

Hollow Cathode Glow Discharge as a Heating Source in Welding and Brazing

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Abstract – The paper presents milestones of researches dedicated to determination of physics of low-temperature distributed gas-discharge plasma of the glow discharge with hollow cathode and its application in technological processes of welding and soldering since 1916. It is demonstrated that powerful-current glow discharge is the perspective and competitive energy source in the processes of joining materials in the solid phase, but there are a number of factors significantly limiting its widespread industrial application because of its insufficient stability at medium pressures and low processability. The usage of glow discharge initiated in a hollow cathode as the surface heating source during the pressure welding allows to eliminate indicated problems.

Keywords – hollow cathode glow discharge; gas-discharge plasma; pressure welding; diffusion welding; brazing; heating source.

I. INTRODUCTION

Glow discharge, which was opened by Faraday in the 30-ies of the 19th century, is associated with many different application and research areas of application of electric current proceeding in a rarefied gas. First, historically, it was electrical engineering and electronics. However, in recent decades, glow discharge had been applied as a powerful welding energy source in electron-beam, laser and diffusion welding. Colorful phenomenon of current proceeding in the gas, named as a glow discharge, is able to provide a concentrated or distributed energy flow. In the second case, the glow discharge determined (possesses) unexpected opportunities as the welding energy source. First, glow discharge allows to provide the heating mode which is controllable in the range of several orders as for the area of heating spot and for the distribution of energy in the spot heating. Secondly, it has the ability to provide uniform surface heating and to penetrate into cracks, cavities and gaps, providing volumetric heating of the honeycomb or hollow structures. Finally, glow discharge has the ability not only to heat but also to activate, chemically and thermally treating of metal surface. Amazing and diverse properties of glow discharge occur due to the wide range of pressures of the gas environment under which it is stable subsists.

II. HISTORICAL BACKGROUNDS

The idea of using of different geometry cathodes during the study of characteristics of gas discharge plasma refers to the

end of the 19th century. Even then, the first researchers mentioned the exceptional characteristics of discharge in the case of using a hollow cathode instead of the plane one. However, the first description of the hollow cathode discharge published in the scientific literature appeared in 1916, when the German physicist Frederic Paschen described the data of the spectroscopic investigations of the hollow cathode discharge in helium environment. He noted the extraordinary richness of spectral lines distributed by the discharge in the hollow cathode at low pressure (few millimeters of mercury) and indicated the absolute uniqueness of this source of radiation.

Paschen's prototype of discharge source in the hollow cathode was as a glass jar filled with helium. Inside this glass jar, the metal cathode in the form of a hollow of rectangular cross section made of thin aluminum foil is placed. The cylindrical anode installs perpendicular to the side surface of the cathode at some distance [1].

The reason, that prompted Paschen to develop such source, was the fact that just a few years ago, in the summer of 1914 Bartels H. together with the staff suddenly discovered that the intensity of the spectrum lines of helium inside the cylindrical cathode of Geissler tubes devised by Fowler had a very powerful bright light in direct current mode.

In further works of 1916-1928 years, Paschen reported the significant contribution of the cathode material in the excitation of intense lines along with the gas that filling the interelectrode distance. It is due to the relatively high energy of ions bombarding the inner surface of the cathode and of electrons emitted from the cathode under the impact of ion bombardment. These works provide detailed description of the nature of the spatial distribution of different areas of the discharge inside the cathode, which differ from each other in luminous intensity and indicate on the main differences of this distribution from the source with a plane cathode. In particular, it was established that in the case of the hollow cathode discharge emission intensity with distance from the cathode dark space with the maximum intensity along the axis for a given value of gas pressure, while in the discharge with plane cathode, the brightest glow is observed near the border of the dark cathode space [2].

In subsequent years, Paschen's experimental device was undergoing many different modifications, mainly by British scientists Naude (1929), Campbel (1933) and Tolansky (1935).

However, without a doubt, the greatest interest attracts the adaptation of scientists such as Schuler and Gollnow for analytical measurements of the emission spectrum in 1937. Their tube was consisted of two main blocks - cathode and anode, which are separated from each other at a distance of 1mm. The distinctive feature of Schuler's device was the use of forced water-cooling of the cathode to reduce the cathode material consumption as a result of its intense sputtering [3]. Carrying out the investigation of the gradient of the electric field of gas-discharge plasma initiated in a hollow cathode Schuler and his staff concluded that almost all the value of the cathode potential drop is concentrated at the cathode with the minimum value of the anode.

Almost in the same period (1923-1928 years), the German investigator A. Gunther-Schulze was carrying out the number of researches to determine the electrical properties of the hollow cathode discharge. In his works, he noted that the cathode potential drop in conditions when the cathode is hollow is much less than for plane cathode at the given current density. It could be explained due to the sharp reduction in ion loss compared to the system with plane electrodes [4].

Gunther-Schulze was measuring the current in the system with cylindrical cathode during the investigation of the characteristics of the discharge. He was also showing the possibility of obtaining the effect of the hollow cathode in the system with two plane cathodes place in parallel with each other during their gradual approach. In both cases, the appearance of the hollow cathode effect was related to the partial joining of the areas of the negative glow discharge. It is accompanied by the abrupt increase in the values of discharge current caused by oscillation of emitted by the cathode electrons inside the hollow. In 1928, Gunther-Schulze introduced the concept of efficiency of discharge with the hollow cathode and for its quantitative determination for different gas environments at various pressures suggested the following equation:

$$q_i = \frac{I_d}{i}, \quad (1)$$

where I_d – the current of discharge with the hollow cathode; i – the current of discharge with the plane cathode.

Further work in the field of research of glow discharge characteristics with the effect of hollow cathode was interrupted by the war and was resumed only in the second half of the 20th century.

III. HOLLOW CATHODE GLOW DISCHARGE IN WELDING AND BRAZING

The prerequisite of usage of glow discharge in the process of heating and processing of materials were the works of English scientist William Crookes, which were made in the late 19th century. During the exploring of electrical phenomena in gases inside the vacuum tube, he made a conclusion that opened in 1859 year by investigator Julius Plücker cathode rays are nothing but the charged particles (electrons) which are emitted from the cathode with great velocity at a right angle to it. William Crookes also showed the possibility of focusing using not plane but hollow cathode with a hemispherical shape. When Crookes placed the platinum plate on the path to rays, he suddenly discovered that in the place of electrons focusing there is a large amount of heat liberation sufficient for the melting of the platinum [5].

However, the necessity of usage of such powerful energy source appeared only in a hundred years. It could be explained due to the rapid development in the second half of the 20th century of processes of surface treatments, coating deposition and welding methods without melting.

So, the first attempts of glow discharge application in technological processes of materials joining was at the beginning of 60-ies of the 20th century, when the Ukrainian scientist V.S. Vanin in the walls of the Nikolayev shipbuilding Institute first carried out the diffusion welding and brazing in the plasma of abnormal glow discharge. He believed that while almost the entire magnitude of the potential drop is concentrated in a narrow region near the cathode, it would not have any problems with the charge of the cathode (welded parts) by the flow of ions that bombarding its surface, which will cause heating of parts.

In the work [6] Vanin demonstrated the first results of diffusion welding of carbon steel 1.1132 and carbon tool steel CT80 in the abnormal glow discharge. During such process the temperature of 1000...1200 °C at the current density of 150 A/cm² and at the working voltage of 2500 V in the environment of acetone and carbohydrates was obtained. In the same work, author indicated the possibility of using of glow discharge in the process of metals brazing using various kinds of brazing alloys. He also demonstrated the first installation scheme for welding and brazing with the usage of ion heating with the power of several kilowatts, which is capable of providing high temperature heat (Fig.1).

The Vanin's investigations intensified the work of other

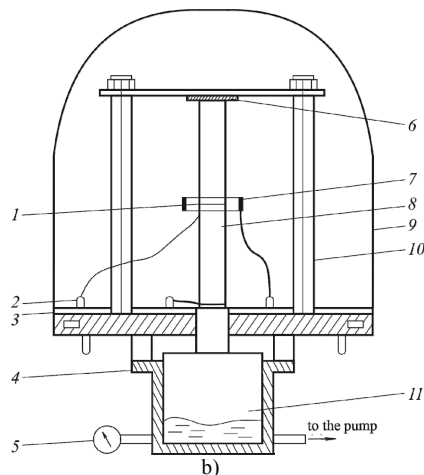
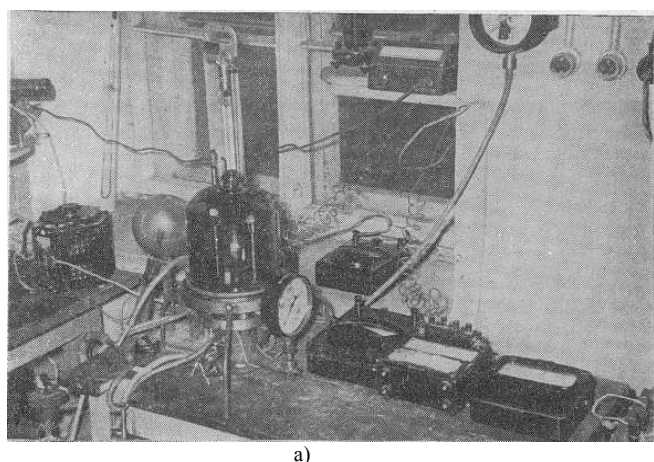


Fig. 1. General view of the Vanin's installation (a) and reactor scheme for welding in abnormal glow discharge (b): 1 - weld point; 2 – thermocouple; 3 - rubber gasket; 4 - hydraulic cylinder; 5 – manometer; 6 – insulation; 7 – anode; 8 - welded specimens (cathode); 9 - vacuum chamber; 10 – rack; 11 – piston [6].

Ukrainian scientists in the field of application of distributed gas-discharge plasma of glow discharge in technological processes of welding and brazing. The works of other Ukrainian scientists such as Kvasnitskiy V. F., Kotelnikov D. I., Muha I. M., Bolotov, G. P., became the basis for the development of native science in the field of welding with the use of ion heating.

Kotelnikov Dmytro Ivanovych became the author of over 160 scientific papers and 11 patents in the field of pressure welding in the glow discharge in the mid 60-ies of the 20th century under the guidance of Dyatlov, V. I., who was the head of Department of welding production in Kyiv polytechnic institute. In their works [7-9] performed in the 1967-1970 years Kotelnikov noted specific features of the glow discharge as a source of surface heating. Among such features, he highlighted the possibility of regulation within wide limits of intensity and area of distribution of thermal energy input into the product.

The first attempts of usage of gas-discharge plasma under the conditions typical for diffusion welding [6, 9, 10] (at pressures of 1.3 to 13.3 kPa) have revealed some difficulties, mainly associated with partial or complete loss of stability of glow discharge and its transition to a more stable form – the electric arc. Among the main reasons of such transition, as Kotelnikov highlights are: the presence of various kinds of oxides, contamination and other particles on the surface of the welded parts (cathode discharge) that can lead to the formation of short-term electric arcs; the heating of the neutral gas as the result of the pulse change of the voltage in the discharge gap, which contributes to the formation of a stable arc discharge. In work [11], author pointed to other causes of loss of stability of a glow discharge in welding conditions associated with its modification within the limits of the one form of gas discharge. Such modifications are primarily due to the constructive-geometrical characteristics of the welded parts. Thus, the presence of various kinds of cracks, gaps, holes or recesses on the surfaces of the joined workpieces can cause another form of glow discharge – discharge with the hollow cathode effect. Having a high current density ($>50 \text{ A/cm}^2$) discharge with hollow cathode effect can leads to the violations of the technological process of welding.

Kotelnikov was investigating the characteristics of various forms of the glow discharge and its influence on to the heating on the example of diffusion welding of carbon steel 1.0503

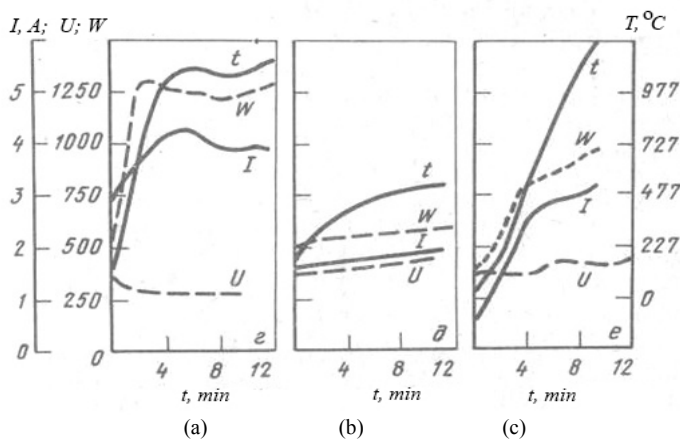


Fig. 2. Characteristics of the heating process in different forms of glow discharge: a) abnormal GD; b) normal GD; c) hollow cathode GD [11].

with chrome-nickel-titanium steel (steel 321) and armco-iron in the nitrogen environment at a gas pressure of 10 kPa and temperature of 1125...1200 °C during the 360 sec. Having analyzed the obtained results, Kotelnikov concluded that the best technological properties are inherent to the normal glow discharge as the most stable form of the glow discharge because it is easily adjustable (Fig. 2b). The maximum heating rate with the highest energy density in the spot heating ensures the discharge in a hollow cathode (Fig. 2c). Kotelnikov identified the abnormal form of glow discharge as the totally unsuitable for diffusion welding at average pressures. It could be explained by the fact that abnormal form of glow discharge possesses increased tendency to transition in an electric arc (Fig. 2a).

Thus, Kotelnikov was the first who proposed to use normal glow discharge as a heating source for diffusion welding [12]. He was also the author of the first installation of semi-industrial type with capacity of 10 kW for diffusion welding of dissimilar metals and alloys with ion heating (Fig.3). During the Kotelnikov's direct participation and consultation, the usage of the glow discharge in the industry for the first time was carried out in our country on the production association n. S.P. Korolev of Kiev city in the mid 70-ies of the 20th century. Such technique was used for the diffusion welding of metals and hardmetal with the non-metals [13].

Acute need of that time in the development of advanced methods of recovery of hardmetal manufacturing equipment and cutting tool, the elements of which, up to that time were connected by soldering contributed to this fact. So, in 1973 the technology of restoration of tungsten (VK6 and VK15) and the tungsten free (TH2O) hardmetal cutting tools by the method of diffusion welding with ion heating in a glow discharge was developed by Muha I. M. and Dovbyschuk M.N. scientists and the staff of production association n. S.P. Korolev of Kiev city.



Fig. 3. Kotelnikov's first installation of semi-industrial type for welding in the glow discharge [12].

Welding process was carried out in the hydrogen environment through the thin metallic layers of 50HXC steel and nickel obtained by thermal vacuum deposition. As the optimal parameters, ensuring high flexural strength of samples was selected: heating temperature is 1250 °C; time of isothermal aging is 7...10 min; gas pressure in the chamber is 13.3 kPa; working voltage is 400...600 V; current of discharge is 3... 5 A [14].

Other Soviet scientists have also pointed out the problems of stability of glow discharge under the conditions of diffusion welding and brazing. The authors [15, 16] demonstrate the possibility of failure of the technological process due to the appearance of the long powerful arc discharges that is accompanied by significant percussion current overload of power source and welded parts.

The long search of ways of eliminate of this drawback led to the development of the first devices of relay-thyristor and thyristor-semiconductor types in 1976 by Kotelnikov D. I. together with the Bolotov G. P. in the walls of the Chernihiv branch of “Kiev Polytechnic Institute”. Such devices combine the protection of the welded product and power source from the overload under the conditions of the formation of the stable arc discharge [17]. The effect of such protective devices based on the usage of the signal from the electric arc. The appearance of electric arc is accompanied by an abrupt increase of current in the circle of discharge as well as the step-by-step decreasing of current until the disappearing of characteristics of the arc. In other words, such decreasing of current will be until the parameters of electric circle will not return to the original mode of combustion of the glow discharge. These devices are called CS-1, CS-2 (CS - control system). Among the advantages of such devices are the combined protection of the product and power source as well as the possibility of self-regulation of its system (Fig. 4). The processing speed of relay circuit is about 0.1 sec., while in the semiconductor circuit is 0.01 sec.

Such devices of automatic stabilization of the glow discharge was introduced by Kotelnikov and Bolotov in 1976 during the manufacturing of the industrial universal installation for welding of hardmetal stamped and cutting tool at the Leningrad design engineering bureau of technical equipment. Later on, in the early 80-ies, such devises was using for the manufacturing of 2-chamber installation for welding of magnetostrictors at the Moscow radio engineering factory (Fig. 5).

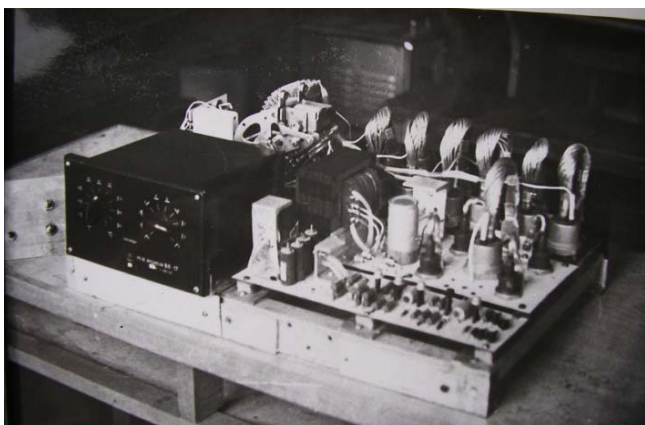


Fig. 4. General view of the glow discharge stabilization device (CS-1) [17].

The specific characteristics of the glow discharge under the conditions of welding heating require, along with arc-suppressing systems, the development of new types of power sources, which are stabilize the discharge current and are able to withstand its powerful jumps. Such stabilizing effect can be achieved only with the coherence of the static volt-ampere characteristic of discharge as well as the external characteristic of power source.

Thereby, in the late 70's and early 80-ies the D. I. Kotelnikov and G. P. Bolotov has developed and implemented a number of power sources of high-current glow discharge with external characteristic that is similar to the high-dipping [18]. The simplest variant of obtaining of such external characteristic is the usage of the source with an external active resistance (ballast) whose value is selected in the range from the 1/3 up to the total resistance of the discharge (Fig. 6a). Such variant of obtaining of external characteristic was wide spread in use of industry. However, such scheme possesses the significant energy loss - coefficient of efficiency of such source does not exceed 0.4...0.6. The replacement of the active resistance in the power source onto the inductive-capacitive converter [19] allowed to obtain the external characteristic that is similar to the vertical (bayonet). It is significantly extended the range of stable existence of the system “source-discharge”.

However, the usage of reactive converters significantly complicates the design of source and increases its cost. In addition, the weight of the source also increases (from 11 kg up to the 22 kg per 1 kW depending on capacity).

For high-power sources, they have developed and implemented more economical power sources with the ability to control the parameters within wide-ranging limits. Such sources was made based on the valve converters (thyristor) the high-dipping characteristic of which is provided by the automatic current control (Fig. 6b).

So, 1981 year was the year of completed of the period under review and was the period of publication of D. I. Kotelnikov’s monograph [20]. In this monograph D. I. Kotelnikov summarizes the research results and experience of industrial applications of glow discharge during the welding process of dissimilar metals, alloys, and non-metallic materials with metals.

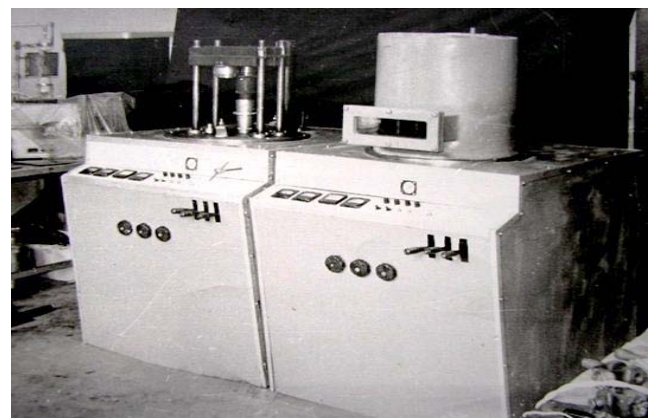


Fig. 5. External view of 2-chamber multiposition installation for welding of magnetostrictors in glow discharge [18].

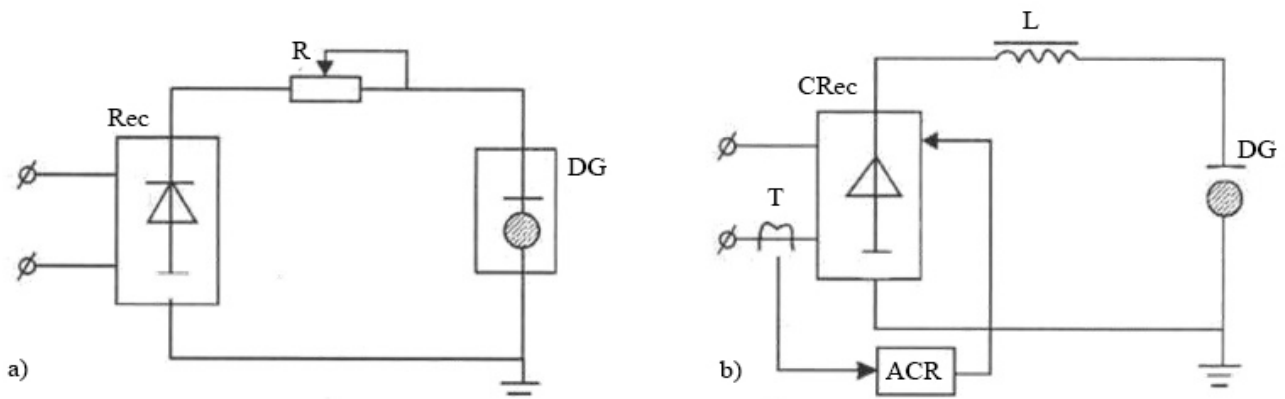


Fig. 6. Schemes of the glow discharge power sources with an active ballast (a) and valve converters (b); Rec – rectifier; CRec - controlled rectifier; ACR - automatic current regulator; DG – discharge gap; R – resistor; L - smoothing reactor; T – transformer [19].

He also examines the processes in gas-discharge plasma of medium pressure, gives features of developed and introduced in industry equipment and indicates the main problems and prospects of application of glow discharge in diffusion welding and brazing.

However, further development and wide industrial application of described energy source for welding and brazing was prevented by several factors, related primarily to the insufficient stability of the glow discharge under the conditions of welding heating and limited range of welded materials, because welded parts at the same time could be cathode discharge. The latter does not allow to weld of dielectric materials, that are nowadays the basis of many devices in electronics, electrical engineering, etc.

Thereby, the particular focus of the Ukrainian scientists in the field of ion heating in the gas-discharge plasma during the last decades has been focused on the search of the ways of enhancement of the technological capabilities of the glow discharge, in particular, through the development and implementation of new, more advanced power sources for welding and brazing. Assigned task of the development of high-tech gas-discharge source of heating was resolved in 2008 by the scientists of Chernihiv state technological University.

G. P. Bolotov and M. G. Bolotov first published the results of researches of stability of the glow discharge initiated in a hollow cathode with respect to the conditions of welding heating [21].

The prerequisite of development of such source were the works [22] concerning formation of electron beams for gas-discharge electron beam guns by means of hollow cathode glow discharge (HCGD).

The main feature of such heating source is the lack of galvanic connection of the product with the electrodes of the discharge. That is, the welded parts possess electroneutrality that can be used for welding both metal and non-metal products in various combinations. Such heating source distinguishes from other discharge sources proposed by the Vanin and Kotelnikov that provide direct heating of the welded components by bombarding the surface with accelerated positive ions of the working gas (Fig. 7). With the replacement of the cathode in the discharge system on the metal hollow cylinder the mechanism of the welding heating in the HCGD has undergone changes.

During such mechanism the heating process is occurs by indirect method in consequence of the bombardment of

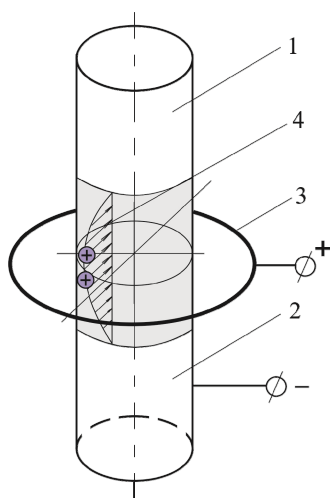


Fig. 7. The scheme of the welding heat in the normal glow discharge field: 1,2 - welded specimens (cathodes); 3 – anode ring; 4 - heating zone (cathode spot).

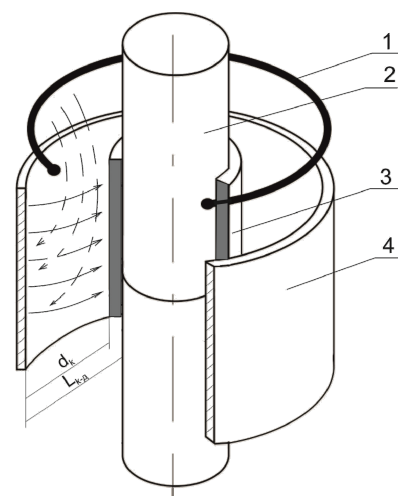


Fig. 8. The scheme of the welding heat in the hollow cathode glow discharge: 1 - anode ring; 2 - welded specimens; 3 - negative glow region; 4 – cylindrical hollow cathode; d_c - dark cathode space; L_{c-s} - cathode – specimens distance.

surfaces by electrons emitted from the surface of the hollow cathode as a result of ion-electron emission and acceleration in the electric field of cathode region of the glow discharge (Fig. 8).

In 2009-2011 the technological process and equipment was developed and introduced into the manufacture for the welding and brazing in HCGD plasma a number of products for electrical and medical devices. As the result, in October 2014, G. P. Bolotov and M. G. Bolotov received a utility patent [23].

The last works dedicated to the study of HCGD as a heating source at diffusion welding focused on research of processes of activation and modification of welded surfaces using gas-discharge plasma with the hollow cathode effect.

Thus, in the work [24] that devoted to the research of ability to control mass-transfer processes in the development of diffusion welding technology of metals that have a limited or unsatisfactory weldability, the fundamental possibility to diffusion processes improving due to ion bombardment in the plasma of glow discharge was shown.

The paper [25] considers the possibility of using plasma of HCGD in the processes of activation and treatment of the inner surfaces of aluminum waveguides for microwave radiation prior to brazing.

In 2016, G. P. Bolotov published a monograph, which is essentially a second attempt at compilation of data on welding and brazing in glow discharge over a period of time that has passed since the publication of the monograph of D. I. Kotelnikov [26].

CONCLUSIONS

The usage of glow discharge in the diffusion welding, which was founded in 1962 by the research of V. S. Vanin and continued by the works of D. I. Kotelnikov, G. P. Bolotov and other several Ukrainian scientists has led to the fact that this heating source pretty quickly took a worthy place among the other energy sources for diffusion welding and brazing. However, the further development and widespread industrial introduction of this heating source was primarily limited to a lack of processability that is associated with a limited range of welded materials.

The increase of processability of the glow discharge as the welding heating source was possible only through the development and creation of new, more advanced gas-discharge source based on a glow discharge that is burning in the hollow cathode.

Experience of application of glow discharge in the solid-phase welding demonstrates that the most perspective directions of further development will be the creation of automated installations and control systems of diffusion welding process in the glow discharge based on the microprocessor technology using mathematical models for the generation of optimal control algorithms.

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