Modernization of high-power (5 kW) broad ion beam source

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Abstract. In the course of the long-term performance (during 5 years) of a high-power source of gas ions (25 keV, 0.2 A, 600 cm²) with a plasma emitter based on cold cathode discharge, the character and rate of key constructive elements faults were determined, which allowed to calculate the inter-repair time, complexity and cost of the repair. The peculiarities of the gas-discharge system and the ion beam forming system limiting the effectiveness of ion beam treatment were revealed as well. Conditions favorable for the decrease in the discharge voltage by 50–200 V and igniting voltage up to 1.5-2 times are determined. The possibilities of lowering the minimal flow of working gas are demonstrated. The design of the discharge system with reduced sputtering rate of local areas of the hollow cathode is offered. The changes added to ion source design aimed to enhance the lifetime of the plasma chamber that is exposed to cyclic heating by the back electron beam leading to the development of through cracks, and to enlarge the rupture life of glow discharge hollow cathode by optimizing its configuration and the conditions of discharge ignition and burning, are described. The upgraded design of a multislit ion-optical system with enhanced performance ensures uniform surface distribution of ion fluence.

1. Introduction
The gas ion source with a large beam cross section was elaborated for modifying large surfaces of materials by ion implantation and for using it in coating deposition processes assisted by ion beam (IBAD) [1]. To generate ion-emitting plasma, the injection of fast electrons into extended cathode cavity (plasma chamber) containing low-area anode was used. The electrons are emitted from plasma of self-sustained glow discharge with hollow cathode through grid electrode and accelerated in double layer of space charge while crossing the grid electrode [2]. As a result of electron oscillations in the cathode cavity, volume plasma is formed whose space inhomogeneity depends on gas pressure across the cathode cavity and method used for feed gas input. It was stated that under one-side injection of electrons into the plasma chamber the acceptable (±10%) inhomogeneity of plasma density on 600 mm length are reached by regulated gas fed from opposite ends of plasma chamber [3]. In order to reduce the rate of ion sputtering of hollow cathode its area was enlarged up to ~ 1300 cm². To rise the grid electrode resource, a space between the grid and the cathode aperture was enlarged till 100 mm, as a result, the electron flow after passing cathode aperture of 0.5-1 cm² area broadened up to 100 cm². 100-fold reduction of emitting plasma density allowed to use a perforated electrode with 4 mm apertures instead of fine-grained grid to solve the problem of the grid resource limited by ion sputtering [4]. The choice of multislit ion-optical system for ion beam formation was specified both by
quasi-linear geometry of the beam cross-section and by the need to adjust many apertures at a long distance and to keep the adjustment while the temperature of electrodes varies in a wide range. One-side rigid fixing of electrodes and single rods forming the slits as well as their floating arrangement from the opposite side provided reliable functioning of ion-optical system. The set of required parameters of ion beam ($25 - 40$ kV, $0.2$ A) also impeded its formation as demanded a long ($6 - 8$ cm) accelerating gap.

All these not only complicated the aperture adjustment, but also led to the increase of the rate of gas ionizing in the gap at plasma-forming gas pressure $0.05$ Pa and caused the back flow of accelerated electrons. As a result, heating of the source and exceptional consumption of power of high-voltage supply take place [1]. Substantial extra energy release required changes in design and productivity of the cooling system.

Therefore, in the course of designing and testing of the ion source the main problems hampering its operation were determined and measures for their overcoming taken. In the present work, the lifetime of key elements of the source under conditions of real pilot use in the installation for modifying surfaces of turbine blades was estimated. Results of experiments aimed at the improvement of technical and operational characteristics of the ion source realized in the new source design are described.

2. Service conditions and technical maintenance of the ion source

The ion source is used in vacuum coater «Victoria-2M» for ion-plasma modifying of the details of aviation technique in Scientific-Production Association «Technopark of Aviation Technologies» working in cooperation with Public Joint Stock Company "Ufa Engine Industrial Association" and Ufa State Aviation Technical University during 5 years. The ion source is used for treatment of low and high-pressure compressor blades and allows to provide ion cleaning (etching) and ion implantation of 200 oversized details by one cycle. Modifying the surfaces of gas-turbine motor components by ion implantation leads to enhancement of fatigue strength of titanium alloys by $6 - 10\%$; nickel alloys by $12 - 14\%$. Besides, ion beam treatment increases the lifetime of components, their microhardness and adhesion strength after successive coating depositions.

Source parameters are as follows: accelerating voltage is $25$ kV, beam current of nitrogen or argon ions is $0.2$ A, the initial cross section of the beam is $600 \times 100 \text{ mm}^2$, the operation gas pressure in treatment chamber equals $0.05$ Pa. The ion source is exploited in cyclic mode: $1 - 3$ cycles a day, one cycle taking 150 min. Total running hours of the source in continuous mode of beam generation made about $3500$ hours, on the average, $5$ hours a day. The ion source design is shown in Fig. 1. At both ends of water-cooled hermetic case 1 ceramic high-voltage bushing insulators 2 are arranged; at one of them hollow cathode 3 is mounted, at the opposite one – plasma chamber 4 and rod tungsten anode 5 are fixed. Plasma chamber and cathode are placed inside metallic screen 6, which equalizes electric field strength in a high voltage gap and blocks plasma feeding from the gap between grid electrode 7 and cathode 3. The large length of the gap $(30 \text{ mm})$ is caused by the significant thermal expansion of the plasma chamber in axial direction when ion source is used for a long time. The ion beam is formed by the ion-optical system consisting of emitter electrode 8 and accelerating electrode 9 and propagated into the treatment chamber through the rectangular aperture in output flange 10.

Routine technical maintenance of the ion source was accomplished by working staff and consisted in periodic (1 time per 6 months, after 600-700 hours of operation) replacement of diaphragm 11 made of stainless steel 12X18H10T in hollow cathode (3, 13, 14) because owing to ion sputtering a diameter of the aperture increased from $8$ to $15$ mm (Fig. 2). This aperture increase led to the growth of the discharge voltage and required rise of gas flow. Tungsten igniting electrode 16 (Fig. 1) was replaced simultaneously because of its shortcircuiting on $10 - 15$ mm. The reduction of electrode length worsened the conditions of the discharge ignition, which also led to the necessity to increase the minimal gas flow. Tungsten rods (Ø2 mm) (12, Fig. 1) of accelerating electrode 9 of ion-optical system (IOS) (8, 9) sputtered by ion beam were periodically (after 1300-1500 hours) replaced. More complicated prophylactic repair was made once after 2500 hours of operation. It included general maintenance or
Figure 1. Ion source. 1.1 and 1.3 – general drawing and image of ion source, 1.2 – draft of the cathode.

1 – case; 2 – high-voltage insulating assembly; 3 – hollow cathode; 4 – plasma chamber; 5 – rod anode; 6 – high-voltage screen; 7 – plasma cathode grid; 8, 9 – screen and accelerating electrodes of beam forming system; 10 – output flange; 11 – diaphragm with constricting aperture; 12 – tungsten rods; 13 – conic cathode insertion; 14 – centering insulators; 15 – cathode insertions; 16 – ignition electrode; 17 – anode of constricted discharge.

Figure 2. Diaphragm in initial state (1) and after 400 hours of operation (2), segment of plasma chamber, with through cracks (3).

Ionization of gas in accelerating gap of the IOS by accelerated ions and formation of back electron flow lead to heating of uncooled case of plasma chamber 4 up to temperatures more than 500°. Multiple cyclic heating and cooling lead to loss of stainless steel plasticity and through cracks development (Fig. 2), hence plasma chamber construction loses its rigidity. The simplest solution of this problem is placing a cylindrical replaceable insert into plasma chamber. Gradual degradation of this insert does not result in emergency effects.

Rather a complicated configuration of the hollow cathode including elements 3, 11, 13, 14 is specified by the necessity of special space for electron flux expansion towards the grid 7; for disposal of fixing
elements of changeable diaphragm 11 with constricting aperture and fixing of insulators 14 to centre position of the plasma chamber. Intensive ion etching of constructive elements of cathode 14 protruding into the cavity resulted in the loss of leak-tightness and final destruction of hollow cathode. Optimized design of the hollow cathode, with a reduced number of intensive sputtering zones, is shown in Fig. 1.2. Arrangement of two cathode insertions 15 with central apertures Ø50 mm inside the cavity provided reduction of discharge voltage from 750 – 800 V up to 600 V; hence, the rate of cathode case sputtering decreased. Sputtering of aperture edges in the insertions does not disturb the source operation.

3. Optimizing the conditions of beam formation and discharge operating

The known disadvantage of the mode of broad ion beam formation by multi-slit ion-optical system (IOS) is that even at high homogeneity of plasma ion emitter such IOS provides almost regular distribution of beam current density along the large axis of its cross section only at definite distance from the beam formation system and definite modes of its operation, conditioned by the combination of beam current and accelerating voltage. Regularity of distribution is provided as a result of angular divergence of elementary beams formed in singular apertures and their overlapping in the space of beam drift. At less than optimal distances from ion-optical system, irregularity of beam current density distribution is observed, characterized by interchange of maximum and minimum values of ion current density along large axis of the beam. Therefore, even at insignificant change of beam generation modes or at treatment of complicated surfaces fluence of ion irradiation of the surface of articles moving crosswise the long axis of beam section also will be irregularly distributed across the surface.

The proposed way to reduce inhomogeneity of ion beam treatment implies the change of the angle of slope of the slits in ion-optical system electrodes: the angle between slit and short axis of beam’s cross section has to differ from 0°. The minimal angle of deviation $\alpha_{\text{min}} = \arctg(h/l)$ is conditioned by length $l$ and width $h$ of single slit aperture. As a result, all parts of surface of the article moving across the long axis of the beam receive approximately equal fluence of ion irradiation. Design and operation principle of IOS are shown in Fig. 3.

In Fig. 4 distributions of ion current measured by collector (length $l$ and width $h/4$) moving lengthwise the long axis of the beam for optic with rectangular slit orientation and for optic with angle of slits rotation $\alpha = 9^\circ$ are shown. Measurements were made at 3 cm distance from ion-optical system, at which the level of inhomogeneity of the beam section is high. Even in such conditions the inhomogeneity of fluence made $<$±15%.

The research on optimizing conditions of ignition and burning of self-sustained glow discharge with hollow cathode was purposed at reduction of minimum value of gas flow, ignition voltage of pulse discharge in cathode cavity and DC voltage, applied between the cathode and anode, providing stable ignition and burning of constricted discharge. The research showed that the change in the potential of diaphragm 11 with outlet aperture imposes significant effect on the conditions of the discharge ignition between the cathode and anode. At cathode potential of the diaphragm disruption of cathode sheath in constricting aperture is required for the discharge development; this is achieved by the increase in the cathode-anode gap’s voltage and growth of pulse discharge current. At the anode potential of the diaphragm, conditions of pulse ignition are practically stable; the ignition voltage of...
the constricted discharge decreases by 300 – 500 V (Fig. 5); and the discharge voltage falls by 50 V (Fig. 6.1). Besides, the diaphragm with the potential close to the anode one (40 – 50 V) is not subjected to ion etching. The effect of cathode insertions (15, Fig. 1) on burning voltage of the constricted discharge is shown in Fig. 6.2. The growth of the amplitude of ignition pulse current from 12 to 50 A leads to the reduction of the minimum flow of feeding gas, at which the constricted discharge ignition is provided, from 11 to 7 sccm.

4. Conclusion
The experience of the long-term (during 5 years) pilot use of the high power source of the broad gas ion beam (25 kV, 0.2 A, 600 cm²) with a plasma emitter based on the discharge with a cold cathode was summarized. The source is easy and reliable in exploitation and does not require frequent repair. Current prophylactic repair of the ion source held twice a year consisted in replacement of the cathode diaphragm because of the significant increase of outlet aperture dimensions as a result of ion sputtering, and also the change of tungsten rods in accelerating electrode of ion-optical system, sputtering by ion beam.

Regular (biyearly) prophylactic maintenance consisted in repair or total change of plasma chamber and hollow cathode. The loss of plasticity of metal and development of through cracks took place owing to cyclic heating of plasma chamber wall by back electron flow. The integrity of hollow
cathode design is destroyed because of intensive scattering of protruding parts. In order to increase the lifetime of these components a new design of hollow cathode was elaborated and use of changeable insertion inside plasma chamber was recommended.

The results of experiments allowed to increase the lifetime of the diaphragm with constricting aperture owing to altering its potential from the cathode to anode one and to reduce the inhomogeneity of ion beam treatment using the multislit ion-optical system with the angle between slits and long axes of beam section different from 90°.

References
[1] Emlin D R and Menshakov A I 2012 Bulletin of the SUSU. Ser. Mechanical Engineering Industry 20(33) 131
[2] Vizir’ A V, Oks E M, Shchanin P M and Yushkov G Yu 1997 Technical physics 42(6) 611
[3] Gavrilov N V, Kamenetskikh A S, Emlin D R, Bureyev O A and Menshakov A I 2008 Proc. 9th Int. Conference on Modification of Materials with Particle Beams and Plasma Flows, Tomsk, Russia. Publishing house IAO SB RAS, pp 7-10
[4] Gavrilov N V and Kamenetskikh A S 2007 Technical physics 52(3) 301

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