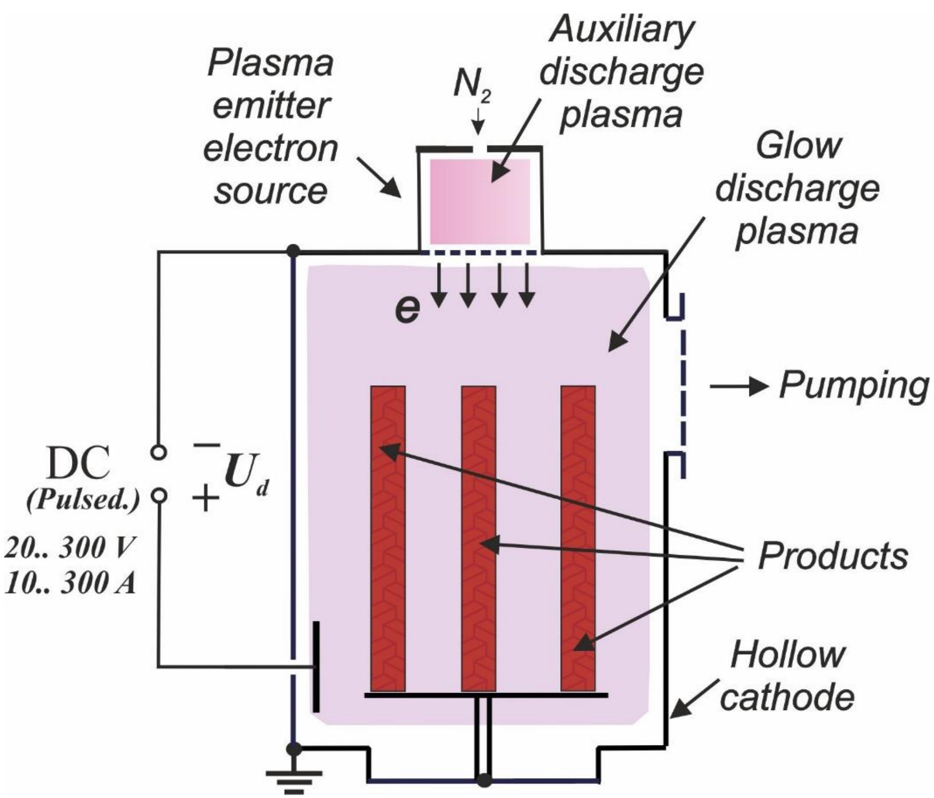
Laboratory of Beam-Plasma Surface Engineering

Institute of High Current Electronics
Siberian Branch of Russian Academy of Sciences

Presentation plan

1. Beam-plasma formations in a high-current non-self-sustained low-pressure glow discharge with a hollow cathode. Main features.
2. Generation of gas beam-plasma formations at low pressure for nitriding of steels.
3. Generation of gas-metal beam-plasma formations for plasma-assisted coating deposition.
4. Electron plasma emitters based on beam-plasma formations generated in low-pressure high-current glow discharge.

Generation of Beam-Plasma formations in a low-pressure non-self-sustained glow discharge with hollow cathode for surface treatment



Self-sustained hollow-cathode glow discharge:
Metel A. S., *Sov. Tech. Phys.*, 29, No.2, 141–144 (1984)

Non-self-sustained hollow-cathode glow discharge:
A.V. Vizir, E.M. Oks, P.M. Schanin, G.Yu. Yushkov, *Technical Physics*, 42, No. 6, 611 (1997)

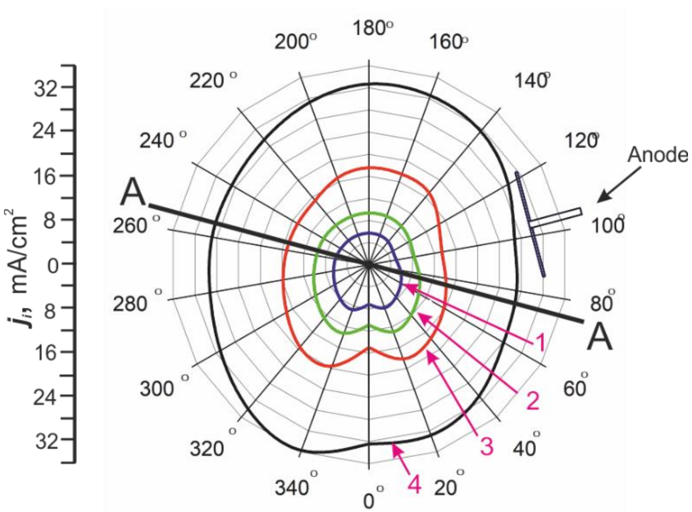
Pulsed high-current non-self-sustained hollow-cathode glow discharge:
Denisov V.V. et al., *Phys. Plasmas*, V.26, 123510 (2019).

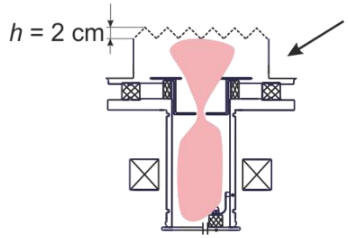
Beam-plasma formation (BPF) is a plasma medium generating firstly by using an electrode system providing discharge self-maintenance in a certain range of operating parameters or discharge burning. Secondly, it is necessary to inject a beam of charged particles, for example electrons, into the discharge system, which is significantly changes the characteristics of the discharge and plasma parameters and its composition and moreover, the beam initiates additional plasma interactions near the substrate and makes physical and chemical impact on the substrate surface.

Features of a beam-plasma formation in such type of discharge:

- Possibility of plasma generation in a wide range of concentrations (10^9 - 10^{12}) cm^{-3};
- Independent adjustment of all operating parameters (pressure, burning voltage, discharge current, etc.);
- Generation of gas-metal plasma for plasma-assisted deposition;
- The ability to activate physico-chemical processes on the surface of materials due to the flow of electrons on it.

Inhomogeneity problem: influence of plasma density on inhomogeneity degree

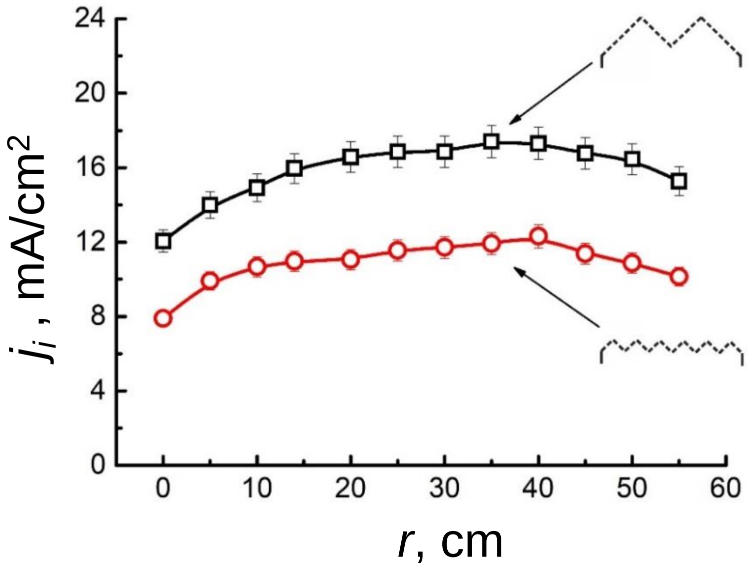




Azimuthal distributions ion current density at $p(N_2)$ = 0,65 Pa, U_d = 182 V :

1 – I_d = 75 A, (k_{inh} = 41 %);
2 – I_d = 120 A, (k_{inh} = 35 %);
3 – I_d = 180 A, (k_{inh} = 26 %);
4 – I_d = 240 A, (k_{inh} = 21 %).

Multy wedge grid emission electrode



Radial distribution of ion current density at: $p(N_2)$ = 0,65 Pa, U_d = 182 V , I_d = 90 A, (k_{inh} = 27%).

We have relatively high degree of plasma ionization:

$$n_e/n_a \approx 1\ \%$$

$$n_i\sigma_{ei} \geq n_a\sigma_{ea}$$

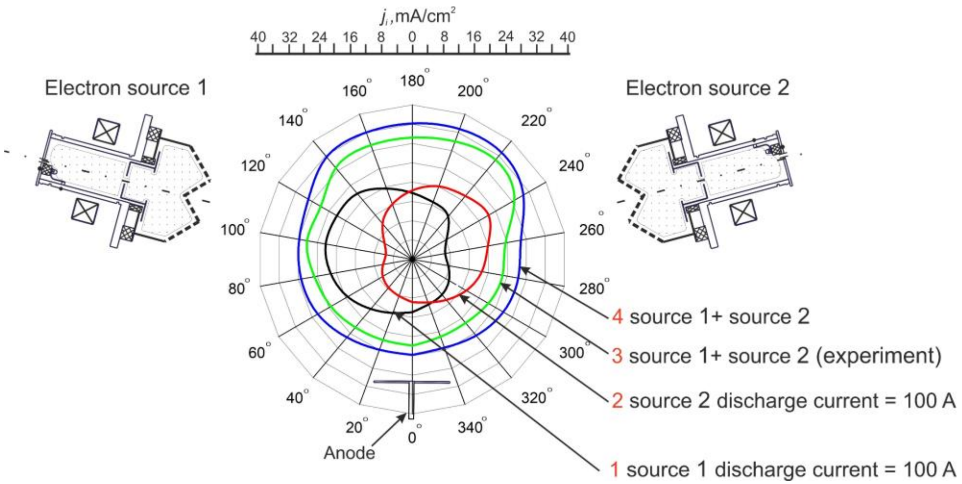
$$\lambda_{ei} \leq \lambda_{ea}$$

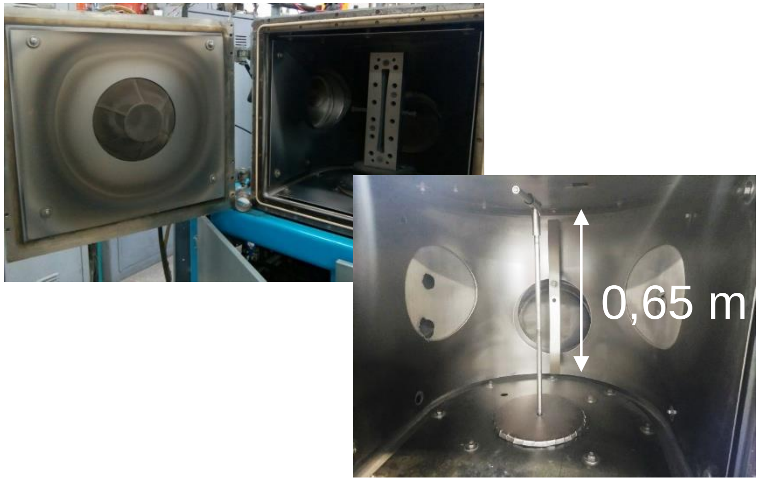
The number of Coulomb interactions is large.

As the glow discharge current increases from 60 A to 240 A, the average ion current density increases 6 times, and the maximum deviation from the average value increases 3 times (from 2.7 mA / cm2 to 6 mA / cm2), which leads to a decrease in the coefficient heterogeneity of distribution 2 times.

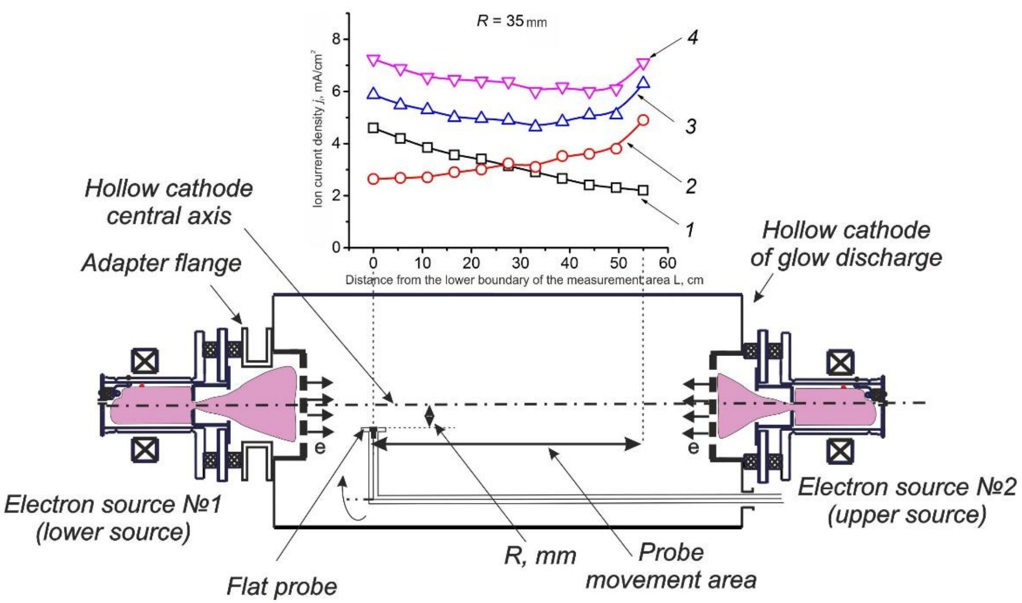
Addition of plasma concentration distributions according to the superposition principle

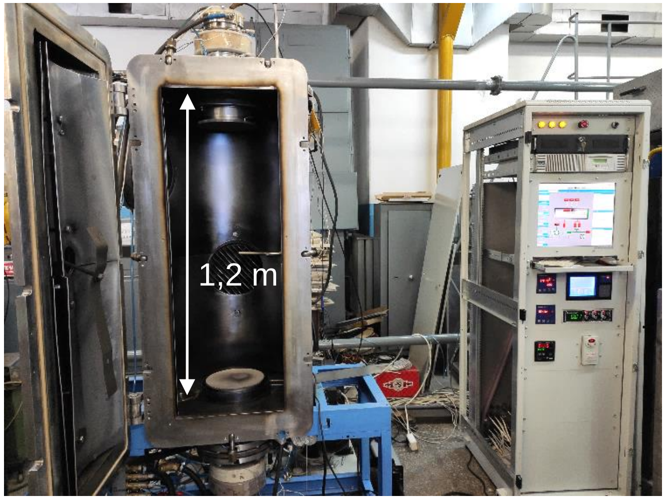
Hollow cathode: Diameter / height ≈ 1:1, $p(N_2)$ = 0,65 Pa, U_d = 180 V, I_d = 200 A.



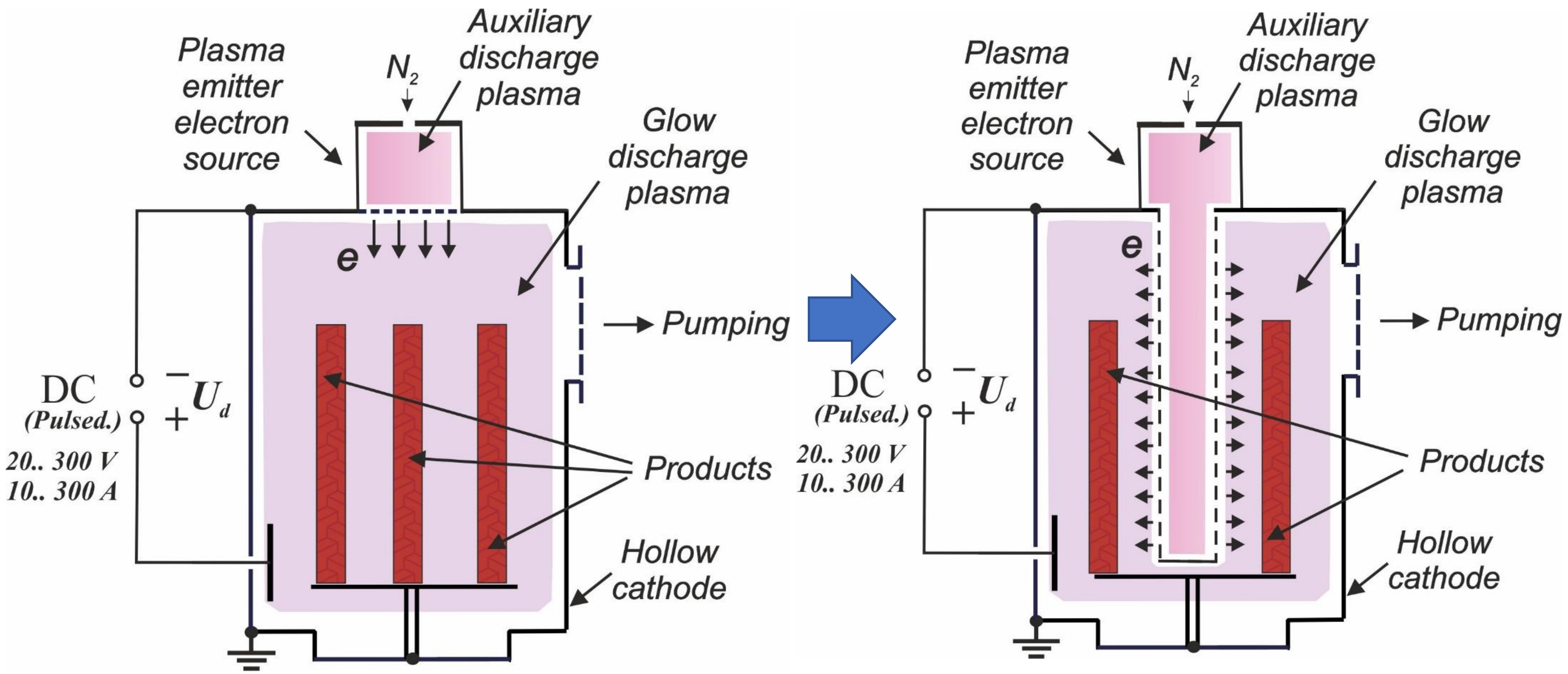


Hollow cathode: Diameter / height ≈ 1:2, $p(N_2)$ = 0,65 Pa, U_d = 180 V, I_d = 200 A.



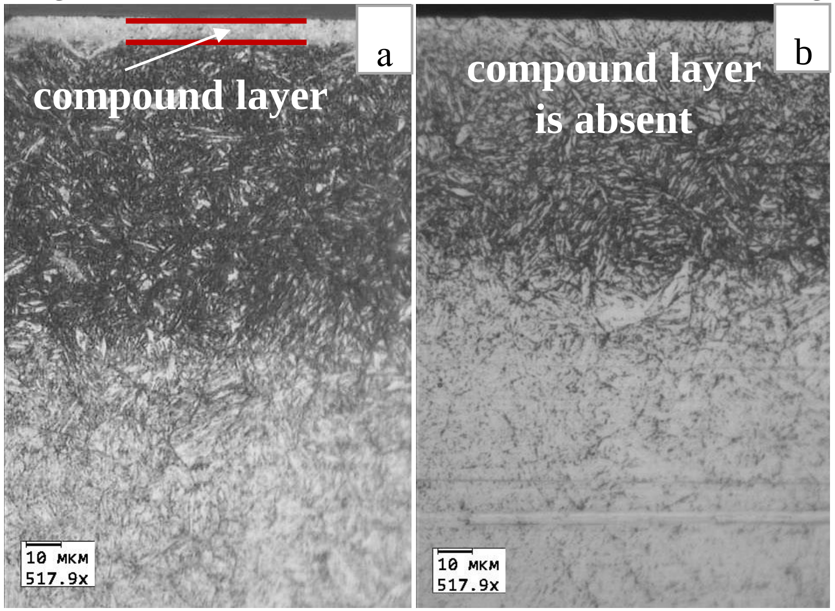


Generation of Beam-Plasma formations in low-pressure non-self-sustained glow discharge with hollow cathode for surface treatment



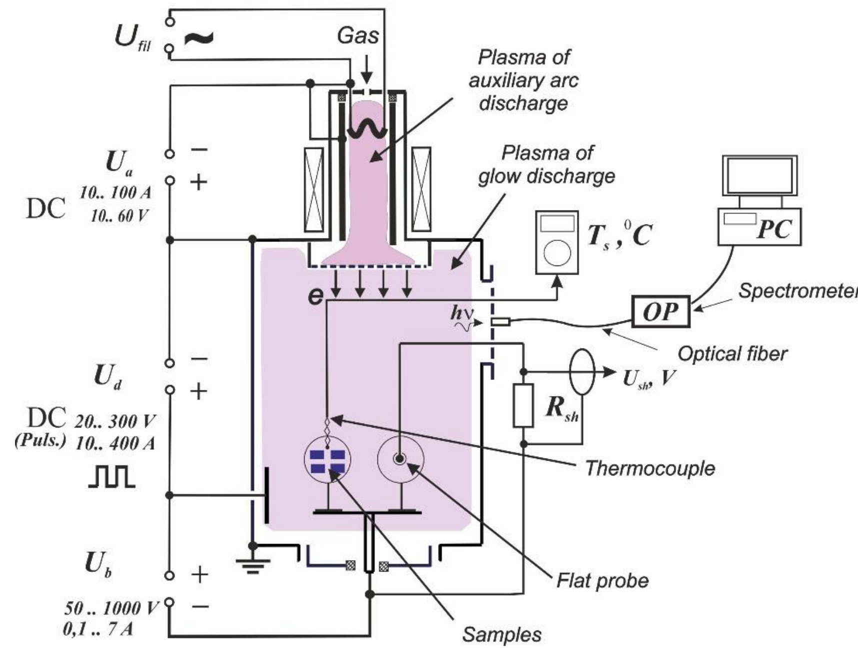
Increase of the wear resistance of the surface of 4Cr5MoVSi and Cr12WV die steels after ion nitriding

Images of the microstructure of steel 4Cr5MoVSi after nitriding

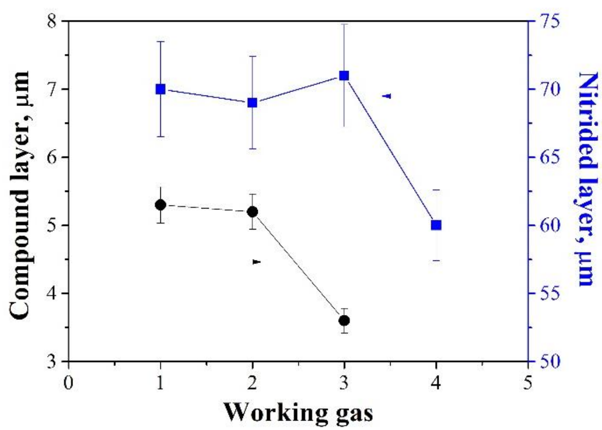


N_2 (100%) N_2 (10%)+Ar (90%)

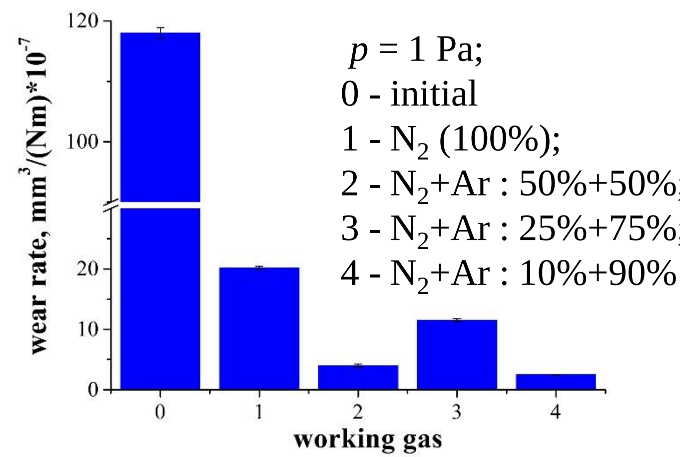
Experimental setup



Thickness of nitride and nitrided layers,
steel formed as a result of nitriding of Cr12MoV

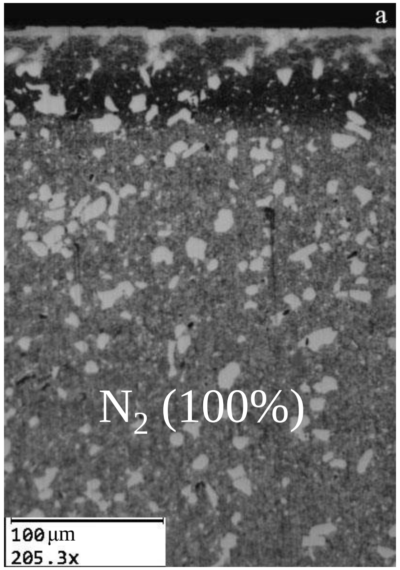


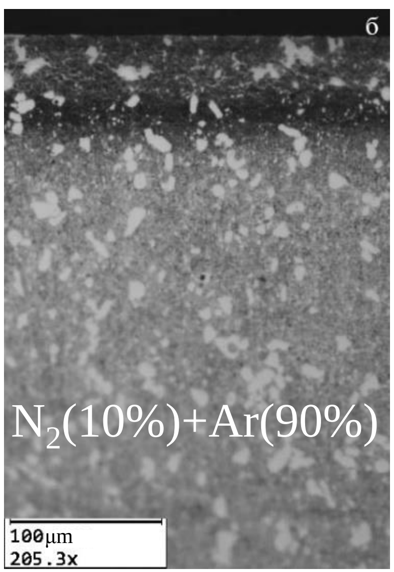
Wear rate of Cr12MoV steel



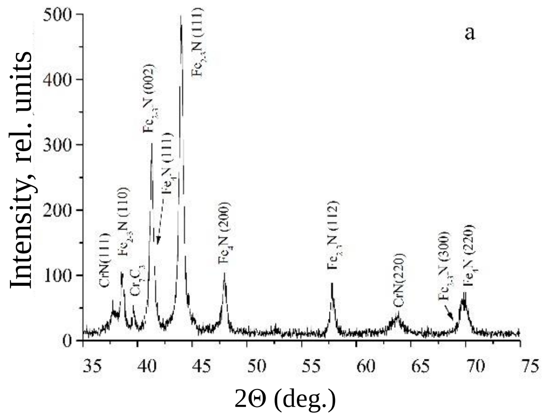
Regularities of change of structure, composition, physical and mechanical properties of modified layer of steels Cr6WV and Cr12MoV

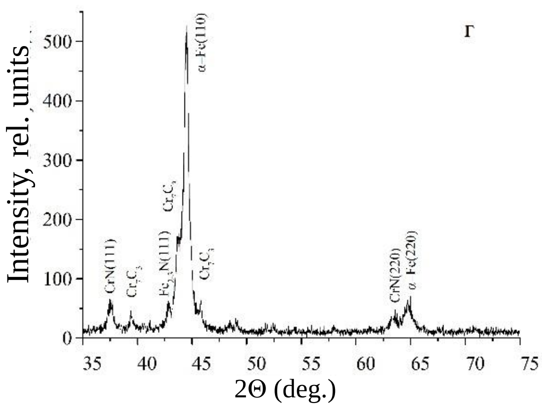
Microstructure image steel Cr6VW after nitriding





X-ray diffraction areas steel samples of Cr12MoV steel

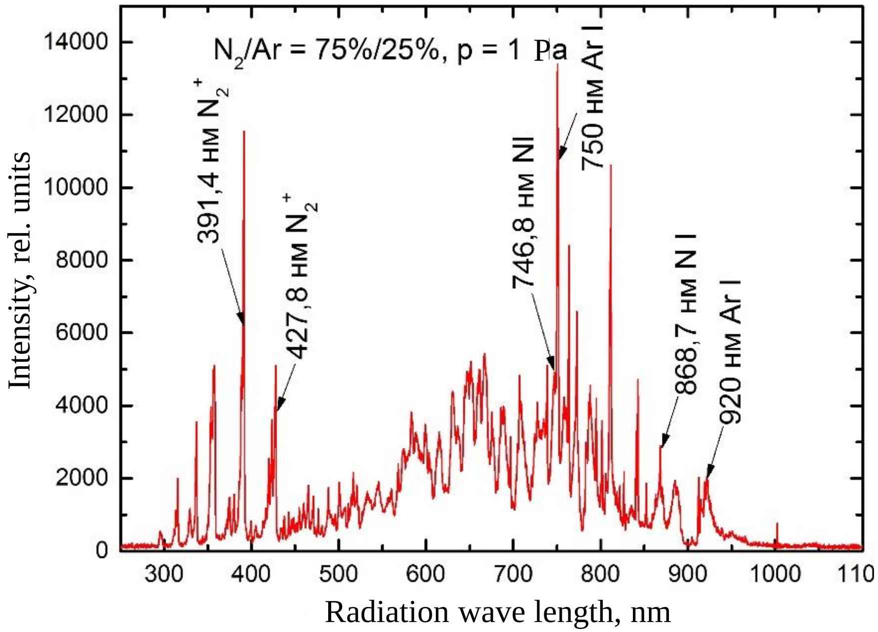


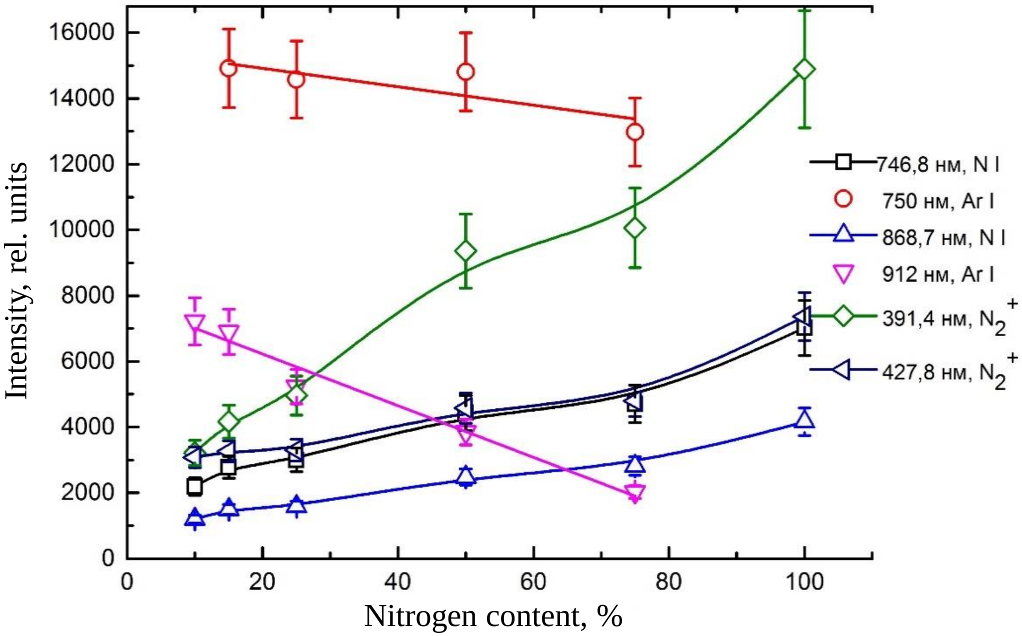


Phase composition of steel Cr12MoV after nitriding at different ratios of argon and nitrogen in the gas mixture

Gas mixture	Phase	Phase content, mas %
N_2 (100%)	ε-$Fe_{2-3}N$	43
	γ-Fe_4N	20
	CrN	19
	Cr_7C_3	16
	$Cr_{23}C_6$	2
N_2 (50%)+Ar (50%)	ε-$Fe_{2-3}N$	42
	γ-Fe_4N	23
	CrN	18
	Cr_7C_3	16
	$Cr_{23}C_6$	1
N_2 (25%)+Ar (75%)	ε-$Fe_{2-3}N$	43
	γ-Fe_4N	37
	CrN	19
	Cr_7C_3	1
N_2 (10%)+Ar (90%)	α-Fe	66
	ε-$Fe_{2-3}N$	2
	CrN	12
	Cr_7C_3	20

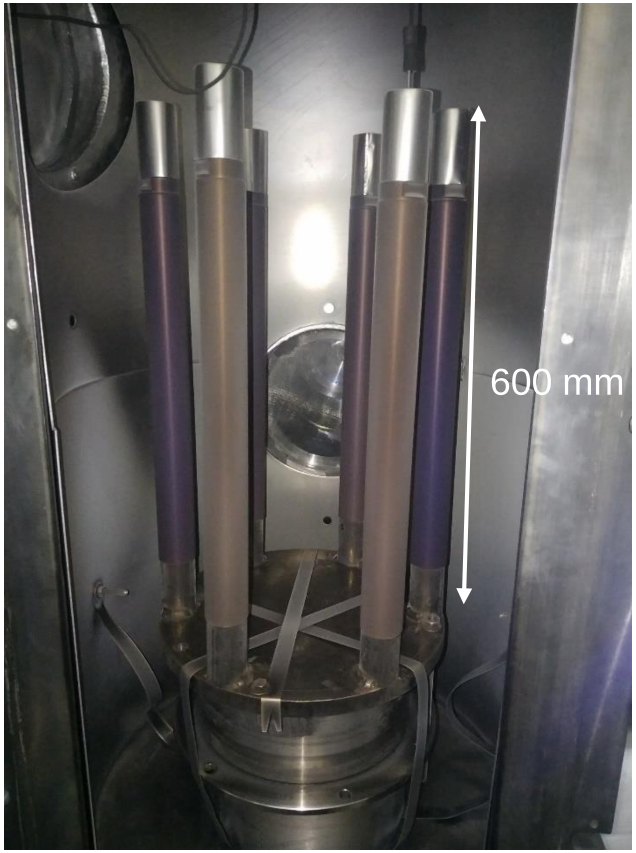
Dynamics of change of nitrogen emission intensity in nitrogen-argon mixture at change of nitrogen partial pressure



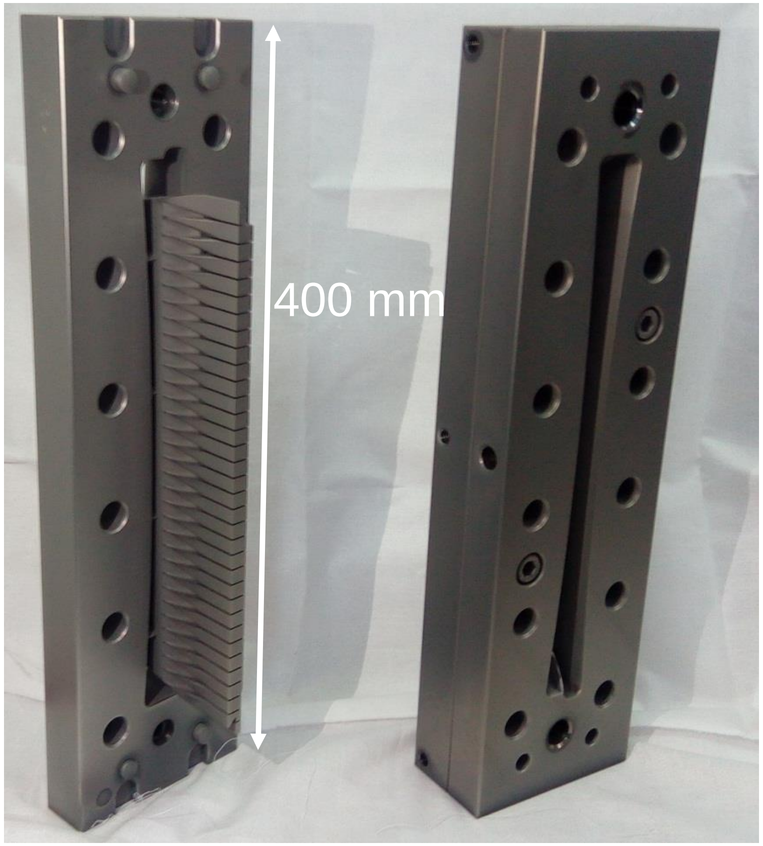


The obtained spectra show that when the nitrogen content in the nitrogen-argon mixture of gases decreases from 100% to 10%, the intensity of radiation of ions and excited nitrogen states drops by 3-5 times, proportionally reducing the saturation capacity of the plasma medium. An important channel of molecular nitrogen withdrawal is resonance recharging reactions on argon atoms. The practical value of these results is that using the obtained relationships, it is possible, by varying the content of ions and excited states of nitrogen, to change the phase composition and physical and mechanical characteristics of the steel surface.

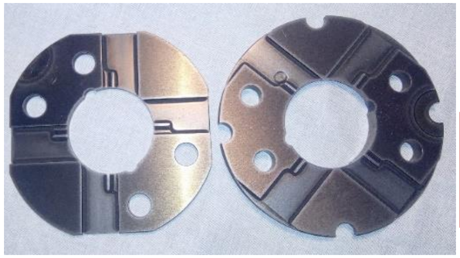
Nitriding of stamping tools low-pressure glow discharge plasma



Punches



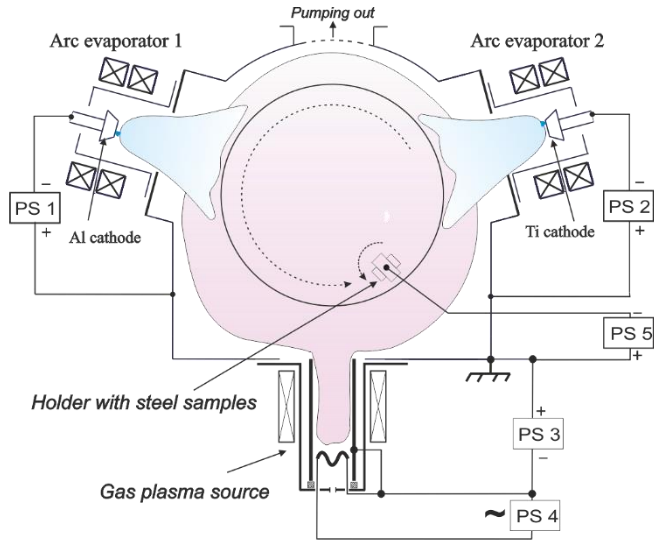
Photograph of dies nitrided in a plasma of a non-self-sustaining glow discharge



Stamps for molding of plastic parts

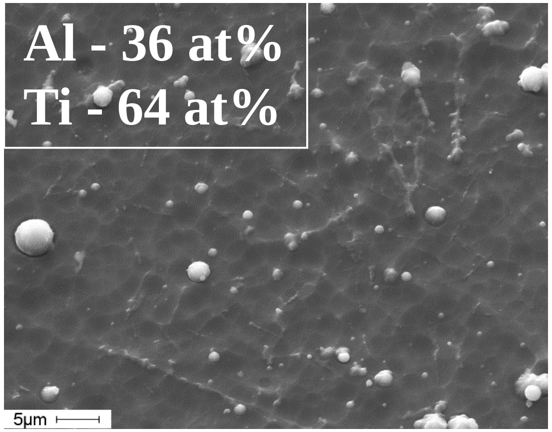
Plasma-assisted deposition of Ti-Al / Ti-Al-N 8-layer film in beam-plasma formation of non-self-sustained hollow cathode glow discharge

Traditional scheme of plasma-assisted deposition:

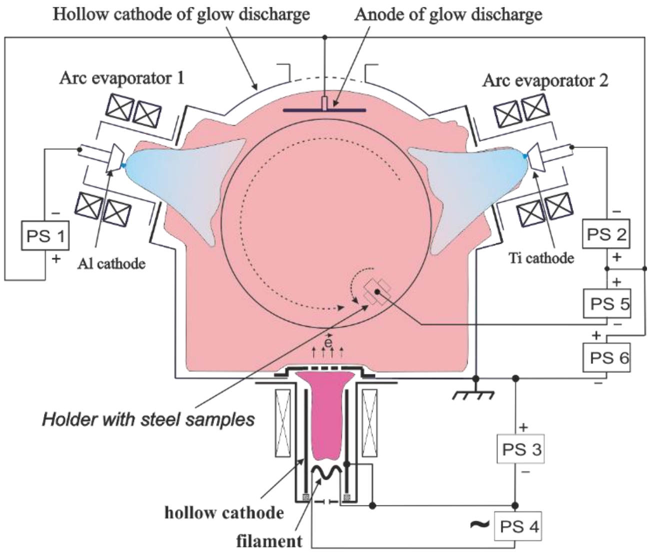


Properties of multilayered film:

1. Thickness ~ 4 μm,
2. Microhardness – 20 GPa,
3. R_a = 0,327 μm.

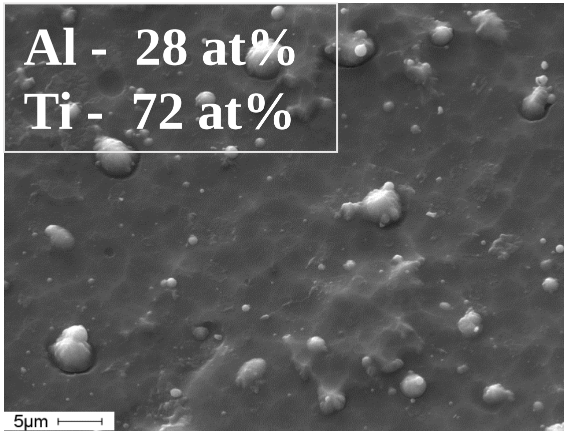


Plasma-assisted deposition using beam-plasma formation:



Properties of multilayered film:

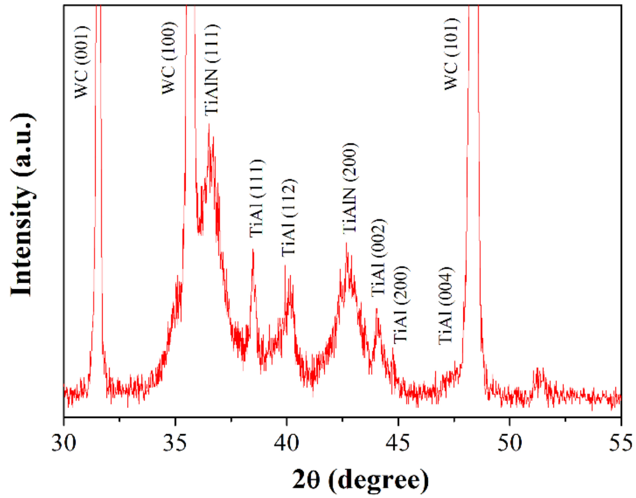
1. Thickness ~ 4 μm,
2. Microhardness – 17,4 GPa,
3. R_a = 0,359 μm.



Plasma-assisted deposition of Ti-Al / Ti-Al-N 8-layer film in beam-plasma formation of non-self-sustained glow discharge

Traditional scheme of plasma-assisted deposition:

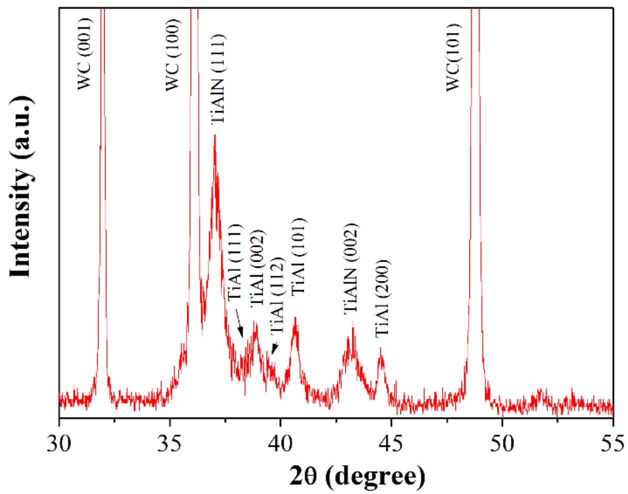
X-ray diffraction pattern of Ti-Al / Ti-Al-N multylayer film



Phase composition	Phase content, vol%
TiAlN	47
TiAl_225	8
TiAl_123	3
TiAl_129	4
WC	38

Plasma-assisted deposition using beam-plasma formation:

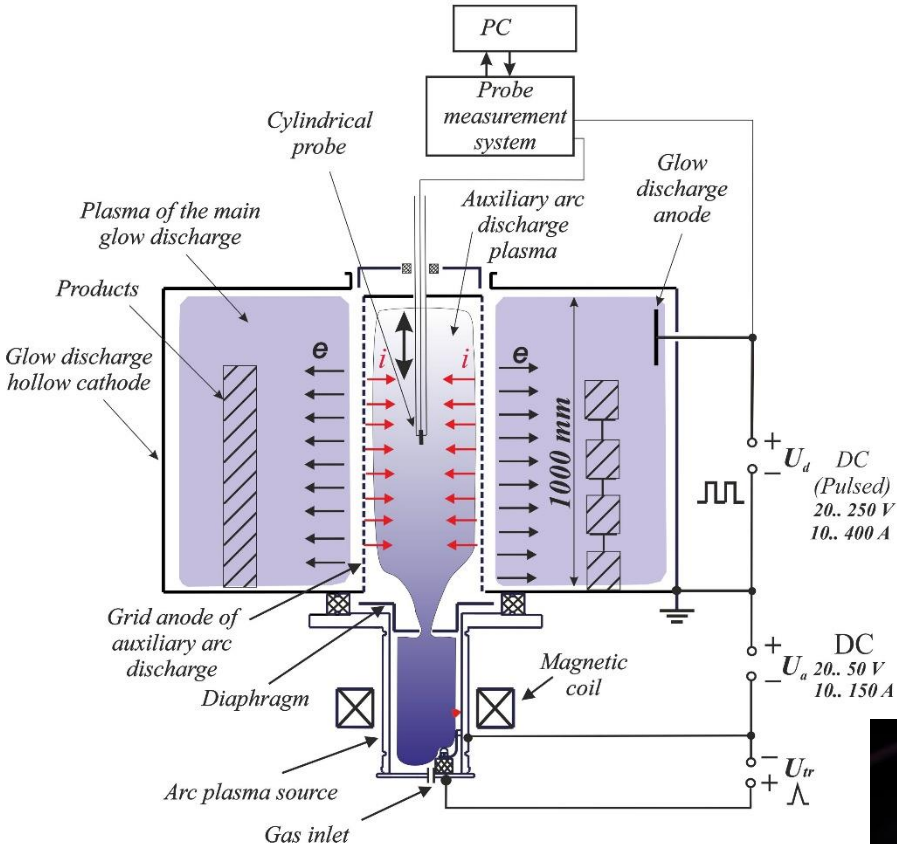
X-ray diffraction pattern of Ti-Al / Ti-Al-N multylayer film

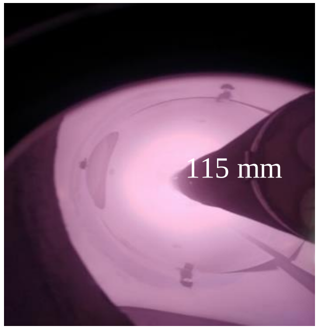


Phase composition	Phase content, vol%
TiAlN	61
TiAl_225	8
TiAl_194	6
TiAl_129	2
WC	23

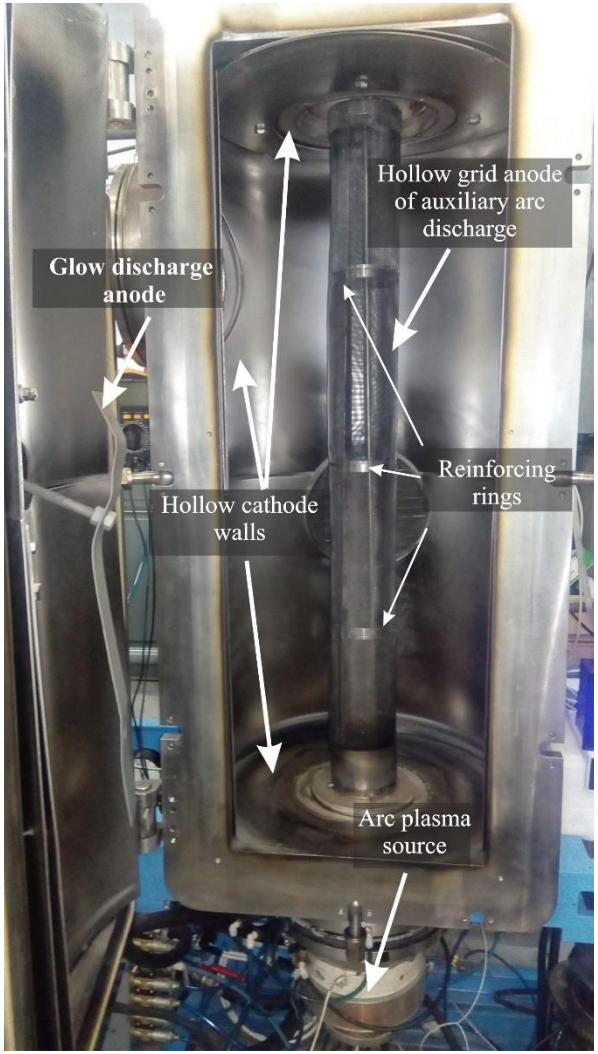
Experimental bench for the generation of beam-plasma formations in a non-self-sustained glow discharge

Glow of a glow discharge plasma with an extended grid electron plasma emitter with a diameter of 115 mm



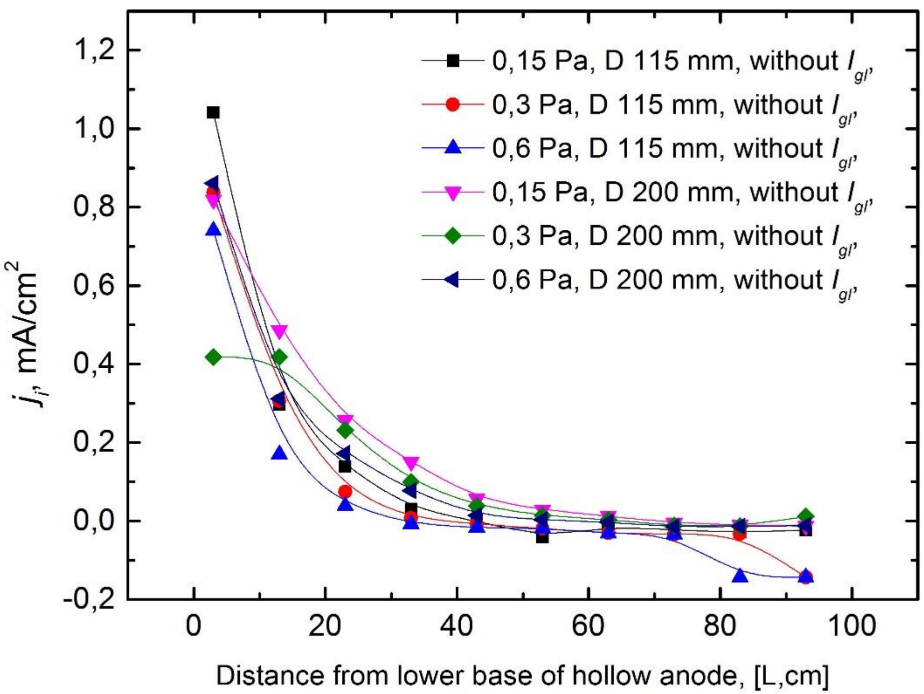


The image of electrode system

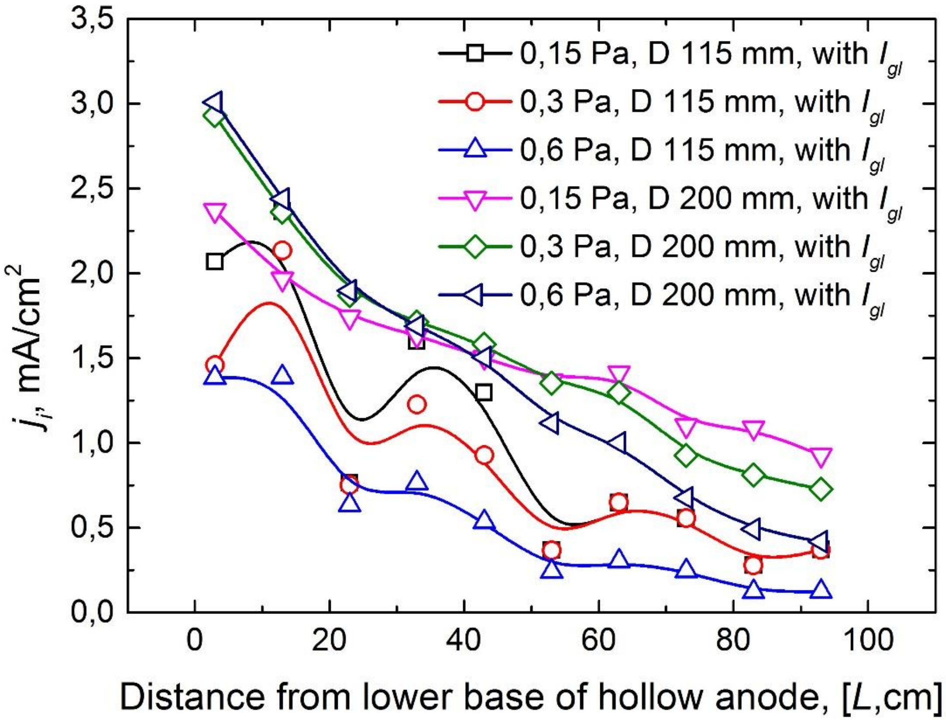


Distributions of the ion current density to the probe along the hollow grid anode of an arc discharge in a nitrogen atmosphere

Without glow discharge



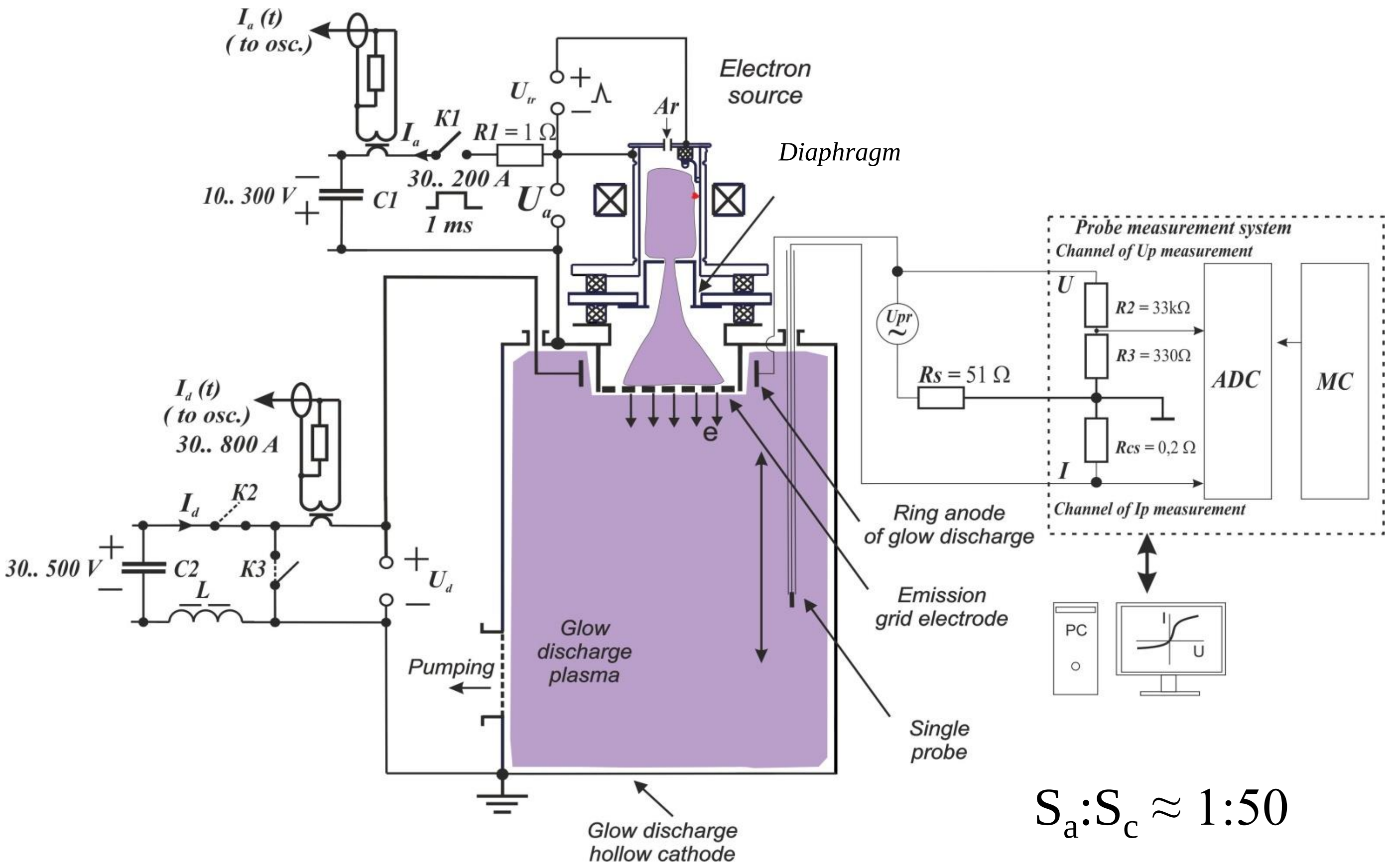
Glow discharge current – 150 A



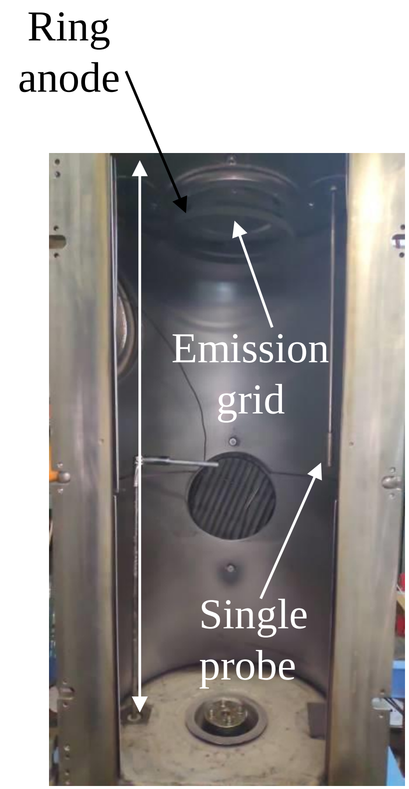
0 cm is the plane of the lower base of the hollow anode

The minimum heterogeneity of the longitudinal distribution of the ion current density at the arc discharge current of 50 A is achieved at a diameter of 200 mm, a pressure of 0.15 Pa, and is about ± 40%.

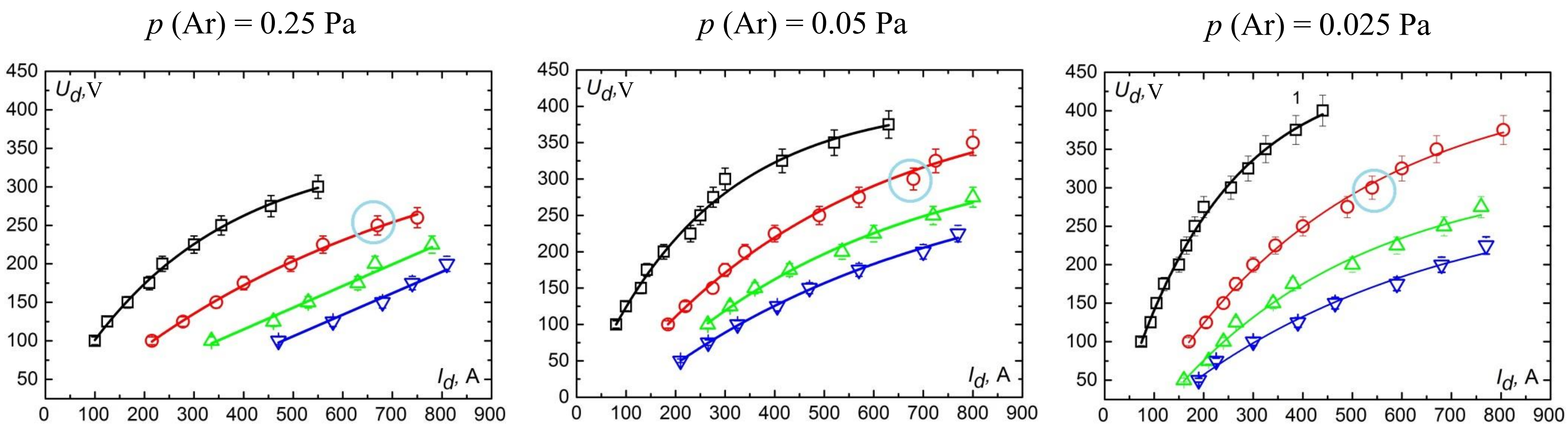
Plasma emitter on the base of high-current non-self-sustained glow discharge with hollow cathode



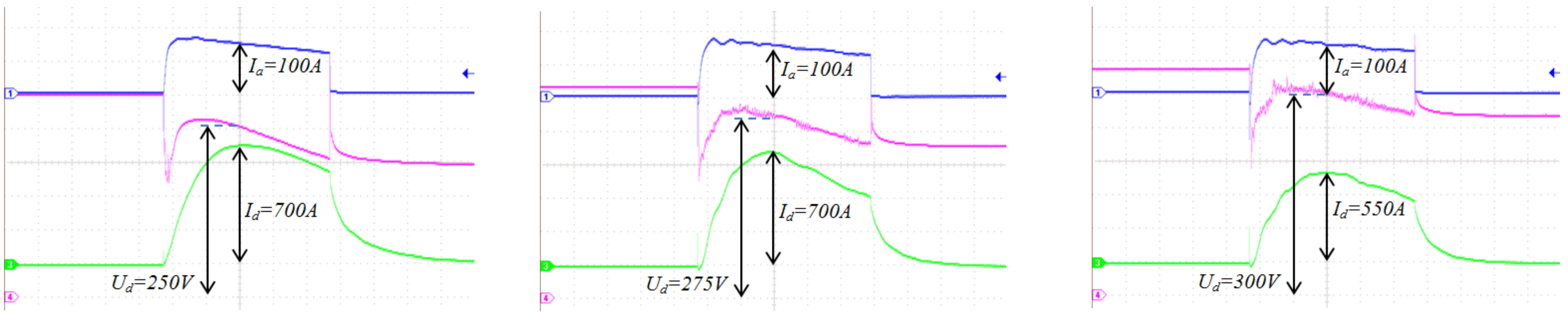
$S_a:S_c \approx 1:50$



Current-voltage characteristics of pulsed non-self-sustained glow discharge with hollow cathode (Argon)

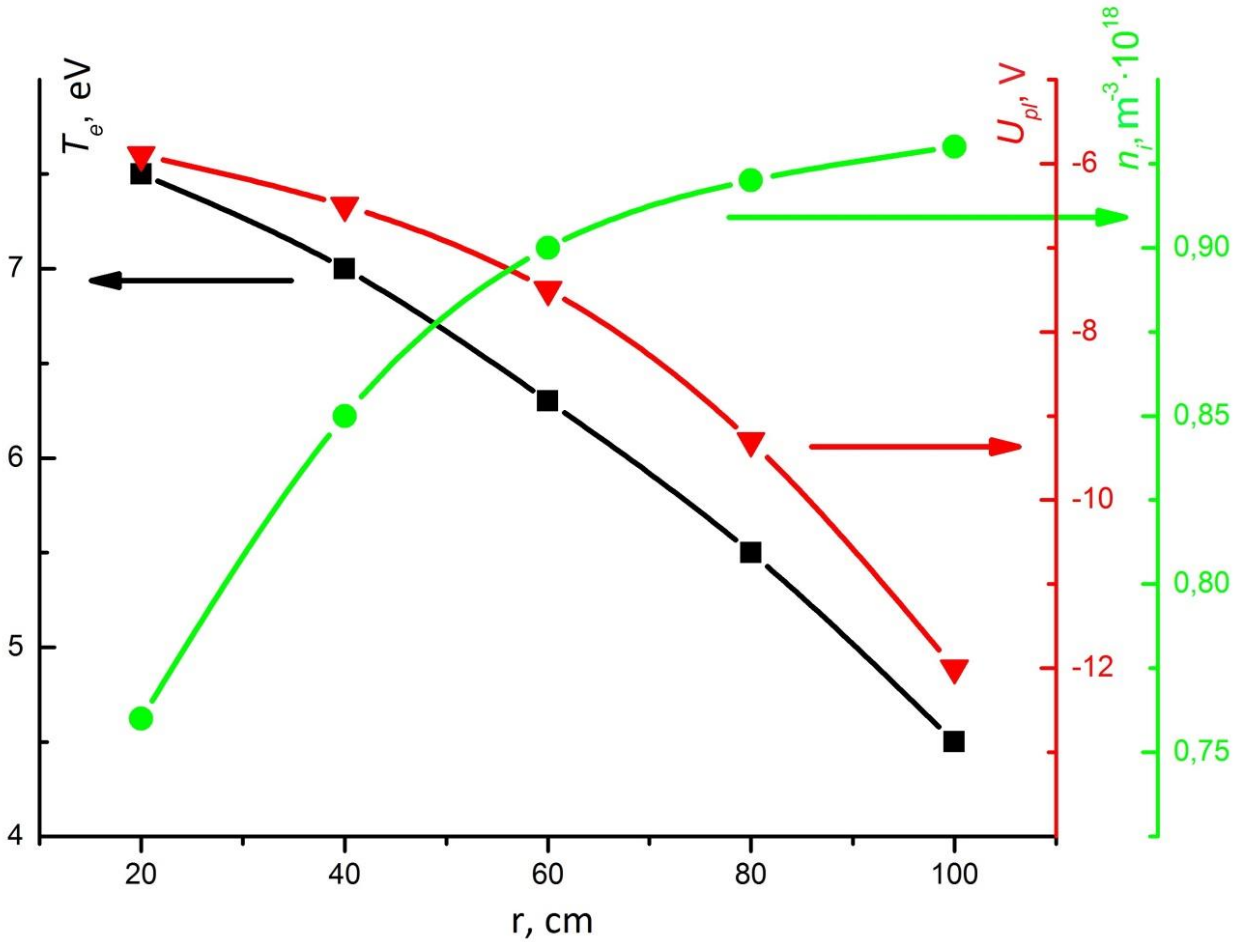


■ I_a = 50A, ● I_a = 100A, ▲ I_a = 150A, ▼ I_a = 200A



I_a : 63 A/div , I_d : 200 A/div, U_d : 50 V/div,

Plasma parameters distribution along the chamber axis



p (Ar) = 0.025 Pa,
I_a = 100 A,
I_d = 750 A,
U_d = 350 V

0 cm is the plane of the emission grid electrode

The plasma concentration exponentially increases towards the lower base of the hollow cathode, and the plasma potential and the electron temperature decrease, which is associated with the influence of a dense flux of electrons injected from the auxiliary arc discharge into the hollow cathode of extended geometry. The difference between plasma concentration values in the regions of the lower and upper bases is about 25%.

Probe measurements

Probe characteristics: D = 0.35 mm, L = 5 mm	p = 0,025 Pa; I_a = 100 A; I_d = 750 A; U_d = 350 V	p = 0,05 Pa; I_a = 100 A; I_d = 780 A; U_d = 325 V	p = 0,25 Pa; I_a = 100 A; I_d = 780 A; U_d = 250 V
Electron temperature, eV	4	3,3	2,2
Plasma potential, V	-14	-8,5	-2,3
Plasma concentration, cm^{-3}	1×10^{12}	$1{,}2\times10^{12}$	$2{,}3\times10^{12}$
Ionization degree, %	16	10	3,8

We have relatively high degree of plasma ionization:

$n_e/n_a \approx 16$ % (p = 0.025 Pa)

$$n_i\sigma_{ei} \geq n_a\sigma_{ea}$$

$$\lambda_{ei} \leq \lambda_{ea}$$

The free path lengths λ_{ei} between Coulomb interactions will be equal to 60 and 40 cm for pressures of 0.025 Pa and 0.05 Pa, respectively, which is approximately 3.5 times less than λ_{ea} when interacting with neutrals. Consequently, Coulomb interactions with such a degree of ionization have a significant effect on the trajectories of charged particles, the diffusion coefficients of charged particles, interparticle interaction, and hence the utilization of the energy of fast electrons in the plasma.

The densities of the saturation electron current per probe at a glow discharge current of about 750 A was 3.7 A/cm^2 (0.025 Pa), 5 A/cm^2 (0.05 Pa), and 6.7 A/cm^2 (0.25 Pa), which sufficient for the formation of pulsed intense electron beams of a large, up to several tens of square centimeters, cross section.

Conclusions

- The nitriding regularities of a number of structural and tool steels in the beam-plasma formations generated in a low-pressure glow discharge with hollow cathode were investigated and determined. Beam-plasma formations suitable for ion-plasma nitriding and plasma-assisting in the deposition of functional coatings.

- It was experimentally shown that the system for generating extended beam-plasma formations in a non-self-sustained glow discharge with a plasma electron emitter based on an arc discharge allows one to obtain a longitudinal degree of inhomogeneity of the concentration of the formed plasma over a length of 1 m in a hollow grid anode of an arc discharge at a pressure of 0.15 Pa in an argon atmosphere about ± 25%, and in pure nitrogen ± 40% at absolute values of the ion current density on the axis of the anode 1-3 mA/cm^2. The results obtained allow us to optimize the dimensions of the hollow extended grid anode and the control of the beam-plasma system as a whole.

- Pulse currents up to 800 A were obtained in a low pressure (0.025-0.25 Pa) non-self-sustained glow discharge with a hollow cathode of 0.34 m^3 at a discharge voltage up to 400 V and a pulse duration of 1 ms. Plasma concentration reaches 10^{12} cm^{-3} with an ionization degree 16 %. The obtained experimental data and estimates show that the free path length λ_{ei} between Coulomb interactions in the pressure range (0.025 – 0.05) Pa is approximately 3.5 times less than λ_{ea} when interacting with neutrals, so Coulomb interactions at a high (10-15 %) degree of plasma ionization have a significant impact on the trajectory of charged particles, interparticle interaction, and therefore contribute to a more efficient utilization of the energy of fast electrons in the glow discharge plasma before they go away to the anode.

Thank you for attention!

Vladimir Denisov

Laboratory of Beam-Plasma Surface Engineering
E-mail: denisov@opee.hcei.tsc.ru
cell: +7-913-807-24-25

Institute of High Current Electronics,
Tomsk, Russia