

Article

An Investigation into the Behavior of Cathode and Anode Spots in a Welding Discharge

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Abstract: The effective development of modern welding technologies and the improvement of equipment and materials inevitably require deep theoretical knowledge about the physical phenomena occurring in the electric arc column and in the near-electrode region. However, there is still no convincing theoretical description of an arc discharge. This article demonstrates, through the generalization of known experimental facts and studies using a high-speed camera, that the conductive channel of an electric arc has a discrete structure, consisting of a set of thin channels through which the main discharge current passes. The cathode spot of an arc discharge is a highly heated and brightly glowing area on the cathode's surface. Electron emission occurs from this region, which supports the discharge as well as the removal of the cathode material. We propose a new technique to study the reverse side of the cathode spot, revealing a structure consisting of individual cells or fragments of the cathode spot. For the first time, we present the anode spots captured by a high-speed camera. We carry out an analysis of the spots' structure. We determine the parameters affecting the mobility of cathode and anode spots. We propose a hypothesis based on the obtained experimental facts about the heterogeneous structure of cathode and anode spots in an arc discharge and the existence of current filaments that affect the mobility of spots during arc combustion.

Keywords: welding arc; vacuum discharge; arc column; optics; cathode spots; anode spots; spark discharge; autograph method; electron microscope



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1. Introduction

Many industries widely use fusion welding technologies for metals and alloys, which use an electric arc as a source of heating and melting [1]. At the same time, many physical phenomena occurring in the cathode and anode regions of the welding arc remain undiscovered [1,2], in particular, the physical nature of the formation, existence, and quenching of cathode and anode spots [3–5]. The development of the work has shown [5–8] that the experimental study of these phenomena is very difficult since one has to deal with a whole complex of complex interrelated physical processes, the course of which strongly depends on the state of the electrode surface. For the same reason, the theoretical description of the cathode and anode regions turned out to be no less difficult [4–8]. Numerous theoretical and experimental studies have shown that the thermal history in the welding arc is closely related to thermal, hydrodynamic liquid and electromagnetic phenomena occurring during electrode melting and in the welding bath, as well as in the arc heat source [2,3,5–20].

Various reviews and monographs [1,4,5,19] summarize the results of numerous studies conducted since 1900 on the processes occurring in the cathode and anode regions of an arc discharge. Refs. [4–19] present the use of atmospheric plasma in the field of material processing, modeling the cathode and anode layers, arc processes in relation to vacuum switches, and surface cleaning from the oxide layer.

To study the behavior of cathode and anode spots in a welding arc, vacuum arc, or plasma arc, various methods are used using high-speed cameras and streak cameras [5,7,10,11,21–23] to obtain high-resolution images of cathode and anode spots and to record spatial and temporal details of spot formation, including the lifetime of the spot. However, the process of obtaining and interpreting recorded images is quite complex and limited, especially in terms of spatial resolution. Moreover, mainly, the use of optical methods gives us information indirectly—by the glow of the plasma above the spot, i.e., a certain optical image. As a physical material object, it is not yet possible to fix the spot itself (cathode or anode). The autograph method is known [7,24], when the property of a cathode or anode spot, size, and shape are judged by the size of the imprint left on the surface of the material. The difficulties of experimental studies are significantly aggravated by the small size of cathode spots and the transience of the processes occurring in them [25].

The literature [7,8,21–23,26–31] presents the types of cathode spots and problematic issues of a theoretical and experimental nature related to obtaining new information. Cathode spots (KS) are complex, nonstationary, self-organizing objects that have microdimensions and exist on microsecond time scales [21]. The KS consists of an overheated, boiling, and exploding volume of metal and a cloud of superdense erosive plasma covering it, the pressure of which reaches tens of atmospheres [5–8]. KS is the source of a supersonic jet of dense, strongly ionized plasma. The current between the metal and the plasma is closed through the KS, which provides the huge energy release density necessary for the existence of the KS [25]. The released energy is absorbed during heating and in the phase transition from solid to liquid and gaseous states, and is also spent on heating, the ionization of this vapor, and the acceleration of erosive plasma and droplets. The lifetime of the KS is determined by the time at which the thermal conductivity in the metal “does not work” [7,8,25]. This is the time during which the heat wave manages to move away along the metal at distances of the order of the spot size. As soon as the heat escapes into the cathode and becomes significant in the energy balance of the spot, it “dies off” because there is not enough energy for its functioning [21–24,26–31]. Instead of a dying spot, a new one appears nearby [7,8]. The need to maintain an energy balance limits the range of currents passed through the control panel [21,22,26–28]. If the current in the electrical circuit exceeds a certain maximum value [24], then the KS is “divided”, i.e., a second KS appears next to it. If the current in the circuit is less than a certain minimum, the KS goes out [24]. The microscopic dimensions of the KP cause a significant influence on various micro-objects on the cathode surface: dielectric inclusions, metal grains, and other inhomogeneities. The cathode material also affects the KP parameters [25].

The successes of recent decades in experimental studies of cathode spots has become possible due to the intensive development of vacuum technology [21–32], the advent of modern computer technology, artificial intelligence [33], digital means of measuring and processing electrical signals, digital photography, etc.

We encountered the issue of a lack of experimental facts regarding the structure and properties of the anode spot in the welding arc when analyzing the sources of information for the literature review. Numerous authors studying arc processes use the term “anode spot” in numerous works, yet no single work focuses on the structure and properties of the spot itself. In open sources of information (scientific journals, monographs, and the Internet), there is not a single photo of the anode spot of the welding arc. Moreover, after analyzing the currently available scientific literature on this issue, we have not been able to formulate the basic properties of the anode spot of the welding arc. Although everyone already knows that the “secret” of the cathode spot of an arc discharge has been “revealed”, so say the author of [25,32] and his associates, that is not the problem; we all

forgot about the anode spot, and it also exists in the arc discharge, and without it, there will be no discharge itself. The paradoxical situation with the anode spot, according to the generally accepted, traditional view, is that the anode spot is a key source of heat during welding, surfacing, and cutting, but in no scientific specialized [2,3,13–16] or educational publications on welding [1] is there even a physical description of this object; there is not a single photo of the anode spot: when welding with coated electrodes, in the environment of protective gases, plasma: welding, surfacing, and cutting.

According to the authors Finkelburg V. and Mecker G. [4], the anode spot has almost unlimited mobility. At the same time, the authors, giving such a definition, believe that the surface of the anode does not play a significant role in the elementary processes of arc discharge at all. They further note that metal arcs with evaporating electrodes of low current strength differ from a carbon arc in exceptional instability. This is due to the instability of the anode and cathode spots [4]. The last mention, in the form of several sentences about the properties of the anode spot on metal arcs, is available in [4]. Specifically, research on the physical processes at the anode of arcs formed by metal vapors has been inadequate. Such arcs can be divided into arcs with compression of the column at the anode and without compression. Arcs with metal electrodes burning in air or in oxidizing gases, as a rule, form a highly compressed anode spot. The anode spot accelerates rapidly along the anode's surface (quantitative values remain unspecified). The high current density (about 103 A/cm^2) often releases steam from the anode. Arcs in inert gases and pure nitrogen have anode compression only at low currents (less than 30 A). Thus, from the fundamental work [4], with a text volume of 370 pages, there is only such brief information on the anode spots of metal arcs. At the same time, there is not a single photo in the text of the work confirming their existence, but it simply declares the existence of anode spots on the faith of the reader.

The classic work by Samerville J. M. [34] presents photographs of the anode spot of an electric arc and autographs left on the surface of metals, along with a brief analysis of their formation. However, if we carefully consider the photographs presented in the work, the following question arises: Which category is being investigated by the author? The photos presented in it belong to the spark category. This statement follows from the references in the photographs given in [34], where these results were obtained [35–37]. For example, in [35], the conditions for obtaining anode prints on the surface of aluminum, copper, and titanium include an arc burning time of 1.5, 20, 200, and 1200 microseconds, a current of 50–80 A, and a spark discharge voltage of 1000–5000 V. The above photographs, taken using a Kerr cell at various intervals after the start of arc ignition, show that the diameter of the anode spot remains approximately constant as the arc length increases. In the case of an arc with a current strength of 80 A, the diameter is 0.03 cm [35]. The authors believe that all current passes through the luminous spot; the average current density is about 10^4 A/cm^2 .

Subsequently, the results of the work [35] formed the basis of the work [34], and, since then, this methodological error has been cited in the works of various authors on welding and vacuum arc. The issue of interpreting the works [35–37] from the point of view of terminology is relevant, since spark discharge and welding arc are two different phenomena, and, therefore, anode prints, having a common nature of occurrence, will differ in shape and properties.

The author of [35] calls the arc a shock arc in terms of exposure time and the rate of current rise, and in [36,37] he already believes that this is a spark discharge. It is possible to assume that at the time of writing this work [34] and setting up the first experiments [35], there was still no clear gradation by types of arc discharge due to the lack of a unified terminology. The above photographs of the formation of the anode spot of a spark discharge [36,37] from disparate spark current channels determined later in more modern works [38–43] over a period of 2 to 50 microseconds show at the final stage (50 microseconds) the formation of a clear large imprint, which we observe in a welding arc [44]. The results of such studies of the microstructure of submicrosecond and nanosecond discharges in air in the mode of single pulses are presented in [41–43].

The studies carried out to date allow us to conclude that with vacuum arcs in the range of currents 200–100 A and voltages 1500–400 V [25,38–41], as well as spark discharges [34–37,42,43] with characteristic parameters in dense gases, the microstructure of channel prints on the surface of flat electrodes is present in a fairly wide range of experimental conditions: different types of gas discharges; different geometries of the discharge gap and electrode materials, as well as their coatings; various gases and their mixtures; different voltage and current levels of nanosecond and submicrosecond duration ranges [41–43]. It is quite natural that the information presented above does not meet the conditions of burning the welding arc on the surface of the molten metal, where the arc burning time is measured from 1 to 100 min, the current is from 10 to 500 A, and the arc voltage, depending on the type of welding, is 10–45 V. Therefore, we cannot correlate the results of the study of the autographs of the anode spots of the work [34,38–43,45–47] and the work of other authors on high-current arc discharge, where currents over 1000 A and voltages over 2000 V correspond to the conditions of the welding arc [1–3,48].

In our work [44,49,50], using modern equipment and new research techniques, it was possible to fix cathode and anode spots in the welding arc. We demonstrate that the cathode spots of the welding arc comprise distinct current filaments and cylindrical channels, whose characteristics dictate the welding arc's technological parameters and the overall behavior of the cathode spot on the metal surface. The welding arc's cathode spots are predominantly circular or oval in shape. The structure of the cathode spot has a spatial hierarchy at the macro-, micro-, and nanoscale levels. It is based on current channels (filaments) with a minimum diameter of 10–60 nm, filling almost the entire area of the spot.

The purpose of this work is to imagine the new methods of visualization of cathode and anode spots of the welding arc developed by us in previous works and to present new results. Based on the new results, a new concept for the study of welding arc discharge should be formulated using the phenomenological method.

2. Materials and Methods

We conducted the experiments at two different experimental facilities. The first of them is an installation for the visualization of cathode and anode spots. To solve this problem, electrical measurements and high-speed photographing of the cathode and anode bindings of the arc were carried out (Figure 1). At the next stage of work, the same installation was partially rebuilt to conduct studies of the reverse side of the cathode spot (Figure 2). In methodological terms, most of the experimental methods are described in detail in our works [44,49,50]. We conducted studies on the visualization of anode spots in the welding arc in a protective gas environment burned vertically between a tungsten nonmelting cathode (4 mm in diameter) and a replaceable copper or steel anode (Figure 1). The massive anode had a flat polished surface (Figure 1b). The thickness of the plate was 10 mm. The anode material was low-carbon steel. The arc's length varied from 3 to 15 mm. The total arc burning time was 0.2 s until the formation of a molten metal bath (Figure 1c). An industrial source of direct welding current, with an idle voltage of 70 V and a maximum current of 250 A, powered the arc. The current was regulated in the range of 5–100 A. A high-voltage pulse ignited the discharge in the welding torch. High-purity argon was used as a protective gas. We used a Tektronix TDC-1012B digital oscilloscope to measure current and voltage. We used low-cost digital SLR cameras (SONY 350 series (Sony EMCS Kosai Tec, Tokyo, Japan), Canon 550d-18–50 series (Canon, Tokyo, Japan)) for optical temperature measurement using the brightness pyrometry method.

Working with the camera proceeded as follows: We switched the camera to manual operation and disabled the image preprocessing functions, particularly noise reduction. The object was photographed with the recording of a file in uncompressed format ("raw"), which was transferred to a computer, and the file was transformed into TIFF format (R, G, B). Then, each channel of this file was recorded as a separate file in TIFF format in grayscale (8 bits), and the output signal was within the range of 0–255 pixels for each channel. We used standard Adobe Photoshop C3 and Lightroom programs for computer

processing. The image quality (objective shooting indicators) was evaluated based on the results of shooting a Kodak Q13 test target and a target (65 × 45 cm, shooting in full frame) to check resolution, distortion, and chromatic aberrations. We calibrated digital cameras for temperature measurement by changing the incandescent current of a SI-8 lamp and fixing the temperature. The temperature resolution for this calibration was 1.2–1.8 K. The temperature in the arc column was determined by the absolute intensity of radiation in the continuous argon spectrum at a wavelength of $\lambda = 480.6$ nm. We recorded the continuum's brightness using a PGS-2 spectrograph. We used the glow of the anode spot of a carbon arc with a known spectral brightness as a reference. We converted the observed arc intensity profiles into radial radiation densities by solving the Abel integral equation. To compare the temperature profile, experimental data obtained from argon radiation in [10–15] were used.

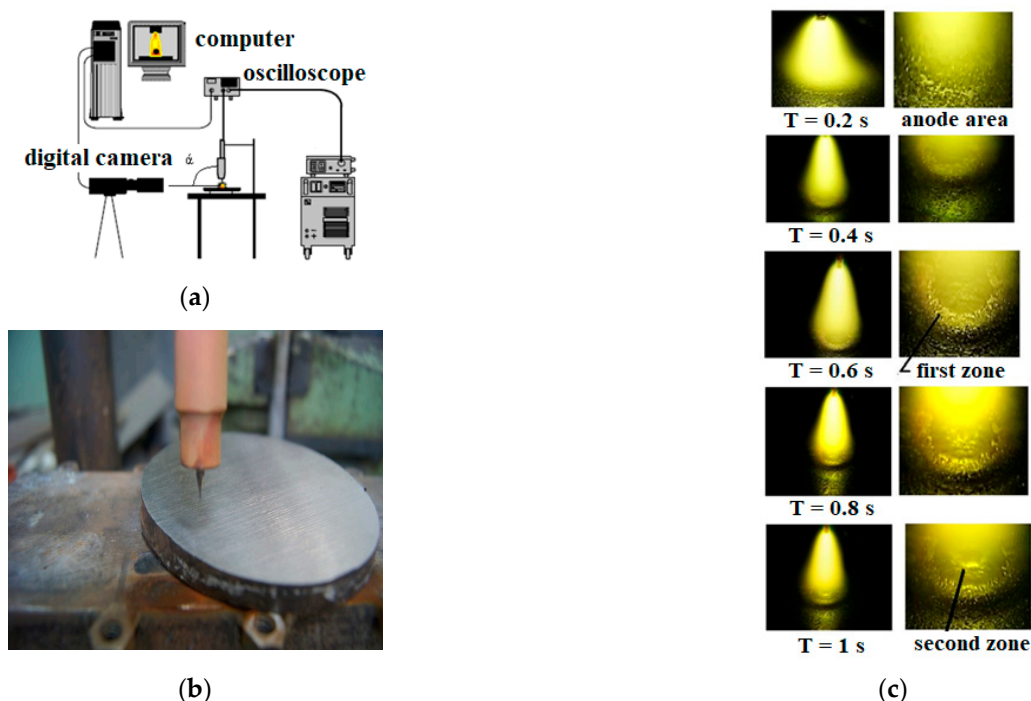


Figure 1. The scheme of the experiments: (a) general, (b) the type of plate and electrode, (c) a fragment of the film from the work [49].

Studies using the autograph method [24] were carried out on film cathodes. In studies, samples with film cathodes were prepared by thermal evaporation in vacuum [41] by applying thin (10–350 nm) layers of copper, gold, and silver to substrates of lime-sodium glass measuring 25 × 60 mm, 2 mm thick, using a vacuum universal post VUP-5M. The films were sprayed at a residual gas pressure of $p = 1 \times 10^{-8}$ Pa and a substrate temperature of $T = 70$ °C. We subjected all substrates to double pretreatment: first, we chemically etched them in a chromium mixture solution ($\text{Na}_2\text{Cr}_2\text{O}_7$ —100 g, H_2SO_4 —50 g, and distilled water—up to a liter), followed by plasma chemical purification using the Nano Clean “Model 1070” installation (Fischione Instruments, Export, PA, USA). Microscopic and gravimetric methods determined the thickness of the deposited films. We studied aluminum films using ready-made samples from aluminum mirrors. The research employed a reverse-polarity direct current welding arc with a current strength ranging from 2 to 60 A, burning vertically between a tungsten nonmelting electrode (2.4 mm in diameter) and a film cathode in argon shielding gas environment.

The arc burned steadily. The total arc burning time was 0.03–1 s. During arc burning, cathode spots form on the surface of the film cathodes, the film evaporates under the action of heat, and a thermal imprint remains on the surface of the glass (autograph)

(Figure 2). The conditions of the experiment correspond to the real technological process of welding with a nonmelting electrode (tungsten) in a protective gas environment (argon) at a direct current of reverse polarity (minus on the product), which is used in industry for welding products made of steel, aluminum, copper, and titanium. The arc-burning process was recorded by a digital SLR camera (a Sony 350). To record the first series of experiments of sequential images during the arc burning act, high-speed cameras were used: RCO.1200 hs, RCO.120 s, NIKON AF-S DX Zoom lens-Nikkor ED, CMOS matrix, pixel size: $12\ \mu\text{m} \times 12\ \mu\text{m}$, resolution: 1280×1024 pixels, exposure time range: 1 Gorenje ns–5 s, interframe viewing time: 75 ns, dynamic range: 59.6 dB, spectral sensitivity: 290–1100 nm. At a maximum resolution of 1280×1024 , the maximum shooting speed is 501 fps. At a minimum resolution of 128×16 pixels, the maximum shooting speed is 32,000 fps. To record the second series of experiments, a high-speed Phantom v711 camera with a CMOS (CMOS) resolution of 1280×800 pixels and a shooting speed of 7530 fps was used. The bandwidth is 7 Gpix/sec with a resolution of 1 megapixel, and the pixel size is 20 microns. The maximum shooting speed is 1,400,000 fps.

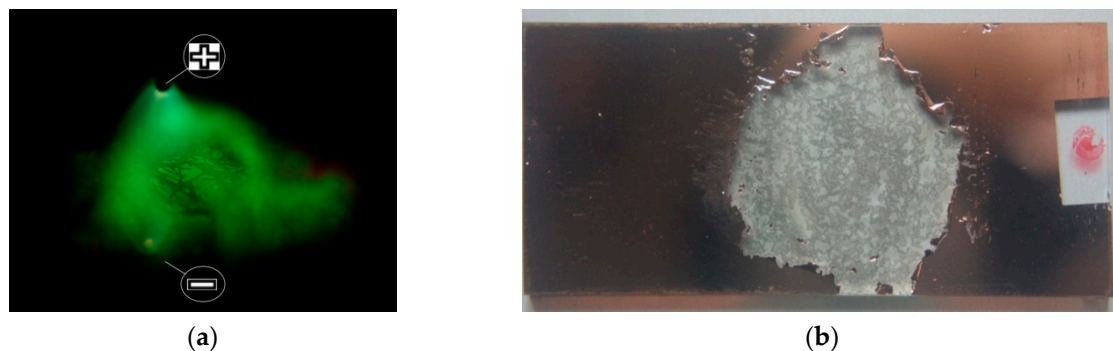


Figure 2. Color photo of the reverse polarity welding arc burning process on a copper film: (a) completion of the process, (b) appearance of the sample surface after evaporation of the copper film [44].

The minimum exposure time is 300 ns. The visualization technique and processing of the obtained images are described in detail in [44,49,50]. In addition, methodological recommendations for image evaluation and the results of various authors' work in this area of research were taken into account [23–25,32–37]. We used the Tektronix TDS-1012 B digital (Tektronix, Beaverton, OR, USA) oscilloscope to measure current and voltage.

The method of shooting was as follows: We used a front trigger to set up the data logger, triggering it either by voltage or current. Registration started when the set voltage and current values were reached. In the process of measuring the state of the data logger, the interval and time for measuring voltage and current during welding were set to 1 microsecond and 50 ms–1 min, respectively. We connected the data logger's output trigger terminal to the input terminal of a high-speed video camera. When the trigger signal was received from the data logger, the high-speed video camera immediately began shooting. The time delay between the data recorder and the high-speed video camera was 2 microseconds. The survey was conducted at an angle of $\sim 7\text{--}15^\circ$ with respect to the cathode, depending on the interelectrode gap. To accurately determine the position of the spots in the immediate vicinity of the electrodes, superminiature lamps (CMN 10-55-2) were placed in such a way that their image fell into each frame. The image size of a single cathode and anode spot in the file containing its image (half-width at half the maximum brightness of the glow) was 4–5 pixels (1 pixel $\approx 0.067\ \text{mm}$), which is determined by the resolution of the camera. Thus, the spatial resolution can be estimated at about 0.25 mm.

We examined the samples with the fingerprint using a JEOL JSM-Z4500 scanning electron microscope (JEOL, Tokyo, Japan) and a Solver P47-PRO probe microscope (NT-MDT, Tempe, AZ, USA). The morphology of the surface of the films was studied by atomic force microscopy (AFM), consisting of sequential scanning of the surface of the samples in

mutually perpendicular directions with a frequency of 0.95 Hz in contact, semicontact, and noncontact modes.

The technique of studying the reverse side of the cathode spot is described in detail in our work [50]. The only difference is the placement of the high-speed camera on the back of the glass samples. Figure 3 shows the schematic diagram of the experiment, depicting the placement of two high-speed cameras that simultaneously record the image of the front (obverse) and reverse (reverse) sides of the cathode spot.

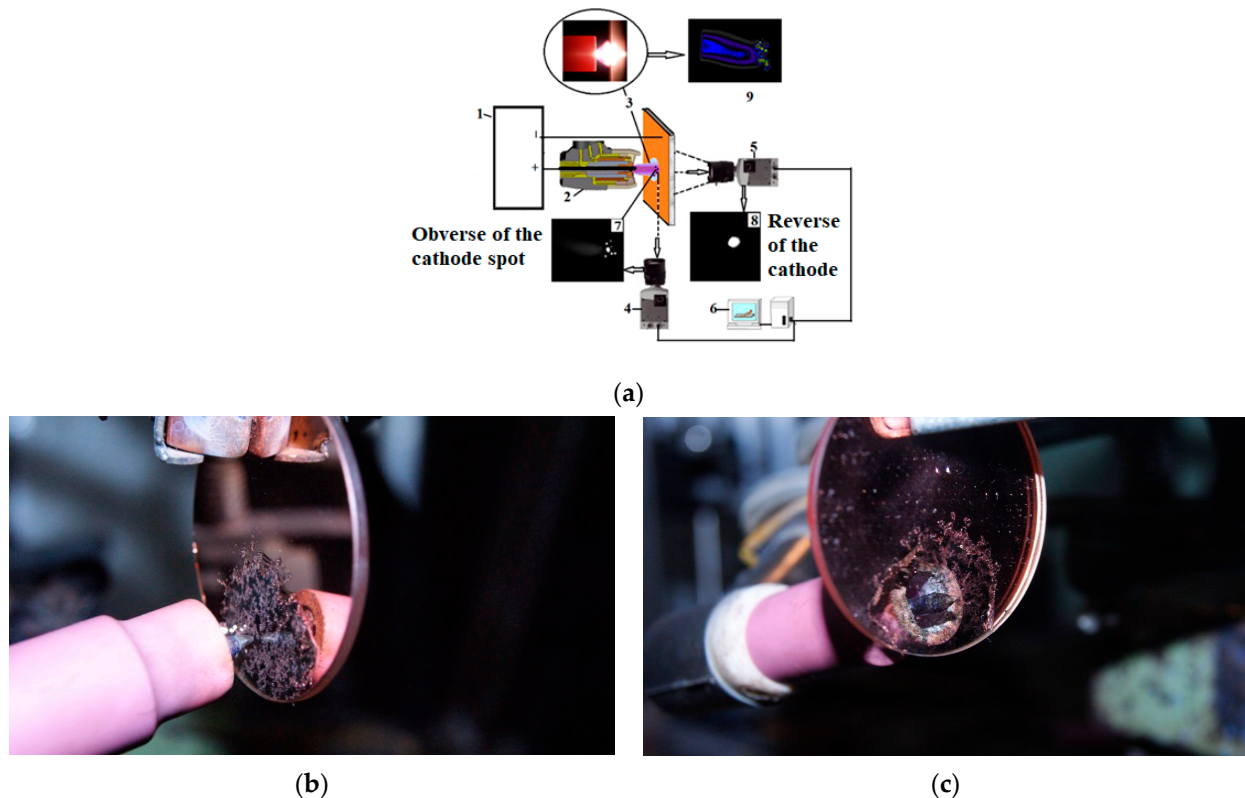


Figure 3. Diagram of experiments on fixing the back side of the cathode spot (a) and the appearance of coated plates after burning the welding arc; the working area of the filming from the front (b) and back side of the plate (c). 1—welding current source; 2—welding torch; 3—spot registration area on the front side; 4, 5—high-speed cameras; 6—image processing unit; 7, 8—example photo of a cathode spot on the front and back of a glass plate; 9—color photo of cathode spots on the front side.

3. Results

To ensure the possibility of photographing the surfaces of both electrodes, the optical part of the installation was as close as possible to the welding arc column and a real image of the working surfaces of the cathode and anode was created in the interelectrode gap. The welding arc can be conventionally represented as separate stages of formation [1–3]. The first stage is the breakdown of the arc gap by a high-voltage pulse (spark discharge) breaking down the arc gap. At this stage, the arc gap ionization creates the conditions necessary to excite the welding arc.

3.1. The Spark Stage

At the first stage, the stages of arc ignition in the form of a high-voltage spark discharge are recorded (Figures 4–6), and the anode glow area is visible before the breakdown. Next, the first anode spots appear (Figure 4b). The cathode region is still in shadow; there is no bright glow. In Figure 4c,d, the spark discharge column is already visible.

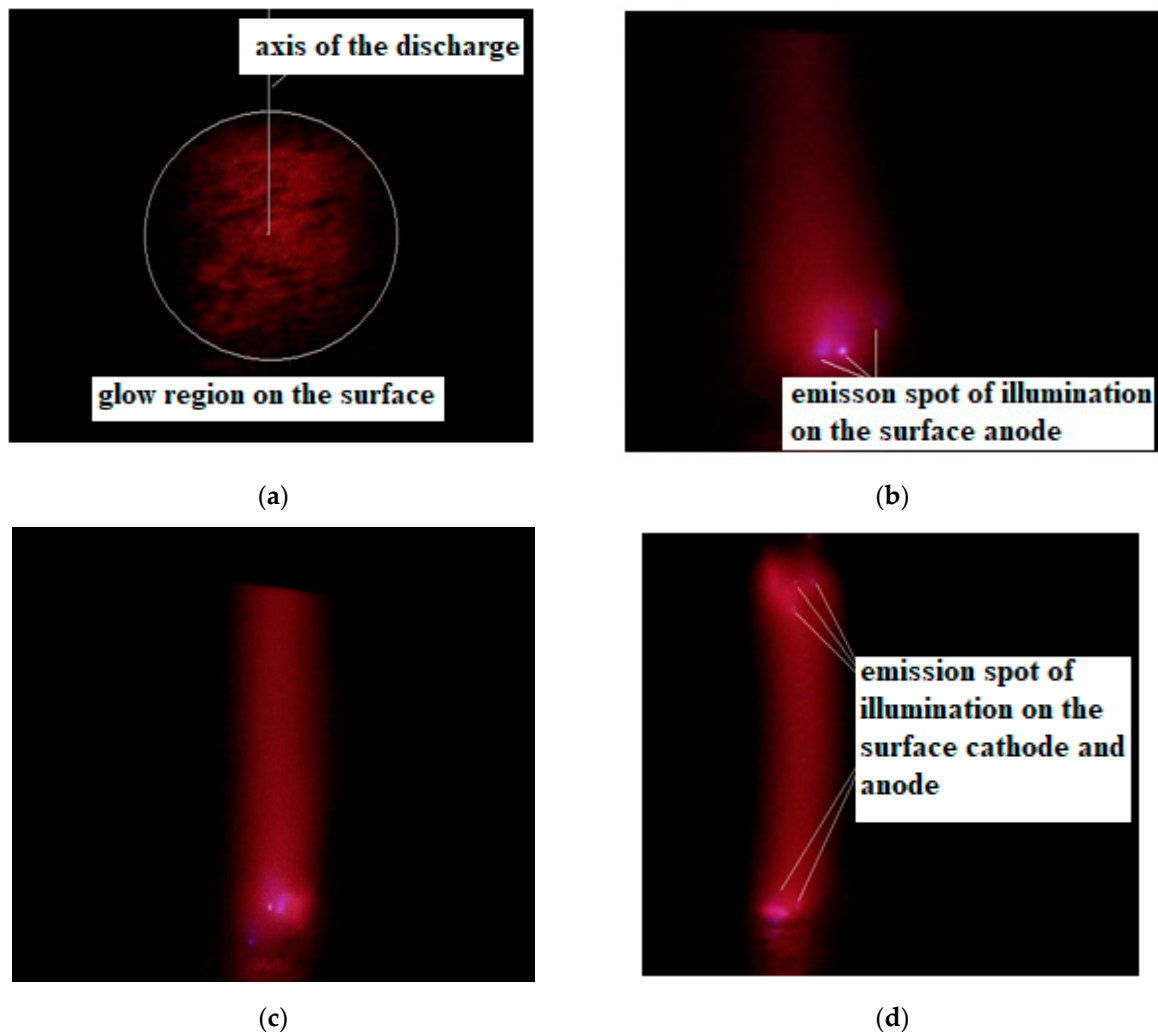


Figure 4. The initial stage of binding the spark row to the steel surface (shutter speed 1/100, aperture $F = 36$, focal length 78 mm): (a) the primary glow on the anode before breakdown, (b,c) the appearance of the first anode spots, (d) emission centers.

In the presented photos, the temporal and spatial resolution of the images of the anode and cathode spots are $39 \mu\text{s}$ and 41 microns per pixel. These dimensions significantly exceed the cathode spot's lifetime and the crater spot's radius. The photo of the spots reflects the brightly luminous plasma that emanates from the cathode and anode spot areas. The size of the dense plasma significantly exceeds the actual size of the cathode spot, i.e., the emission site, which can be considered a crater. Therefore, the cathode spot looks much larger than its actual size. We then increased the flash duration to 1.5 ms, enabling us to visualize the electrode processes throughout the entire shooting time. As a result, we obtain the opportunity to capture both the anode surfaces and the actual image of the cathode surface simultaneously. Figure 7 illustrates the outcome of the photography process. The anode is located at the bottom of the frame, and the upper part of the frame is the cathode. The cathode surface is inaccessible for photographing, and we see part of its image, 5 A, in the frame. In the image, the cathode spots are clearly visible. We take a direct photo of the anode's surface. We draw a thin line on the anode's surface in the photo for ease of viewing. Experiments showed that near the anode, one can observe fairly clear contours of the anode glow (Figure 4a), which allows one to determine its location.

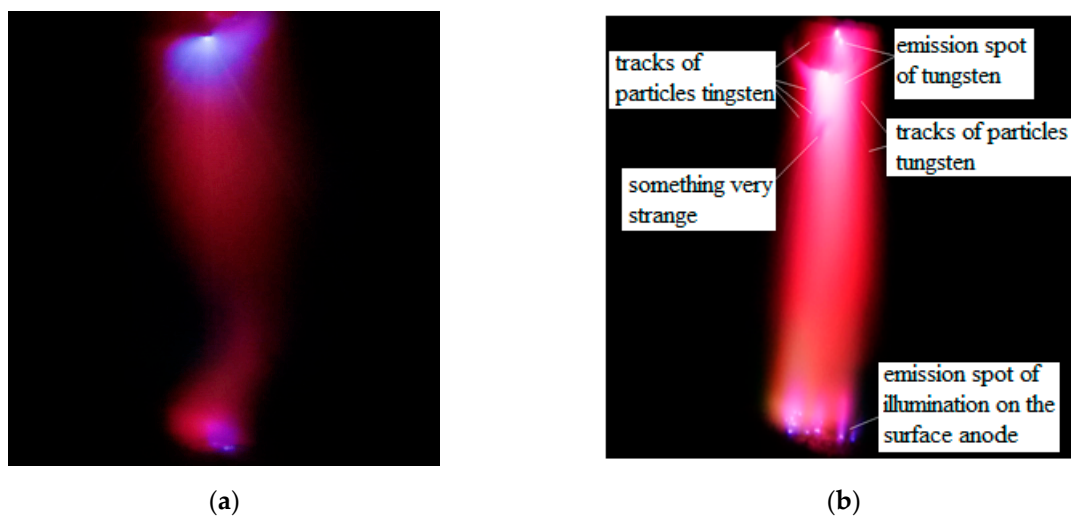


Figure 5. The cathode spot on the tungsten electrode and the anode spot on the surface (shutter speed 1/25, aperture F = 32, focal length 82 mm): (a) single spot, (b) series of spots.

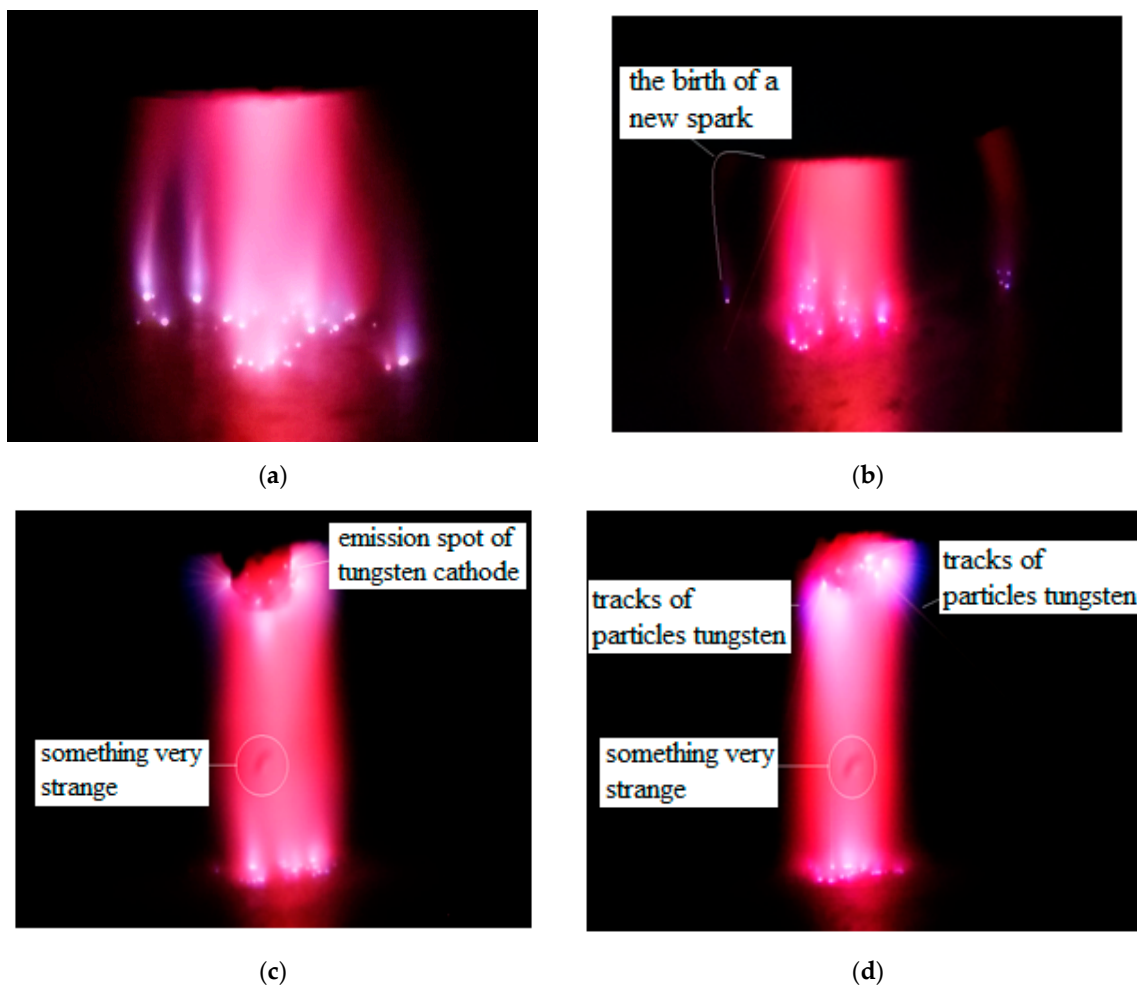


Figure 6. Multiple anode (a,b) and cathode spots (c,d) on the metal surface in the stage of spark breakdown of the arc gap (shutter speed 1/3, aperture F = 32, focal length 82 mm).

Thus, in principle, it is possible to simultaneously determine the position of the arc bindings on both electrodes using such photographs. However, a thorough examination of the photographs revealed distortions in the electrode images. The fact is that the

experimental conditions dictated the need to use large angles of field of view. As a result, distortions appeared in the electrode images. The distortion of the anode was weak because it was photographed directly, and the distortion of the cathode was stronger because not the entire cathode was photographed, only part of it. Figure 6 clearly shows multiple anode spots in the stage of spark discharge development.

In the presented photos, the temporal and spatial resolution of the images of the anode and cathode spots are 39 μ s and 41 microns per pixel. These dimensions significantly exceed the cathode spot's lifetime and the crater spot's radius. The photo of the spots reflects the brightly luminous plasma that emanates from the cathode and anode spot areas. The size of the dense plasma significantly exceeds the actual size of the cathode spot, i.e., the emission site, which can be considered a crater. Therefore, the cathode spot looks much larger than its actual size. We then increased the flash duration to 1.5 ms, enabling us to visualize the electrode processes throughout the entire shooting time. As a result, we obtain the opportunity to capture both the anode surfaces and the actual image of the cathode surface simultaneously. Figure 7 illustrates the outcome of the photography process. The anode is located at the bottom of the frame, and the upper part of the frame is the cathode. The cathode surface is inaccessible for photographing, and we see part of its image, 5 A, in the frame. In the image, the cathode spots are clearly visible. We take a direct photo of the anode's surface. We draw a thin line on the anode's surface in the photo for ease of viewing. Experiments have shown that near the anode, one can observe fairly clear contours of the anode glow (Figure 4a), which allows one to determine its location. Thus, in principle, it is possible to simultaneously determine the position of the arc bindings on both electrodes using such photographs. However, a thorough examination of the photographs revealed distortions in the electrode images. The fact is that the experimental conditions dictated the need to use large angles of field of view. As a result, distortions appeared in the electrode images. The distortion of the anode was weak because it was photographed directly, and the distortion of the cathode was stronger because not the entire cathode was photographed, only part of it. Figure 6 clearly shows multiple anode spots in the stage of spark discharge development. Figure 7 shows the stages of one spark (Figure 7a) and two (Figure 7b), as well as the transition from the spark stage to the arc, which is recorded for the first time (Figure 7c,d). The contact area with the anode spots is clearly visible (Figure 7a,b). A current channel is visible. Nearly every anode spot has a torch pointing towards the cathode.

We can divide the spark discharges observed at the first stage of welding arc excitation into two types. The first kind of spark discharge happens when an arc discharge forms in the space between the cathode and anode. The current flow of charged particles in a conductive medium known as plasma causes this (Figure 4b–d). The second type of spark discharge manifests as an auxiliary spark discharge, taking place in a section far from the anode's surface, near the maximum value of 2–3 mm (refer to Figure 6b). Spark bindings and the formation of anode spots are visible on the periphery of the first spark discharge. We see a pronounced arc discharge column due to the strong, intense glow (Figure 7c,d). A column of plasma is clearly the brightest source of radiation, at least in the optical range of the spectrum. The column has grown, but at the same time, anode spots formed during spark discharge remain on the anode's surface. The cathode region has an intense glow, but already in Figure 7, individual cathode spots are visible, and new anode spots of arc discharge have formed on the surface of the anode in the cathode–anode gap. Simultaneously, the cathode spot (Figure 7d), located at the base of the cathode column, serves as the center of a diffusely luminous discharge region resembling a hemisphere. In the future, these anode spots will combine into one spot and cause strong heating and melting of the anode surface. The formation of a molten metal bath transforms the arc binding that pushes back through the anode spots into the diffusion form of discharge binding [50,51].

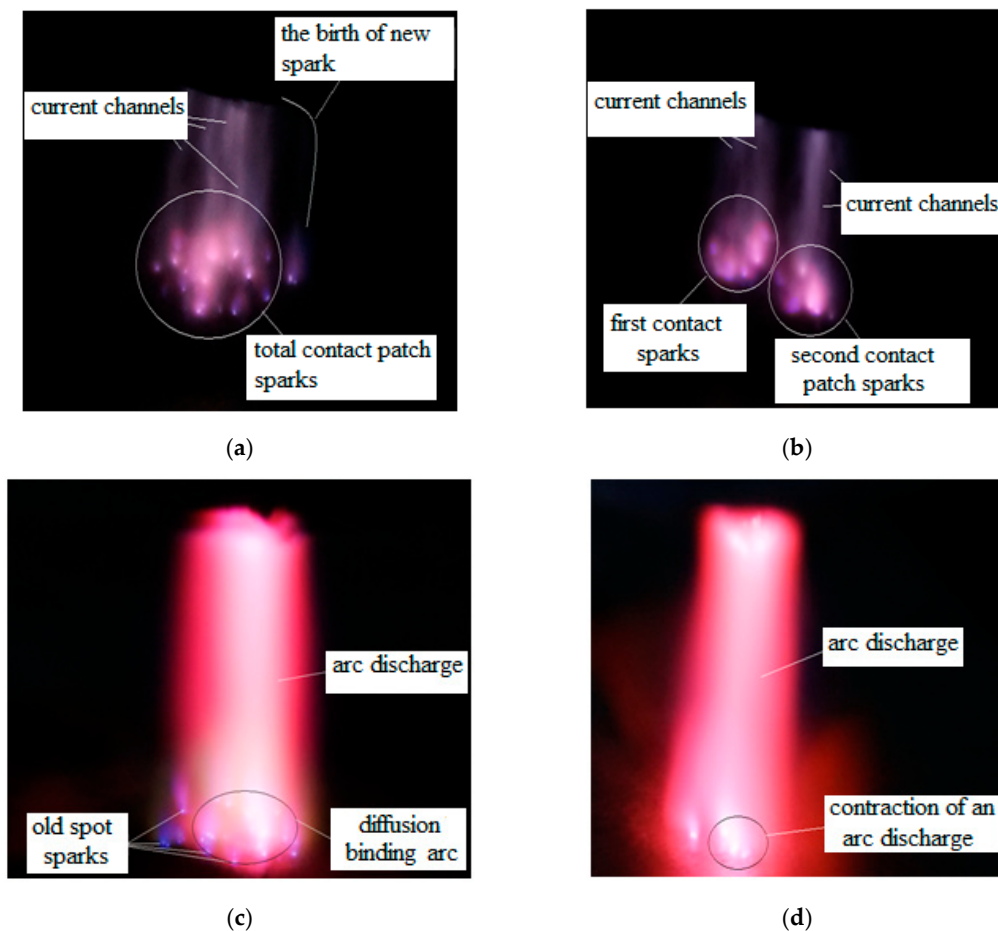


Figure 7. Stages of spark discharge with current channels of one spark (a); the second spark (b); transition to arc discharge (c,d).

It is well known [51] that current transfer to the cathodes of arc discharges in surrounding gases can occur both in the point mode, when most of the current is localized in cathode spots occupying a small part of the cathode surface, and in the diffuse mode. This mode distributes the electric current more or less evenly over the cathode's front surface. The diffuse mode is favored by a high average cathode surface temperature, which can be achieved by reducing the size of the cathode [51]. Many observations show that there are two main ways for the arc to burn at the anode: (a) with a counteracted (compressed) anode spot and (b) with a diffuse (spread out over a large surface) arc–anode contact zone. The shape of the plasma contact zone with the anode surface is due to the action of a number of factors, such as arc current, pressure, type of plasma-forming gas, plasma velocity, etc. With a diffuse arc–anode contact zone (diffuse binding), the current density at the anode is either comparable to or less than the current density in the arc column. In this mode, an increase in the current in the anode region of the arc is not required; on the contrary, sometimes it may be necessary to reduce the electronic current. In this case, the anode, under the action of an electron flow, can take on a negative charge and begin to slow down excess electrons from the arc column. With a counteracted arc, the current density at the anode is noticeably higher than in the plasma of the arc column. In this case, an ionization amplification of the current occurs in the anode layer, which is possible with an additional contribution of energy to the electron flow.

3.2. Arc Discharge Stage

The welding arc is a source of not only visible but also infrared and ultraviolet rays. It is known that about 70% of the radiation energy is released in the form of ultraviolet,

15% in the form of infrared radiation; these are all rays not visible to the human eye and only 15% in the form of visible light [1–3]. The UV radiation of the welding arc is divided into three types by wavelength: UV-A (320–380 nm), UV-B (290–320 nm), and UV-C (180–290 nm). Open shooting without special filters will not give us the opportunity to obtain high-quality photos of anode spots due to the intense glow of the welding arc column. We use radiation from the molten metal of the welding bath and metal vapors above its surface when building passive video surveillance systems. The radiation from the arc column present in the general spectrum should be considered a source of illumination and, at the same time, an obstacle. The intrinsic radiation spectrum of the arc column and its reflex reflection from the surface of the welding bath, consisting of atoms and molecules of ionized shielding gas, are predominantly of nonmetallic origin. On the spectral spectrum, it occupies the ultraviolet, red, and near-infrared zones [1]. The radiation from the welding bath is metallic in nature (glow lines Fe, Ag, Mo, Mn, etc.) and manifests itself in a wide range of spectral frequencies. Interference filters with a degree of monochromatism of 10–20 Å are used to increase the ratio of the radiation intensity of the bath to the arc, which provides contrasting boundaries of the contour of the welding bath. The wavelength of the filter is selected in the areas of the spectrum where there is a significant attenuation of radiation from the arc and where the maximum radiation from the welding bath and metal vapors is located at its surface (Figure 8).

By looking at a group of graphs for the type of welding being considered, it is possible to pick the wavelength of an interference light filter that blocks the most radiation from the arc while letting the most radiation from the welding bath pass through. In the case under consideration, we observe the highest signal ratio from the bath to the arc at a filter wavelength of about 830 nm. We see in Figure 7d a bright spot on the surface of the melt. The spectral sensitivity of CCD arrays reflects the matrix's sensitivity in relation to the wavelength of the received radiation. Most cameras typically have a wider spectral sensitivity than the human eye, extending into the infrared range up to wavelengths of 1000 nm, unless they use special filters during matrix production. Thus, unlike the eye, whose spectral sensitivity is limited to the visible range of radiation, the camera, due to its fundamentally different device, is also able to register the near range of IR radiation.

Television cameras perfectly record infrared radiation, which is not visible to the human eye. In this scenario, we select these wavelengths to place the radiation spectrum in the near-infrared zone, commonly referred to as the near IR range, where the matrix's sensitivity is still sufficient to produce a monochrome image. The camera's sensitivity to near-infrared radiation makes it possible to use IR illumination. Many studies have been carried out on how to see vacuum and arc discharges [11–22,26–29]. Based on what we learned, we chose light filters with a wavelength of 400–1100 nm from the brands IKS-1, IKS-3, IKS-5, IKS-6, and IKS-7 (GOST 9411–911). We settled on the X-5 light filter (a foreign analogue of the infrared filter B + W 092), which blocks the visible spectrum up to 650 nm. It passes only 50% from 650 nm to 730 nm (hence the dark red color), 730–2000 nm—passes more than 90% of the spectrum.

Figure 9 shows a photo of a stationary burning welding arc, where the cathode is at the top, and a molten metal bath with an anode spot at the bottom. After removing the ultraviolet radiation with a light filter, we immediately reached the high-temperature areas in the welding arc. This is the cathode region where electron emission occurs, the almost cylindrical shape of the welding arc column, and the anode spot on the surface of the molten metal (Figure 9). With an increase in the welding arc's burning time and the volume of molten metal, the anode spot changes position and size. Figure 10 shows a visualization of the anode spot in the welding arc in motion (3.5 mm/s). We see that in the first stage of Figure 10, the arc has diffusion binding, the molten metal bath is relatively calm, and there are no disturbances on the surface. There is an intense glow around the edges. Next, an anode spot of a blurred shape (Figure 10b) is formed on the surface of the bath. As the arc moves, the spot is located in the center of the bath. In Figure 10c, six anode spots already appear, in a shape close to a circle, which combine into large spots (Figure 10d,e).

Of interest is Figure 11, which shows the surface of the cathode and anode at the moment of switching off the welding current. The cathode spot continues to emit a low-intensity plasma torch towards the anode on the cathode's surface (Figure 11b,d).

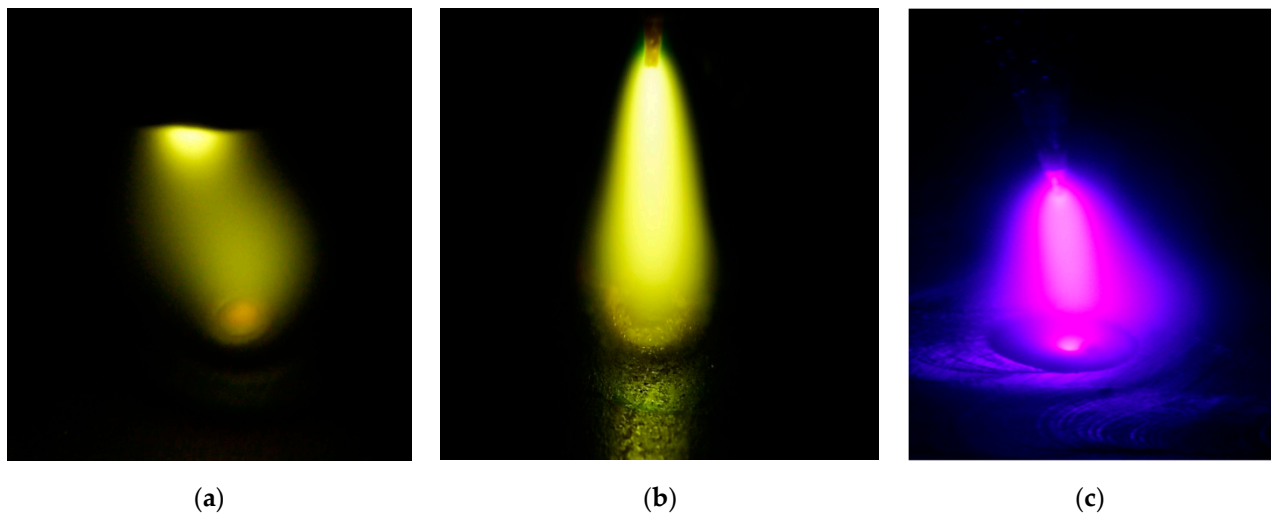


Figure 8. Welding arc shooting under different shooting conditions: (a) shutter speed 1/3, aperture $F = 32$, focal length 82 mm; (b) shutter speed 1, aperture $F = 16$, focal length 82 mm; (c) light filter: the wavelength of the filter is about 830 nm.

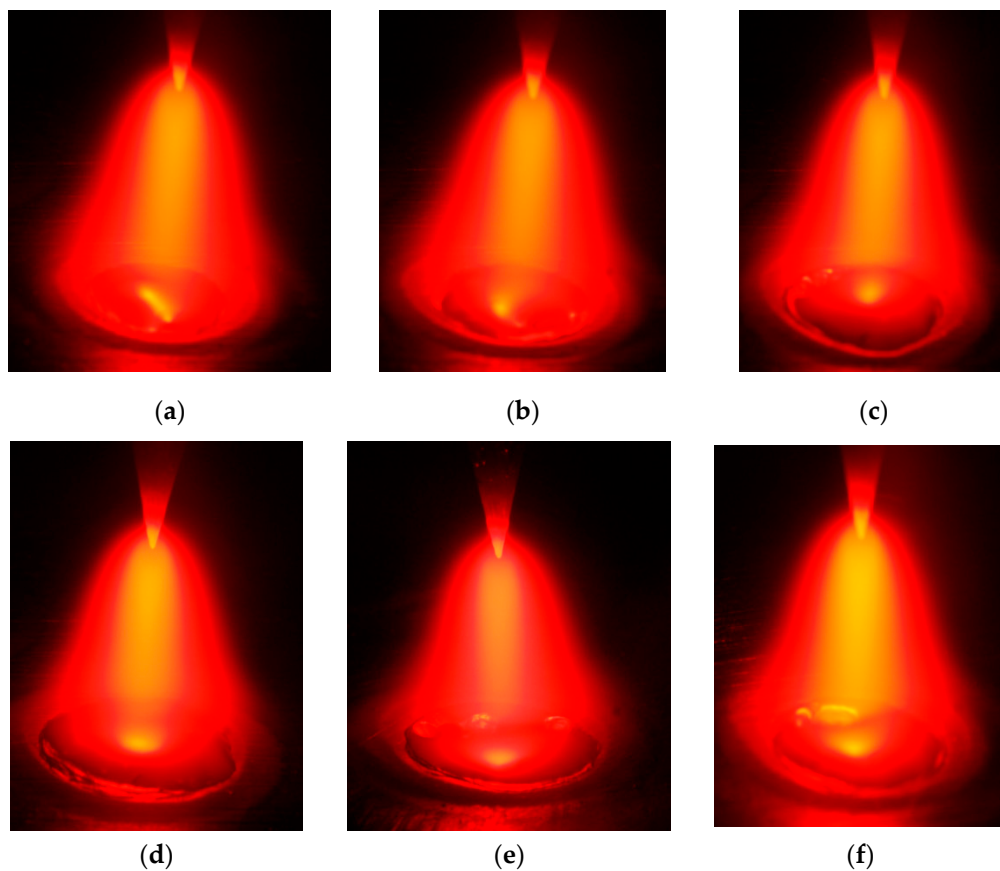


Figure 9. Visualization of the anode spot in the welding arc depending on the burning time: (a) 5 c, (b) 7 c, (c) 10 s, (d) 12 c, (e) 15 s, (f) 20 s (mode-I = 30 A, $U = 14.5V$).

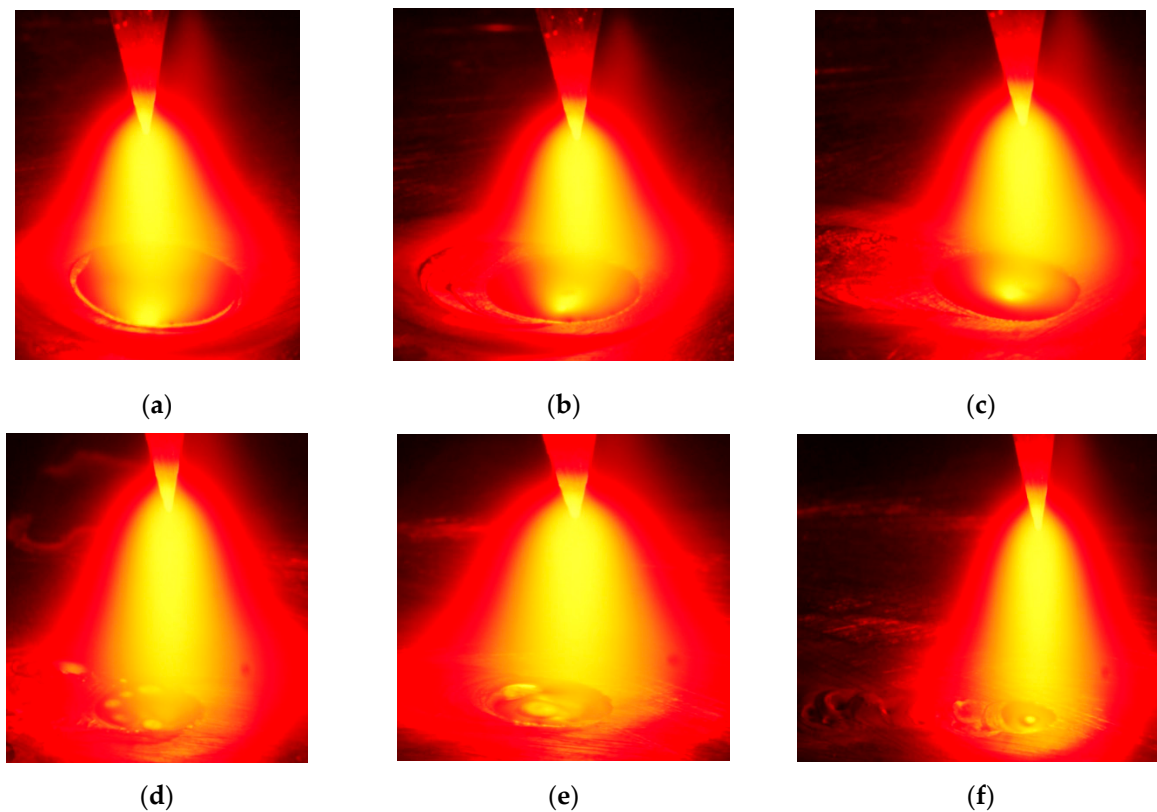


Figure 10. Visualization of the anode spot in the welding arc in motion 3.5 mm/s, $I = 50$ A, $V = 12.5$ V: (a) 2 s, (b) −5 s, (c) 9 s, (d) 12 s, (e) 15 s, (f) 18 s.

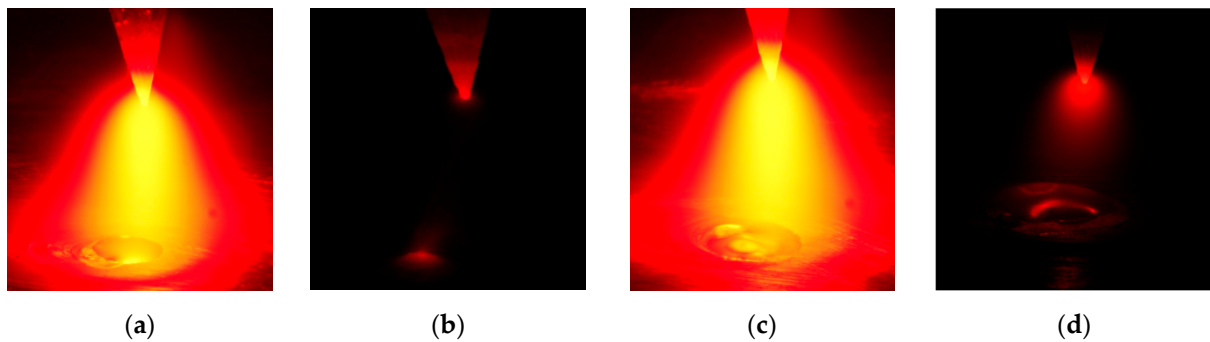


Figure 11. Visualization of the inertia effect of emission processes in a stationary burning welding arc: (a)—anode spot under current load; (b)—turn off the current; (c)—anode spots under current load; (d)—arc switched off, no electric current.

The effect of inertia on emission processes in a moving welding arc is particularly well visualized in Figure 12. It can be seen that as the welding arc moves towards the edge of the sample, the shape of the anode spot changes (Figure 12a–c). At the very edge of the sample, the anode spot has a plasma torch, which is directed parallel to the surface of the sample, and the arc column deviates (Figure 12b). Further, as the welding arc lengthened and closed on the substrate of the table, the anode spot continued to exist and also deviated to the side (Figure 12d). After switching off the current at the cathode, the cathode spot with a plasma torch continued to function (Figure 12e).

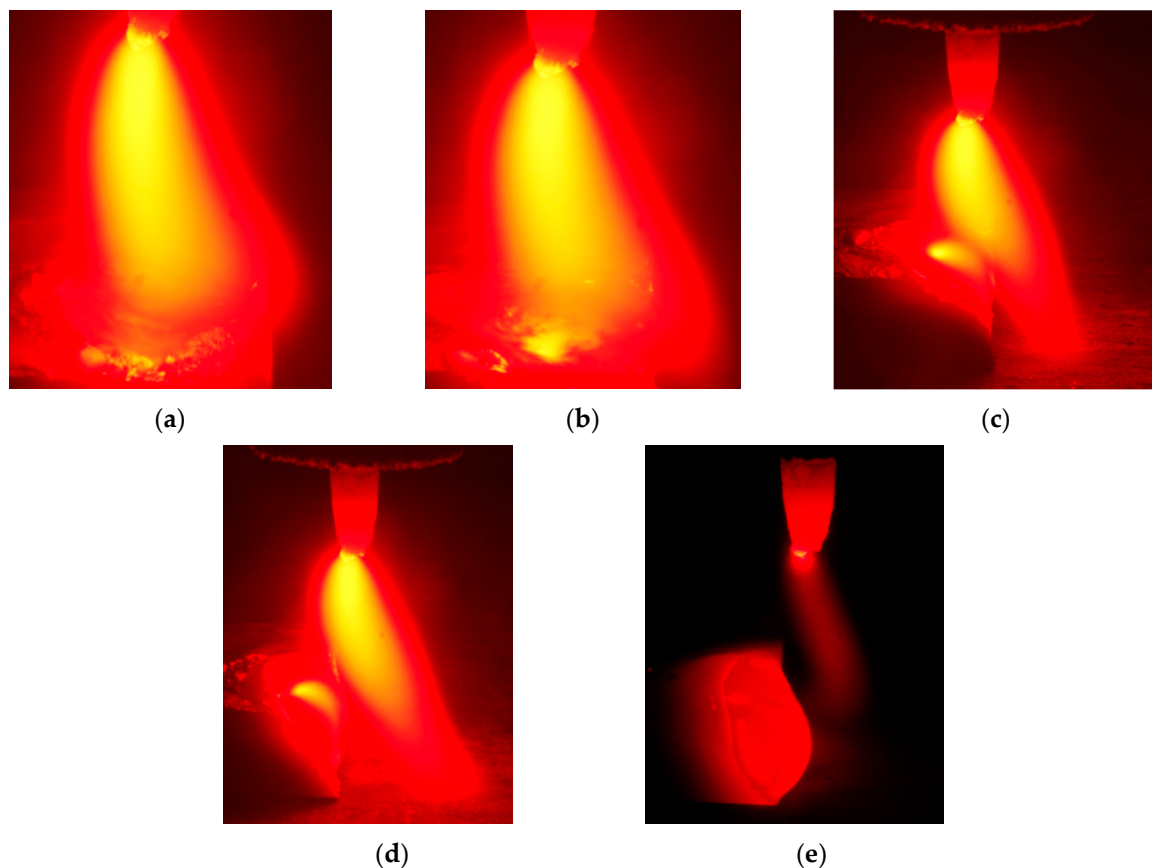


Figure 12. Visualization of the inertia effect of emission processes in a moving burning welding arc (mode: in motion 3.5 mm/s, $I = 50$ A, $U = 12.5$ V): (a)—weld pool along the edge of the sample; (b)—formation of a network of anode spots; (c)—contraction of the spot network into one large anode spot; (d)—division of the welding arc into anode and cathode string modes (e)—switching off the current, the anode and cathode spots continue to exist.

Figures 13 and 14 show anode spots that form a round melt spot on the surface of the molten metal. We see that round-shaped anode spots have formed on the surface of the molten metal.

In Figure 13a, the burning time of the welding arc was 5 s; this did not prevent a large volume of the welding bath from forming on the surface, which was formed by round-shaped anode spots. Next, we see Figure 13b–d, where the arc burning time increases and the spots on the surface of the bath do not disappear. Simultaneously, the current and voltage waveforms do not show any spikes.

Figure 14 shows the shape of the anode spot with the location of the spots along the circumference and with one central spot, similar to a wheel with spokes. During the experiments, we found that at the moment of ignition, a brightly glowing central region appears in the discharge. After 100–250 ms, a less bright second area appears, surrounding the first. A third, dark area, poorly reflecting light, is located along the edge of the spot. Comparing the size of the anode spot in the autographed photo shows that the maximum dimensions in the photo are comparable to the size of the bottom of the shallow edges of the well. As the discharge develops and the current increases, the central region oscillates in the direction of increasing and decreasing size, with particularly noticeable fluctuations on materials with low thermal conductivity. When the current increases to 10–25 A, it rebuilds the spot, expands the central area to the “limit”, and transforms into a ring of individual spots (Figures 13c and 14).

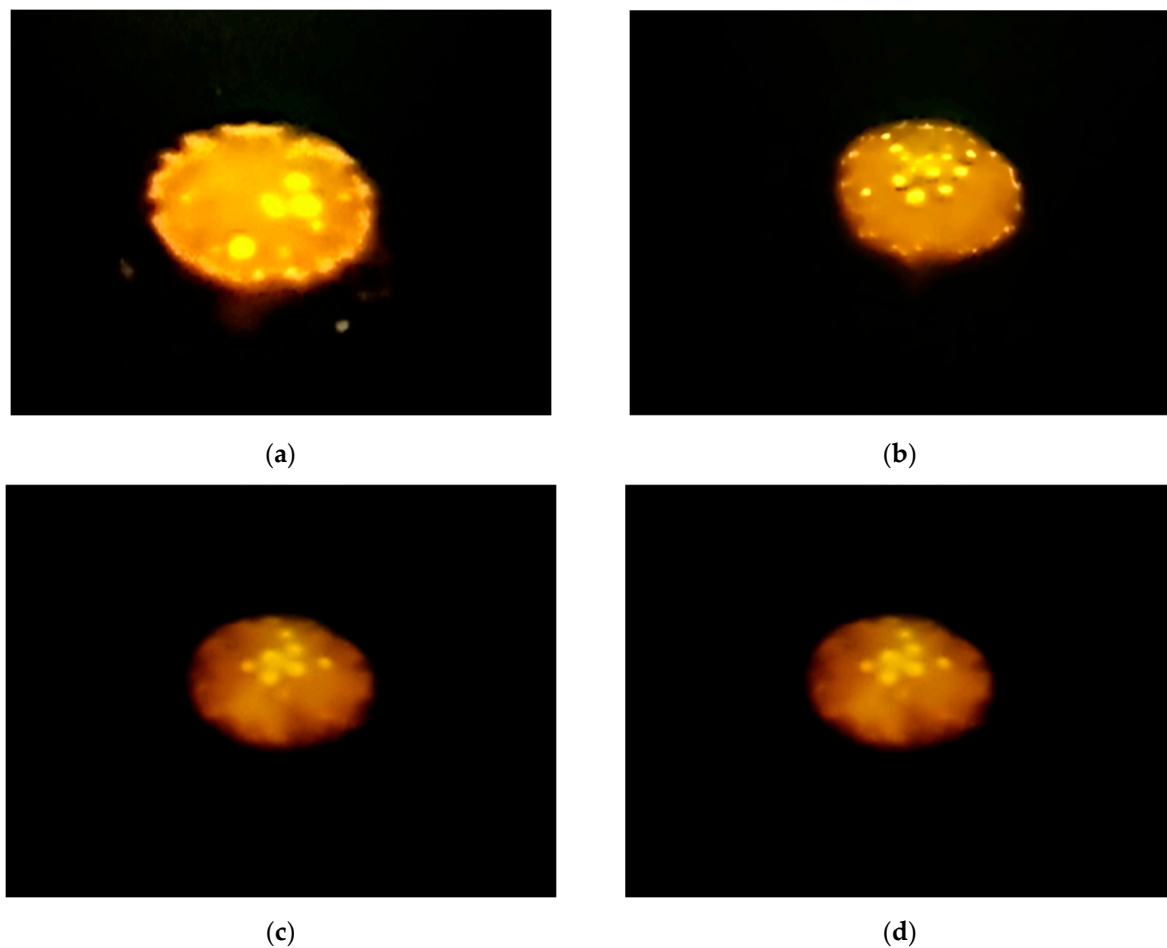


Figure 13. Anode spots on the surface of molten metal (a) 5 s; (b) 7 s; (c) 9 s; (d) 12 s (mode-I = 20 A, $U = 10.5$ V).

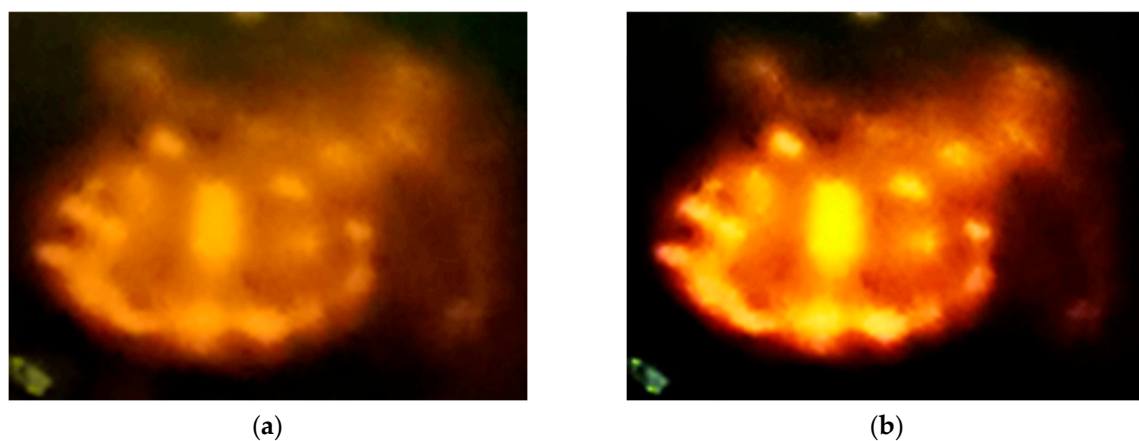


Figure 14. Anode spot with peripheral binding: (a) original photo, (b) the processed photo using a brightness gradient filter.

Moreover, the size of the spots is approximately equal to the central spot at the time of ignition. After several tens of milliseconds, the ring disappears, and one spot in the center or only one of the spots in the area of the ring begins to glow. Similar changes are taking place in the second area. As the discharge current decreases, the size of the rings and spots also decreases. The process of crushing the anode spot begins earlier, the greater the current strength, with an increase in current on materials with a low boiling point and thermal

conductivity. The size of the second region increases with increasing current and duration of the discharge: the greater the thermal conductivity coefficient, the lower the melting point of the anode material. From the very beginning of combustion, the anode region presents a multitude of spots scattered over a relatively large area of the anode. Although individual spots are stationary, the entire group of spots can move along the anode's surface. In this case, as one moves, the old spots disappear and new ones appear. The mobility of the anode region increases depending on the atomic weight of the gas, a decrease in pressure, and an increase in the melting point of the anode material. The cathode spots on the surface of the tungsten cathode, depending on the current strength, and the welding discharge minus at the cathode and plus at the anode are shown in Figure 15. The number of spots on the cathode decreases as the current increases. However, the anode spots do not decrease at the same time. With such a large number of anode spots, the arc column bends due to their movement along the surface of the anode. The cathode spot also moves along the cathode's surface.

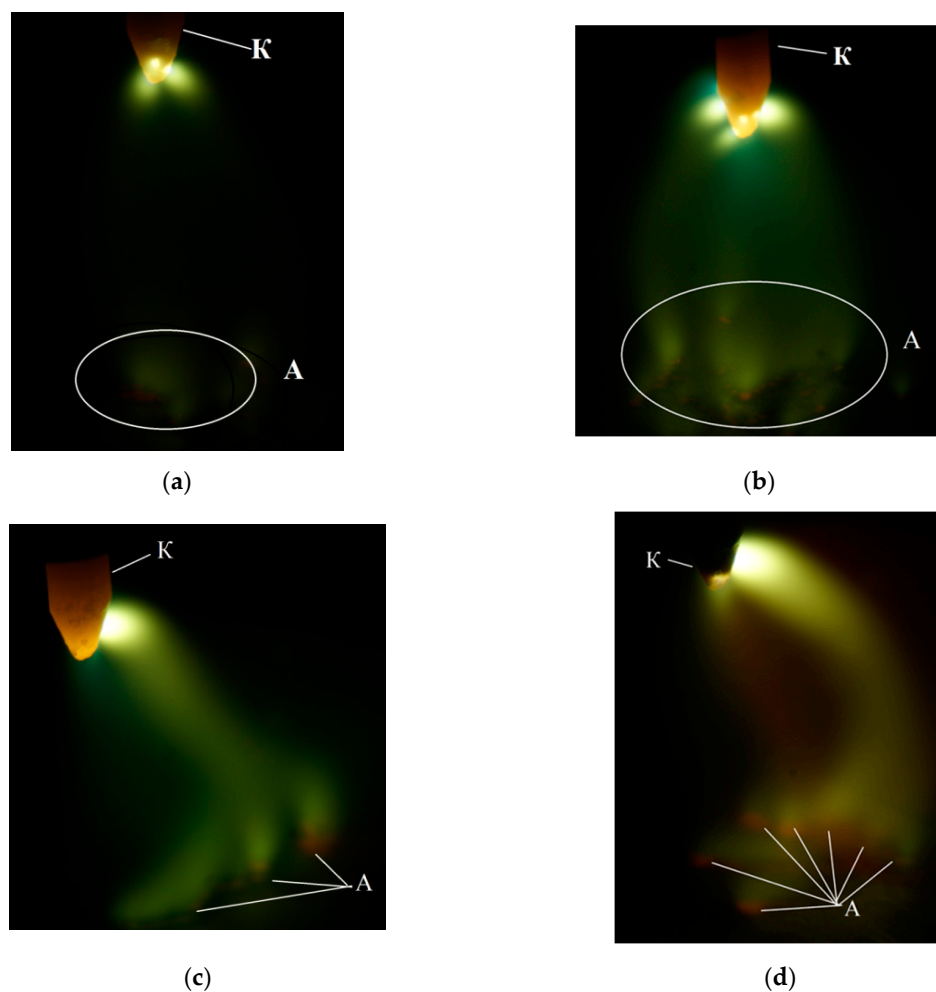


Figure 15. Cathode spots on the surface of a tungsten cathode depending on the current strength, welding discharge minus at the cathode, plus at the anode: (a) current 8 A, (b) 10 A, (c) 15 A, (d) 18 A.

Figure 16 shows cathode spots (KS) on the anode surface when the minus is on the anode and the plus is on the cathode. In Figure 16a,b, we see a round cathode spot of the second kind, with a plasma corona slowly moving along the surface. A powerful stream of vaporized matter and the emission of (thermo-auto) electrons are coming from the checkpoint. The plasma source in the gap is also droplets coming off the surface and generating plasma microclusters with plasma parameters close to the parameters of the

spots—the so-called “droplet spots”. In Figure 16b,c the anode spot formed on a tungsten cathode is shown for the first time.

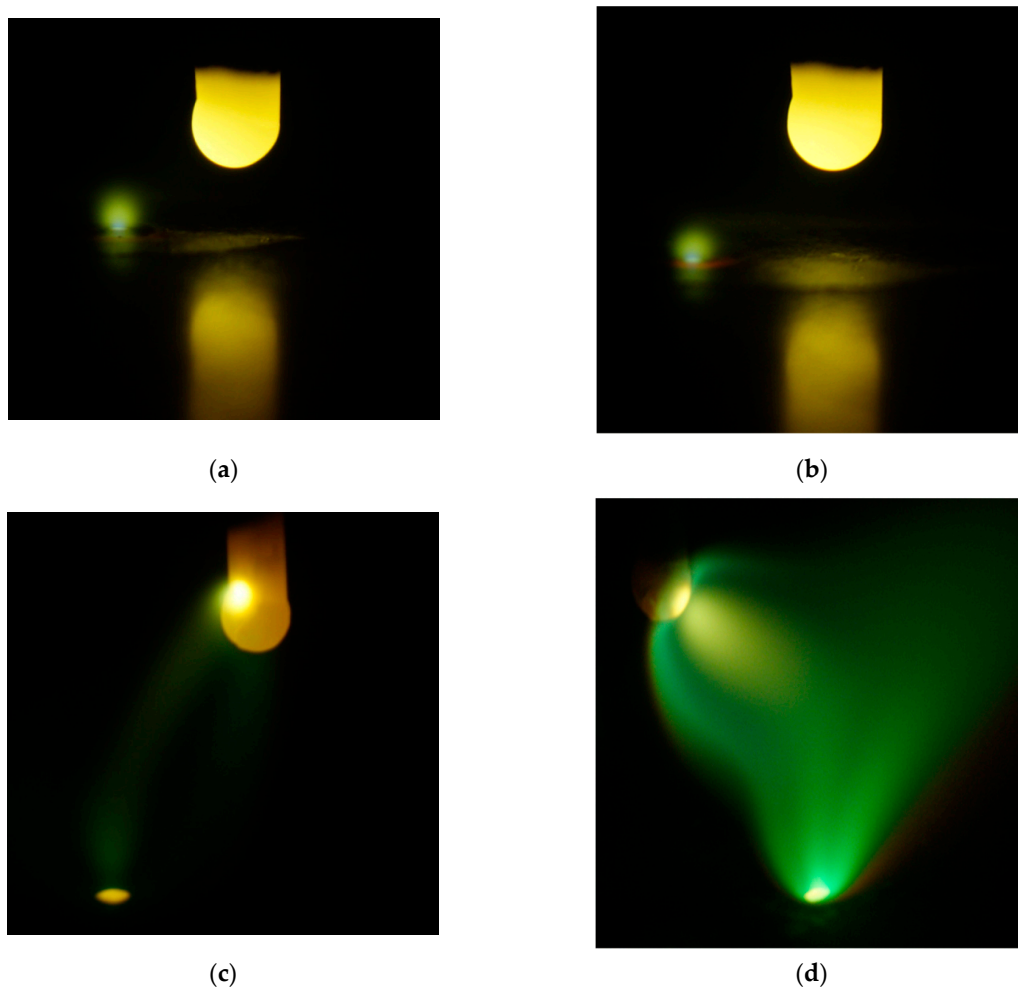


Figure 16. Cathode spots on the surface of the anode when the minus is on the anode and the plus is on the cathode: (a) cathode spot on the surface of aluminum (reverse current polarity), there is no anode spot on tungsten (b) cathode spot on the surface of steel (reverse current polarity) coated with iron oxide, no anode spot on tungsten (c) cathode spot on the surface of steel (reverse current polarity) coated with iron oxide, a large anode spot on tungsten (d) a large spot on tungsten in the anode jet mode and a cathode spot on steel.

Studies have shown that KS of the second kind has a complex hierarchy [21,26,27]. On the same material, different researchers observed spots of different sizes passing different currents. This difference is due to the difference in arc burning modes (current and arc burning duration), as well as the spatial and temporal resolution available to one or another researcher. Consequently, the hierarchy of cathode bindings in a low-current vacuum arc is divided into distinct levels. For each level, a specific term is used to denote the observed spot and speak about its characteristic size, lifetime, current carried in the spot, and the level of voltage noise on the arc. Different authors use different terms. We will stick to the most common terminology here. The term “macrospot” is used to define objects of the highest level (in terms of size and transmitted current). The term “spot” is used for the middle level. The term “cell” refers to the lowest level with the smallest current and size. A “macrospot” type spot is an association of several “spot” type spots. The very spot of the “spot” type consists of a “cell”. For copper, the characteristic dimensions of “macrospot” are $(1-3) \times 10^{-2}$ cm, for “Spot” $(1-2) \times 10^{-3}$ cm, and for “Cell” $< 5 \cdot 10^{-4}$ cm. In [27], it is also indicated that “macrospot” can also create associations called “group spots”.

Later, we conducted studies of the cathode spots left on the surface of the massive anode and film cathodes. Shown in Figure 17a,b are the autographs of the cathode spot on the massive anode. The spot exhibits an ellipsoidal shape and multiple, primarily circular, depressions. Along the stain's periphery, the entire metal surface has numerous round-shaped depressions. The film cathodes (Figure 17c,d) provide a clearer picture of the cathode spot's shape. Indeed, the cathode spot has a round shape, inside which there is a characteristic structure in the form of many holes (Figure 17c).

Photos of the reverse side of the cathode spot on film cathodes taken with a high-speed camera are shown in Figures 17 and 18. Instead of connecting to a bright spot for arc discharge at a large cathode, the spots disperse over a relatively small area. In addition, the spots on the surface practically do not change their trajectory during observation, while the spots move randomly in a time distribution for a volumetric surface. The spot's motion has a Christmas tree trajectory, similar to massive cathodes. We managed to fix the relatively true size of the cathode spot on the reverse side because there is no flow of vaporized matter. At the same time, fluctuations arise from two parts: intrinsic perturbations in plasma and cathode processes associated with spot movement. Unlike a stable discharge, during an arc discharge, the spots move along the cathode surface quickly and randomly, which is the result of the quenching and ignition of emission centers. Cathodic processes emit a large number of electrons and vapors of ionized metal into the interelectrode plasma. Therefore, the movement of spots is believed to explain the observed fluctuations.

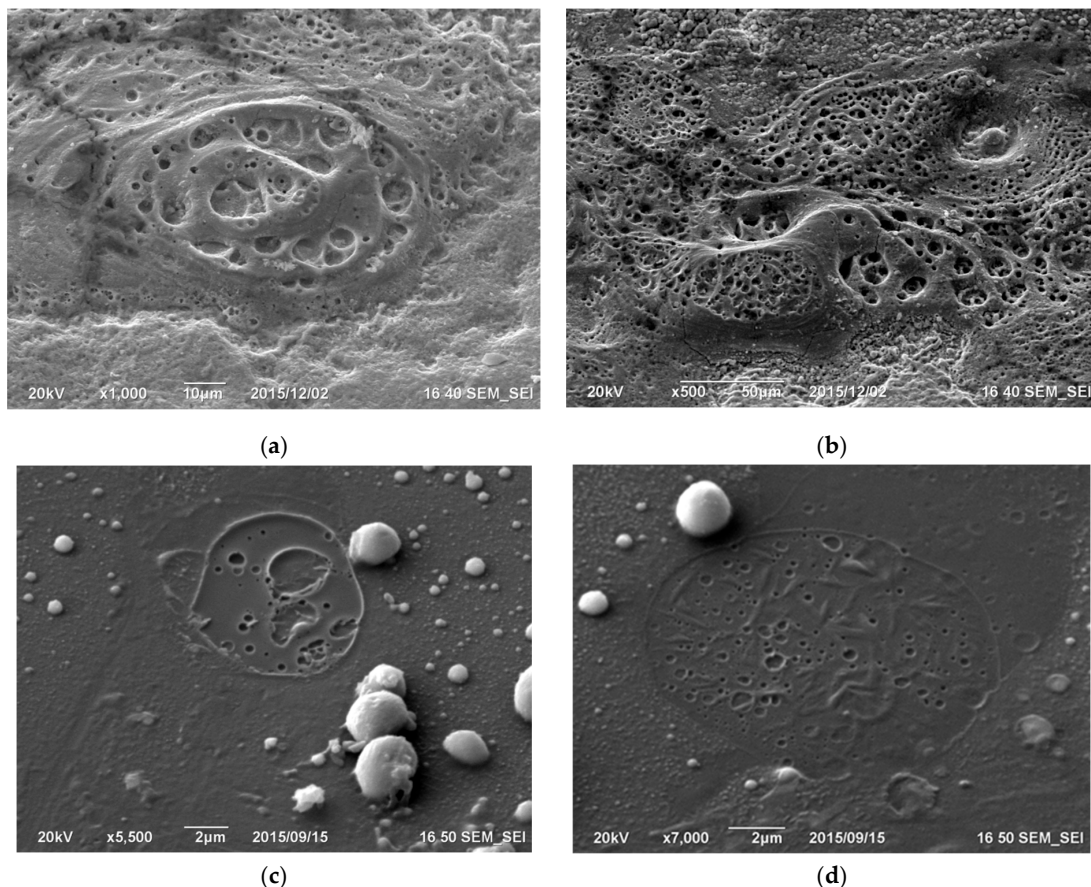


Figure 17. Electron microscopic photos of cathode autographs on the surface of a massive anode (steel) (a,b) and film cathodes (c,d).

During the study of the reverse side of the cathode spot, dependences were obtained—the dependence of the number of cathode spots on the exposure time; the dependence of the average lifetime of the cathode spot on the thickness (Figure 19).

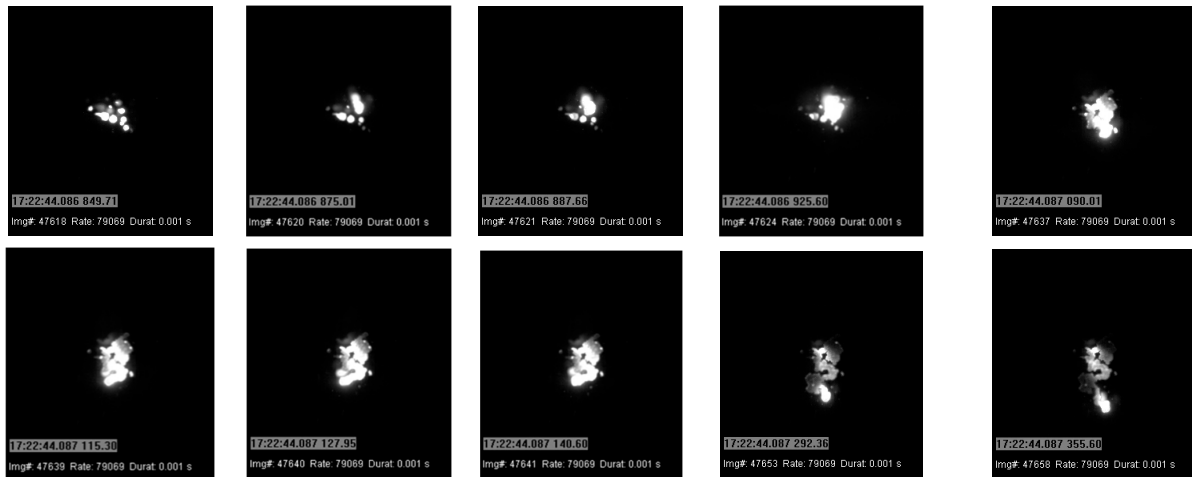


Figure 18. Reverse side of cathode spots in dynamics for a current of 20 A, copper film thickness 140 nm (frame rate 79,000 fps, exposure time 0.0037 s).

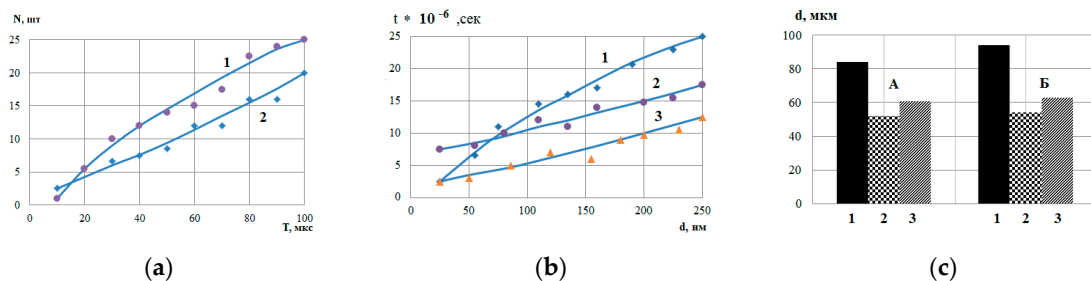


Figure 19. The results of studies of the dynamics of cathode spots obtained by visualizing the reverse side of the cathode spot: (a) dependence of the number of cathode spots on the exposure time: 1—aluminum film; 2—copper film; (b) dependence of the average lifetime of the cathode spot on the thickness of the film: 1—aluminum; 2—copper; 3—silver; (c) comparative histogram of the ratio of cathode spot diameters for different thicknesses of copper film (A = 250 nm, B = 350 nm): 1—the average diameter of the cathode spot on the front side; 2—the average diameter of the cathode spot on the back side; 3—the average diameter of the thermal imprint of the cathode spot on the glass.

4. Discussion

The results presented above on the visualization of anode and cathode spots using new methods and equipment allow us to analyze the results from a phenomenological point of view. Despite the large number of welding works presented in the scopus system, the authors use high-speed cameras and digital cameras to study the processes of droplet formation, droplet transfer, and bath formation at a macro level. Simultaneously, the exposure time ranges from 80 microseconds and beyond [1–3]. Under such shooting conditions, it is impossible to record the formation of anode and cathode spots. Additionally, researchers are only studying the diffusion binding of the welding discharge [2,3,18,48]. We will specifically focus on the work associated with modeling the welding arc. For many years, arc modeling and welding modeling were essentially distinct fields. While arc models included the arc, electrode, and workpiece as boundary conditions, welding models included the workpiece and the arc as boundary conditions [1–3,48,52,53]. Welding arc modeling requires solving related equations of hydrodynamics and electrodynamics, as for other applications of thermal plasmas. But most authors do not include processes in the cathode and anode parts of the welding discharge in their models. Some authors do not even say that cathode and anode spots exist, because they see the electrode and the workpiece as a solid volume [54].

In the first approximation, we already have an idea of a vacuum discharge by analogy. At the same time, the results of the visualization of anode and cathode spots in the

welding arc require a separate analysis, taking into account the methodological features of our experiments.

Let us focus on key points to discuss the results found in the scientific literature. In vacuum, as the authors of the review article [39,40,55] write, five modes of anode discharge can manifest themselves: (1) a low-current mode in which the anode is mostly passive and acts only as a collector of particles escaping from the cathode; (2) the second low-current mode, which may occur if the electrode material is easily sprayed (a stream of atomized atoms will be emitted by the anode); (3) the low-point mode, characterized by the appearance of one or more small luminous spots on the anode (the low points are usually much colder than the real anode spots present in the last two modes); (4) anode spot mode, in which one large or several small anode spots are present (such spots are very luminous, have a temperature close to the boiling point of the anode material at atmospheric pressure, and are an abundant source of vapors and ions); and (5) intensive mode, in which the anode spot is present, but accompanied by severe erosion of the cathode. The voltage is relatively low and quiet in two low-current and high-current modes. It is usually high and noisy in the low-point mode, but it can also be in the anode spot mode. The erosion of the anode is small, even negative, in two low-current modes and from low to moderate in the low-point mode. Severe anode erosion occurs in both the anode spot and intensive modes. The authors of [39,40,55] suggest that the formation of an anode spot depends on the geometry and material of the electrode and the current wave in the particular vacuum under consideration. Under specific experimental conditions, the transition can be caused either by magnetic tightening in the gap plasma, by coarse anodic melting, or by local anodic evaporation. However, the most likely explanation for the formation of an anode spot is a combined theory that takes into account the magnetic constriction in the plasma along with the material flows from the anode and cathode, as well as the thermal, electrical, and geometric effects of the anode when analyzing the behavior of the anode and nearby plasma.

In [56], the mechanism of the occurrence of the anode spot is described. When a large amount of KS leaves the side surface and the sign of the anode potential drop changes, the anode region turns out to be unstable relative to evaporation and ionization processes. If there is local overheating at the anode during arc burning, then evaporation of the anode material and ionization of vaporized atoms will actively occur in this area. This, in turn, will cause a local increase in plasma concentration. A positive drop in the anode potential, as opposed to a normal, negative one, will result in an increase in current density. This, in turn, will direct energy flow towards the floating surface area, causing it to heat up even more. In a very short time, once the arc is able to control the anode, an anode spot will appear. We refer to this form of arc burning as the “anode jet” mode [56], and also demonstrated that the anode serves as the “additional” plasma supplier in the gap, complementing the cathode spots. The cathode spot generates primary ions, which emit atoms from the anode’s surface. For a copper anode, the average energy in the distribution of secondary atoms is ~5 eV. In addition to the “diffuse” mode and the “anode jet” mode, there are also “intense arc” and “diffuse channel” modes [39]. In the “intense arc” mode, discharge contractions occur on both electrodes and severe erosive lesions on the latter. In the “diffuse channel” mode, the arc is also somewhat counteracted on both electrodes; however, erosive lesions are insignificant. Numerous studies, for example [57,58], have made it possible to determine the boundaries of the existence of each of the modes (Figure 20). In arcs with a varying interelectrode gap, the modes in which the arc will reside depend on the current (the amplitude value and the magnitude at which the ignition occurred), the contact dilution rate, the size of the electrodes, and the material used. It can be seen from the arc mode diagram that, regardless of the “trajectory”, the arc remains in a diffuse mode before extinction. However, after the extinction of an arc with a high amplitude current (for example, an arc that passed along trajectories 2 or 3, Figure 20), the trace of the counteragent binding will not have time to cool down to zero current. Therefore, for successful current

switching, it is necessary that, from the moment of ignition to extinction, the arc exists in a diffuse mode.

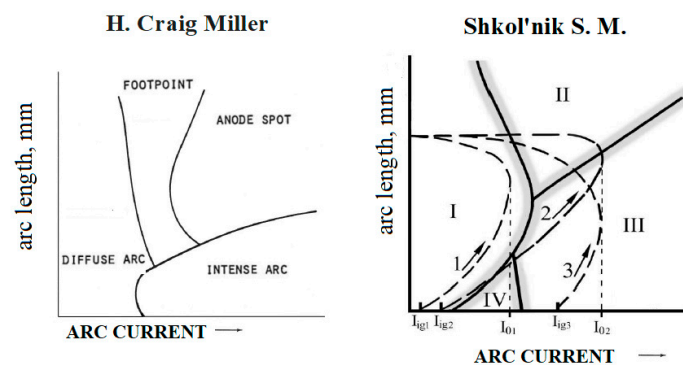


Figure 20. Anode modes of spot formation depending on current and gap length: versions by H.C. Miller and S.M. Shkol'nik: I—diffuse mode, II—anode jet, III—intense arc, IV—diffuse channel. Dashed curves are “arc trajectories”; I_0 is the amplitude value of the current; I_{ig} is the value of the current at the moment of ignition of the discharge; 1,2,3—vacuum arc modes.

Despite the fact that the study of anode processes in arc discharges has been conducted for a long time, the causes of the formation of various forms of “binding” of the arc to the anode remain poorly understood—multiple and single contraction, erosion-free diffusion binding. This is obviously explained by the extraordinary variety of phenomena in the anode region, which are realized in various conditions of discharge combustion, depending on the type of plasma-forming gas, current, gas flow rate [1–3], the method of arc stabilization, the shape of the electrodes, and even the surface condition of the processed products, which may change during processing. The following main processes take place on the metal anode of the welding arc: The surface of the anode is bombarded with plasma electrons from the positive column and neutral gas particles. The energy received by the anode is spent mainly on the melting and evaporation of the anode material, on radiation, and on heat transfer to the mass of the metal of the anode. As a rule, the anode in the welding arc receives more thermal energy than the cathode, and the anode material evaporates especially intensively. The vapors of the anode material play a predominant role in creating a positive column gas environment. The electrode material of a metal welding arc has a significant impact on its properties, and this effect can be very diverse. The properties of the arc depend on the melting point, the heat of melting, the thermal conductivity of the material, its boiling point, and the heat of evaporation. For example, the higher the melting point of the electrode material, the more favorable the arc burning conditions are, since an excessively low-melting electrode rod gives too much cold molten metal passing through the positive arc column and cooling it. Metal electrodes typically produce vapors with a low ionization potential, and, in most cases, an increase in the electrode material’s evaporation increases the arc’s stability. The diffusion anode layer is defined as the low-temperature zone in front of the anode. For an arc welding situation, this layer has a thickness of about 0.1 mm, which is significantly greater than the average free path of an electron. In this zone, large temperature gradients and particle concentrations cause diffusion fluxes. The temperature of heavy particles, for example, drops in this zone from the plasma temperature to the anode’s surface temperature. If local thermal equilibrium prevailed in this zone, the electrical conductivity would be almost zero in front of the anode, violating the law of continuity of current. This implies that the electron temperature should be significantly higher than the temperature of heavy particles, which causes noticeable deviations from the local thermal equilibrium within the boundary anode layer. The next spatial charge zone is several orders of magnitude thinner than the boundary anode layer. Strong electric fields present in the spatial charge zone due to a deviation from quasi-neutrality identify the anode voltage drop. We need information on the force

distribution along the heating spot to assess the hydrodynamic processes in the bath. P. Shoek [59] proposed measuring the pressure distribution of the arc plasma over the surface of the receptor plate with a gating hole in it. His findings indicate the normal law of pressure distribution over the anode spot. In [53,54], the authors proposed a model that simulates the hydrodynamic situation in a bath during plasma-arc remelting, along with a method to study the nature of the bath metal's movement by measuring the hydrodynamic pressure. The study revealed that electromagnetic forces are the primary forces driving the melt's movement. The speed of movement of the melt increases with an increase in the current passing through it. The movement is directed from the arc down along the axis of the bath, at the surface, from the periphery to the center of the bath. We performed an experiment on a model to study the flows in the bath during plasma-arc remelting. It has been proven that the main driving force in the bath during plasma arc remelting is electromagnetic force. The high-speed pressure of the plasma arc gas flow acting on the melt's surface does not cause significant volume movement. The arc's base directs the main melt flow deep into the bath along its axis. The movement of the melt at the surface is from the periphery to the center. In the middle part of the bath's radius, vortices form. With an increase in the arc current, the nature of the flows does not change; their intensity increases.

The structure of the anode layer of the vacuum arc bulk charge has been studied, taking into account the dependence of the negative anode drop on the ratio of the directional velocity of electrons to their thermal velocity for different values of the flux density of atoms evaporated from the anode [39,40,55]. The Poisson equation was solved in the layer, taking into account the volume charge of electrons, fast cathode ions, and slow ions formed during the ionization of atoms evaporated from the anode. We solved a kinetic equation for atoms and slow anode ions, considering the collision integral that accounts for ionization. We analytically obtained solutions for both the distribution function of atoms and slow ions by velocities, as well as for the concentration of the latter. The description of the nonequilibrium plasma in front of the metal surface emitting the electrodes is of great importance for theoretical studies of the thermal plasma of arcs because the correct boundary conditions on the electrodes are crucial for modeling arc discharge in general [48–50]. Experimental work shows that the arc voltage varies depending on the chemical composition of the anode [1–3,54,60]. In [61], a mathematical model of the interaction of electric arc plasma fluxes and molten metal fluxes in the processed product was proposed, which allows us to consider interrelated processes in an electric arc on the surface and inside the product as a single picture. The developed model made it possible to obtain more complete information about the dynamics and interaction of processes in an electric arc and a welding bath and allowed us to determine such important characteristics as the melting depth of the base metal, the intensity of mixing of the metal, the transportation of impurities into the melt, etc. This model's unique solution describes the processes in each region using the same set of magnetic hydrodynamics (MHD) equations. It was found that the formation of liquid metal flows occurs under the influence of the viscous interaction of radially spreading plasma flows with the anode surface; under the influence of surface tension forces, the welding bath forms a “mushroom” shape. The shape of the surface of the welding bath and the depth of penetration of the base metal are determined by the balance of pressures from the arc and the welding bath. With increasing pressure in the energy balance of the arc column, heat losses increase due to increased radiation.

In the above arguments, we see that most authors consider the molten bath as a whole as an anode spot or use the concept of a heating spot in general, considering that this is the anode spot. These are not entirely correct representations. In fact, as our experiments have shown, the anode spots do not belong to the melt bath, and even more so to the heating spot (Figures 9–13 and 15). We see that anode spots form on the surface of the molten bath (Figure 13). They bind the arc column (Figures 9 and 10), emitting the anode torch towards the cathode rather than the entire melt surface. The experimental results presented by us indicate that the anode spots in the welding arc are functional in nature,

associated with electrical processes in the arc, and are a new property of electric current. The electric current at the solid–gas–solid interface is capable of forming functional spatial and temporal structures for the flow of electric charge; this is especially clearly seen in Figure 9a–d. The welding arc column (in the form of a cylinder) rests on an anode spot, which, having high thermal power, melts under it as a metal, and a melt bath is formed. The situation with cathode spots is similar.

We have always believed that cathode spots are a continuation of the aggregate state of the cathode material and tried to theoretically describe the state of the material in it by successive transitions: solid, liquid, vapor, and plasma. Perhaps this is not the right way, because we have exhausted all known physical effects of the cathode spot and have not yet been able to understand its nature. If we move in a different direction with our research and think of cathode spots as a functional element, their main job is to make sure that there is a lot of electric current and electron emission into the arc gap. This means that cathode spots are a new (unknown) property of electric current. It is not a solid that needs to maintain current in a broken cathode–anode circuit. They act as ordinary conductors of electric current because they have electrons that ensure the flow of current. When a current passes through a solid, the number of electrons does not decrease or increase. There are always electrons in a solid, with or without current. On the contrary, an electric current that encounters an obstacle in the form of an air gap (dielectric) on its way through must “create” such temporary functional structures at the solid–gas–solid boundary (metal–dielectric–metal), allowing the circuit to be closed to compensate for losses from a break in the circuit. And it (electric current) “creates” such temporary functional structures in the form of cathode and anode spots, which create a medium temporarily conducting electricity from (or in) a dielectric (e). Then everything falls into place: the initial stage of the formation of cathode spots of the first type, the transition of spots of the first type to the second, third, and fourth, according to the classification [7–11], the current density in the cathode spots, the reverse movement of the cathode spot, the cathode potential drop, the threshold current, etc. All of this is due to a change in the fundamental properties of the surface electric current. These changes are mostly “controlled” by the current strength (the amount of electricity flowing through the whole dS cathode surface), the electric current density in the area of the cathode spot, and the thermal and physical properties of the cathode surface. Both of these factors affect the changes that happen. The amount of electricity (dI) is determined by the volumetric density and velocity of the charges. This determines in space and time the mechanism of electron emission from the surface of a solid (liquid or mixed state), the dominance of one mechanism over another, the sequential change or simultaneous existence of several emission mechanisms, etc. Plasma processes in the cathode region are important, but they are secondary because they are the fundamental processes of current flow on the surface and in the surface layer of the cathode. The word structure of the cathode or anode spot does not accurately reflect the physical essence; it will probably be more correct if we talk about the amount of electricity dI and introduce the concept of “the energy state of the cathode spot”. And we are, indeed, currently observing cathode and anode spots as an energetic state of matter. As soon as the conditions for maintenance ceased, these energy states disappeared without a trace, leaving no material traces of themselves. A gas remains a gas, and a solid remains a solid, having only the imprints of energy action on the surface. Of course, when creating such temporary functional energy states, the material of a solid and a gas gap will be used as primary functional elements. Considering the nature of electric current, we can assume that electrons and ions serve as such materials. Consequently, we arrive at various types of crystal lattices of metal conductors of electric current, ranging from electronic levels to the Fermi level. If in our reasoning we proceed from the well-known position that the surface of a solid body is a two-dimensional system, and then not only its structure but also many phenomena manifest themselves on it in a completely different way than in the volume [62–65]. For example, the discovery of the quantum Hall effect was preceded

by the discovery of another interesting effect: the disappearance of the resistance of a two-dimensional metal in a strong magnetic field.

Atoms in a solid's surface layers are in special conditions compared to atoms in volume. These special conditions are associated with a violation in one of the directions of the strict periodicity of the crystal lattice and a break in the translational symmetry of the crystal. Electrons moving near the surface "feel" this break [63,64]; therefore, the behavior of electrons on the surface of a solid body is not at all the same as in its volume [43]. This issue is partially analyzed in [19,66–71], where the authors present experimental results of changes on the surface of the emitter at the atomic level. From the point of view of electronic properties, the near-surface region of a solid, its "shell", is a special state of matter [63–65,72]. The structure of the crystal at the atomic level, that is, the location and properties of its lattice layers near the surface, are also completely different from its volume. In essence, the surface of a solid and its "interior" are two different forms of the same substance, and, consequently, the nature of an electric current's behavior most likely has its own characteristics. One of the manifestations of such features is that the cathode spots on the surface are one example of such features. The above results, obtained using a new cathode spot research technique, outline a new conceptual view of the cathode spot's nature. The results obtained do not fit into the traditional hypotheses about the nature of the cathode spot. The experimental fact of the existence of a "free" cathode spot recorded by us [50] is not explained from the standpoint of modern hypotheses of the nature of the cathode spot. Moreover, this fact refutes the correctness of their basic postulates. It must be admitted that neither the explosive hypothesis of the ectonic mechanism [6] of the nature of the cathode spot nor the classical hypothesis of the mechanism considering the sequence solid–liquid–evaporation–plasma [4–18] advance us in the theory of knowledge because they study the phenomenon (consequence) and do not reveal the essence (causes). The new conceptual approach formulated above requires a separate presentation, detailed consideration, and discussion, and is beyond the scope of this article.

Thus, the presented material shows the first results of the newly developed experimental technique for studying the reverse side of the cathode spot, and the anode spots are shown for the first time. To obtain analytical dependencies according to the type of Figure 20, there is not enough experimental material yet, and in future publications we will try to present it. Most of the results presented in this paper are new and are of interest from the point of view of physical electronics and the physics of arc welding discharge. The results can be used to simulate the movement of the gearbox as well as to select the optimal configuration of the magnetic field to control the dynamics of the gearbox in various power sources of the welding arc. The development of new electrode materials can benefit from versatile measurements of KP properties on different metals.

Let us focus on key points to discuss the results. We acknowledge the ongoing research in the field of self-organized structures concerning electric discharge at atmospheric pressure. The concept of anode spots in the welding arc is developed by the author in [73,74]. "The simulations are based on a single fluid-electromagnetic plasma flow model numerically implemented within a second-order-accurate multiscale finite element framework that changes with time and space", says the author [73]. As the level of cooling at the anode rises, simulations show that spot patterns gradually form, starting with a single diffuse spot for low cooling levels and ending with small spots covering the whole anode region for intense cooling. The characteristics of the patterns, such as the number, size, and location of the spots, markedly depend on the imposed total current. Furthermore, for high cooling levels, the patterns transition from steady to dynamic with decreasing total current. The dynamics of the pattern demonstrate the creation of new spots through the splitting of existing ones in the center of the plasma, along with the movement and eventual extinction of spots at the plasma boundaries. Different types of anode patterns, ranging from diffuse to self-organized spots, significantly influence the total voltage drop across the plasma column, while they have a minor impact on other plasma characteristics. The findings show that thermal instability and the balance between heavy species and electron

energy play a major role in how anode patterns form in arc discharges. In fact, by adopting the new perspective of viewing anode spots as self-organizing structures (Figure 21), we can understand the physics involved in the transition from the diffusion discharge of binding to the anode to the oppositely charged form that forms anode spots. Figure 21 depicts the VAC of an arc discharge, emphasizing the impact of self-organization in a glow discharge and casting doubt on the arc itself. Simultaneously, studies [73,74] demonstrate that welding conditions can lead to purely mathematical anode spots. Simultaneously, the author explores the concept of competition between the energy entering the anode and the energy lost due to Joule heat and evaporation. The author uses a variational multiscale FEM to numerically implement the model of fluid flow and electromagnetic plasma. This makes sure that the results are accurate to the second order in both space and time. This study focuses on the effect of the anode cooling rate on the formation of anode spots. Figure 21 shows the cooling levels on the anode surface for two modes: natural when $h = 0$ and fast for $h = \infty$. The simulation results show that spots appear gradually as the anode cooling levels rise. At low cooling levels, there is a single diffuse spot. Later, small spots appear around the main spot in the middle. Finally, during intensive cooling, the anode area is completely covered with small spots. The number, size, and location of the spots depend significantly on the total current introduced. Computational modeling shows that the spots transition from stable to dynamic with a decrease in the total current for equivalent (high) cooling levels. The changing patterns show that new attachment spots are made by splitting up old ones in the middle of the plasma welding arc column. Spots at the plasma boundaries also move and eventually go away. Different types of anode patterns, from diffuse to self-organized spots, slightly influence the overall voltage drop on the plasma column [75–77], and they also slightly influence other plasma characteristics not directly related to the anode region. The results [73,74] show that the cooling of the melt bath causes thermal instability, which in turn leads to a decrease in electrical conductivity. Additionally, the balance between heavy particles and electron energy plays a dominant role in the formation of self-organized anode patterns, which take the form of spots in an arc welding discharge area, as documented in the scientific literature.

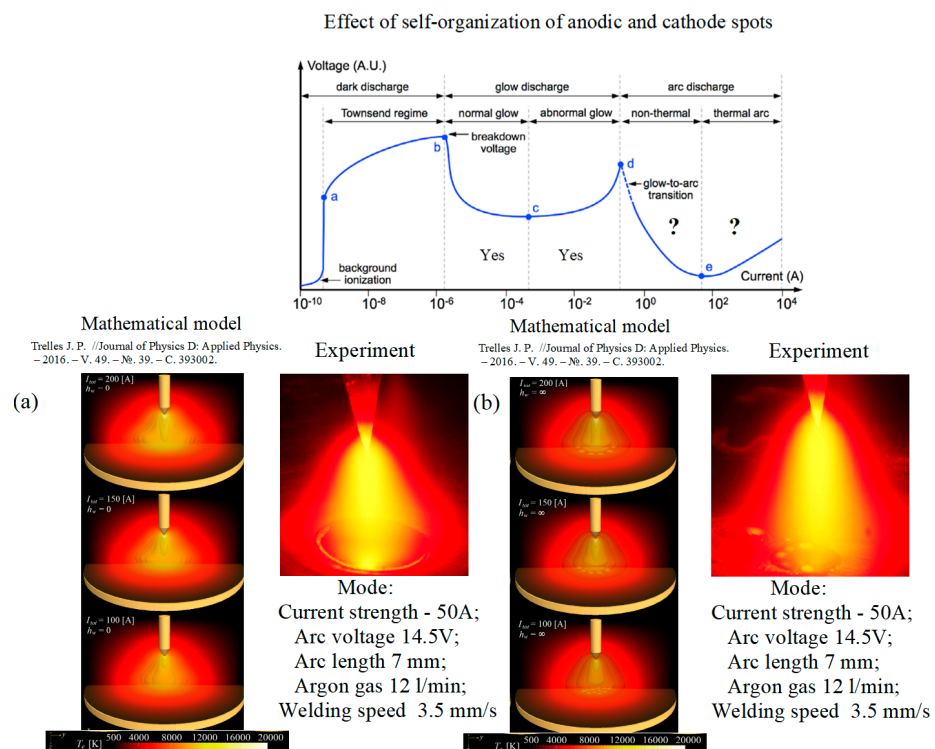


Figure 21. A new concept for studying anode spots in a welding arc based on the self-organization effect: (a,b) ranges of existence different types of electrical discharge [73].

5. Conclusions

1. Using optical and high-speed camera methods, we studied in situ the optical properties of the arc spot on various surfaces of the cathode in a welding arc. We established a strong influence of the cathode anode surface on the discharge characteristics.
2. The display of anode spots in a high-resolution welding arc is a first. The mode of the anode spot in the welding arc is a high-current mode, when a more pronounced cylindrical arc column appears in the interelectrode gap while one cathode spot is covered by the cathode. At the anode, one large or (less often) several small, very bright round spots are formed in the center of the molten bath. We propose a technique for studying anode and cathode spots using an optical and high-speed camera.
3. The reference point mode differs from the vacuum arc by primarily filling the interelectrode gap with a sufficiently bright diffuse glow. However, unlike the diffuse arc mode, where the molten metal bath, which is the anode, does not glow, in the lower point mode, small, bright anode spots appear on the surface of the molten bath (anode) along the periphery of the molten bath. There may be several such spots. The heating spot designates these spots as the welding arc's reference points. The reference points are characterized as small luminous spots usually associated with the surface of the nonmolten metal and the melting of the anode. The appearance of the anode flares along the binding boundary of the reference points towards the cathode.
4. We show the dependence of the number of anode and cathode spots on the current strength and arc length. On an oxidized surface, the movement of cathode and anode spots is more stable than on a clean steel surface. The presence of oxide on the cathode surface leads to a change in microexplosive processes, which increases the stability of the spot plasma.
5. An experimental technique for studying the reverse side of the cathode spot is described, and the results of visualization are presented. We obtained experimental dependences of the cathode spot's average lifetime on the film thickness for various film cathode materials when studying from the reverse side. We experimentally determined the number of cathode spots fixed on the reverse side of the exposure period. We compared the geometric dimensions of the cathode spot, obtained using classical methods, with the proposed method.

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References

1. Lancaster, J.F. The physics of welding. *Phys. Technol.* **1984**, *15*, 73. [[CrossRef](#)]
2. Murphy, A.B. The effects of metal vapour in arc welding. *J. Phys. D Appl. Phys.* **2010**, *43*, 434001. [[CrossRef](#)]
3. Murphy, A.B.; Tanaka, M.; Tashiro, S.; Sato, T.; Lowke, J.J. A computational investigation of the effectiveness of different shielding gas mixtures for arc welding. *J. Phys. D Appl. Phys.* **2009**, *42*, 115205. [[CrossRef](#)]

4. Finkelburg, V.; Mekker, G. *Ehlektricheskie Dugi i Termicheskaja Plazma [Electric Arcs and Thermal Plasma]*; M. Pub. Izdatelstvo Inostrannoj Literatury [Foreign Literature Publishing House]: Moscow, Russia, 1961; p. 370. (In Russian)
5. Anders, A. *Cathodic Arcs: From Fractal Spots to Energetic Condensation*; Springer: New York, NY, USA; Volume 50.
6. Mesyats, G.A. Ecton mechanism of the vacuum arc cathode spot. *IEEE Trans. Plasma Sci.* **1995**, *23*, 879–883. [[CrossRef](#)]
7. Lyubimov, G.A.; Rakhovskii, V.I. The cathode spot of a vacuum arc. *Sov. Phys. Uspekhi* **1978**, *21*, 693–718. [[CrossRef](#)]
8. Beilis, I.I. State of the theory of vacuum arcs. *IEEE Trans. Plasma Sci.* **2001**, *29*, 657–670. [[CrossRef](#)]
9. Shi, Z.; Jia, S.; Wang, L.; Yuan, Q.; Song, X. Experimental investigation on the motion of cathode spots in removing oxide film on metal surface by vacuum arc. *J. Phys. D Appl. Phys.* **2008**, *41*, 175209. [[CrossRef](#)]
10. Agarwal, M.S.; Holmes, R. Cathode spot motion in high-current vacuum arcs under self-generated azimuthal and applied axial magnetic fields. *J. Phys. D Appl. Phys.* **1984**, *17*, 743. [[CrossRef](#)]
11. Oh, K.; Kalanov, D.; Birtel, P.; Anders, A. High-resolution observation of cathodic arc spots in a magnetically steered arc plasma source in low pressure argon, nitrogen, and oxygen atmospheres. *J. Appl. Phys.* **2021**, *130*, 183304. [[CrossRef](#)]
12. Tendero, C.; Tixier, C.; Tristant, P.; Desmaison, J.; Leprince, P. Atmospheric pressure plasmas: A review. *Spectrochim. Acta Part B At. Spectrosc.* **2006**, *61*, 2–30. [[CrossRef](#)]
13. Shkol'nik, S.M. Anode phenomena in arc discharges: A review. *Plasma Sources Sci. Technol.* **2011**, *20*, 013001. [[CrossRef](#)]
14. Sanders, N.; Etemadi, K.; Hsu, K.C.; Pfender, E. Studies of the anode region of a high-intensity argon arc. *J. Appl. Phys.* **1982**, *53*, 4136–4145. [[CrossRef](#)]
15. Ushio, M.; Tanaka, M.; Lowke, J.J. Anode melting from free-burning argon arcs. *IEEE Trans. Plasma Sci.* **2004**, *32*, 108–117. [[CrossRef](#)]
16. Heberlein, J.; Mentel, J.; Pfender, E. The anode region of electric arcs: A survey. *J. Phys. D Appl. Phys.* **2009**, *43*, 023001. [[CrossRef](#)]
17. Schutze, A.; Jeong, J.Y.; Babayan, S.E.; Park, J.; Selwyn, G.S.; Hicks, R.F. The atmospheric-pressure plasma jet: A review and comparison to other plasma sources. *IEEE Trans. Plasma Sci.* **1998**, *26*, 1685–1694. [[CrossRef](#)]
18. Sarrafi, R.; Kovacevic, R. Cathodic cleaning of oxides from aluminum surface by variable-polarity arc. *Weld. J.* **2010**, *89*, 1S–10S.
19. Rakhovskii, V.I. *Fizicheskie Osnovy Kommutatsii Elektricheskogo Toka v Vakuume. [Physical Bases of Switching Electric Current in a Vacuum]*; Nauka: Moscow, Russia, 1970.
20. Golizadeh, M.; Martin, F.M.; Kolozsvári, S.; Anders, A.; Franz, R. Cathode spot behavior in nitrogen and oxygen gaseous atmospheres and concomitant cathode surface modifications. *Surf. Coat. Technol.* **2021**, *421*, 127441. [[CrossRef](#)]
21. Jüttner, B. Nanosecond displacement times of arc cathode spots in vacuum. *IEEE Trans. Plasma Sci.* **1999**, *27*, 836–844. [[CrossRef](#)]
22. Tang, Z.L.; Yang, K.; Liu, H.X.; Zhang, Y.C.; Li, H.; Zhu, X.D. Dynamics of cathode spots in low-pressure arc plasma removing oxide layer on steel surfaces. *Phys. Plasmas* **2016**, *23*, 033501. [[CrossRef](#)]
23. Golizadeh, M.; Anders, A.; Martin, F.M.; Kolozsvári, S.; Franz, R. Insights into surface modification and erosion of multi-element arc cathodes using a novel multilayer cathode design. *J. Appl. Phys.* **2020**, *127*, 113301. [[CrossRef](#)]
24. Kesayev, I.G. *Katodnye Protssessy Elektricheskoi Dugi (Cathode Processes of Electric Arc)*; Nauka: Moscow, Russia, 1968; p. 253. (In Russian)
25. Mesyats, G.L. *Ektonyi v Vakuumnom Razryade: Proboy, Iskra, Duga*; RAS: Moscow, Russia, 2000; p. 424. (In Russian)
26. Daalder, J.E. Random walk of cathode arc spots in vacuum. *J. Phys. D Appl. Phys.* **1983**, *16*, 17. [[CrossRef](#)]
27. Jüttner, B. Cathode spots of electric arcs. *J. Phys. D Appl. Phys.* **2001**, *34*, R103. [[CrossRef](#)]
28. Beilis, I.; Djakov, B.E.; Jüttner, B.; Pursch, H. Structure and dynamics of high-current arc cathode spots in vacuum. *J. Phys. D Appl. Phys.* **1997**, *30*, 119. [[CrossRef](#)]
29. Siemroth, P.; Schulke, T.; Witke, T. Investigation of cathode spots and plasma formation of vacuum arcs by high speed microscopy and spectroscopy. *IEEE Trans. Plasma Sci.* **1997**, *25*, 571–579. [[CrossRef](#)]
30. Jüttner, B. The dynamics of arc cathode spots in vacuum: New measurements. *J. Phys. D Appl. Phys.* **1997**, *30*, 221. [[CrossRef](#)]
31. Jüttner, B. The dynamics of arc cathode spots in vacuum. Part III: Measurements with improved resolution and UV radiation. *J. Phys. D Appl. Phys.* **1998**, *31*, 1728. [[CrossRef](#)]
32. Dos Santos, E.B.F.; Kuroiwa, L.H.; Ferreira, A.F.C.; Pistor, R.; Gerlich, A.P. On the Visualization of Gas Metal Arc Welding Plasma and the Relationship Between Arc Length and Voltage. *Appl. Sci.* **2017**, *7*, 503. [[CrossRef](#)]
33. Yu, R.; Cao, Y.; Chen, H.; Ye, Q.; Zhang, Y. Deep learning based real-time and in-situ monitoring of weld penetration: Where we are and what are needed revolutionary solutions? *J. Manuf. Process.* **2023**, *93*, 15–46. [[CrossRef](#)]
34. Somerville, J.M. *The Electric Arc*; Methuen and Company, Ltd.: London, UK, 1959.
35. Somerville, J.M.; Blevin, W.; Flether, N.H. Electrode Phenomena in Transient Arcs. *Proc. Phys. Soc. B* **1952**, *65*, 963. [[CrossRef](#)]
36. Somerville, J.M.; Fletcher, N.H. Ring Conduction in the Early Stages of Sparks. *Br. J. Appl. Phys.* **1956**, *7*, 419. [[CrossRef](#)]
37. Somerville, J.M.; Williams, J.F. The Early Stages of Spark Channel Expansion. *Proc. Phys. Soc.* **1959**, *74*, 309. [[CrossRef](#)]
38. Kimblin, C.W. Anode phenomena in vacuum and atmospheric pressure arcs. *IEEE Trans. Plasma Sci.* **1974**, *2*, 310–319. [[CrossRef](#)]
39. Miller, H.C. Anode modes in vacuum arcs. *IEEE Trans. Dielectr. Electr. Insul.* **1997**, *4*, 382–388. [[CrossRef](#)]
40. Miller, H.C. Anode modes in vacuum arcs: Update. *IEEE Trans. Plasma Sci.* **2017**, *45*, 2366–2374. [[CrossRef](#)]
41. Perminov, A.V.; Tren'kin, A.A. Microstructure of the current channels in a nanosecond spark discharge in atmospheric-pressure air in uniform and highly nonuniform electric fields. *Tech. Phys.* **2005**, *50*, 1158–1161. [[CrossRef](#)]
42. Tren'kin, A.A.; Karelin, V.I.; Shibitov, Y.M.; Blinova, O.M. Parameters of a Microstructure of Erosion Regions during the Action of a Spark Discharge on a Copper Electrode Surface in Air. *Tech. Phys.* **2018**, *63*, 1473–1478. [[CrossRef](#)]

43. Tren'kin, A.A.; Almazova, K.I.; Belonogov, A.N.; Borovkov, V.V.; Gorelov, E.V.; Morozov, I.V.; Kharitonov, S.Y. Formation of the Microchannel Structure of a Spark Discharge in Air in the Gap Spike-Plane. *Tech. Phys.* **2023**, *68* (Suppl. S3), S613–S617. [\[CrossRef\]](#)
44. Balanovskii, A.E. Structure of the Welding Arc Cathode Spot with a Nonconsumable Electrode. *High Temp.* **2018**, *56*, 1–9. [\[CrossRef\]](#)
45. Chase, T.F.; Savage, W.F. Effect of anode composition on tungsten arc characteristics. *Weld. Res. Suppl.* **1971**, *11*, 467.
46. Sanders, N.A.; Pfender, E. Measurement of anode falls and anode heat transfer in atmospheric pressure high intensity arcs. *J. Appl. Phys.* **1984**, *55*, 714–722. [\[CrossRef\]](#)
47. Khakpour, A.; Gortschakow, S.; Uhrlandt, D.; Methling, R.; Franke, S.; Popov, S.; Batrakov, A.; Weltmann, K.-D. Video spectroscopy of vacuum arcs during transition between different high-current anode modes. *IEEE Trans. Plasma Sci.* **2016**, *44*, 2462–2469. [\[CrossRef\]](#)
48. Ivanchik, N.N.; Balanovsky, A.E.; Shtayger, M.G.; Sysoev, I.A.; Karlina, A.I. Capability enhancement of production of activating fluxes for arc welding using ultradispersed products of silicon waste processing. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *411*, 012035. [\[CrossRef\]](#)
49. Balanovskii, A.E. Visualization of the process of metal heating and melting in the anode zone in an arc discharge with a tungsten electrode. *High Temp.* **2016**, *54*, 627–631. [\[CrossRef\]](#)
50. Balanovskii, A.E. Invisible Structure of the Cathode Spot of a Welding Arc with a Tungsten Anode and a Film Cathode Burning in an Inert Gas. *High Temp.* **2019**, *57*, 8–16. [\[CrossRef\]](#)
51. Polishchuk, V.P.; Usmanov, R.A.; Melnikov, A.D.; Vorona, N.A.; Yartsev, I.M.; Amirov, R.K.; Gavrikov, A.V.; Liziakin, G.D.; Samoylov, I.S.; Smirnov, V.P.; et al. Vacuum Arcs with Diffuse Cathode Attachment (Review). *High Temp.* **2020**, *58*, 476–494. [\[CrossRef\]](#)
52. Benilov, M.S.; Benilova, L.G. Physics of spotless mode of current transfer to cathodes of metal vapor arcs. *IEEE Trans. Plasma Sci.* **2015**, *43*, 2247–2252. [\[CrossRef\]](#)
53. Rykalin, N.N.; Kublanov, V.Y.; Zherebovich, A.S. Study of hydrodynamic flows in bath models applied to plasma-arc remelting. In *Physics and Chemistry of Materials Processing*; The Chemical Rubber Publishing Co.: Cleveland, OH, USA, 1974; pp. 33–37.
54. Murphy, A.B. A Perspective on Arc Welding Research: The Importance of the Arc, Unresolved Questions and Future Directions. *Plasma Chem. Plasma Process.* **2015**, *35*, 471–489. [\[CrossRef\]](#)
55. Miller, H.C. A Review of Anode Phenomena in Vacuum Arcs. *Contrib. Plasma Phys.* **1989**, *29*, 223–249. [\[CrossRef\]](#)
56. Shkol'nik, S.M. Secondary plasma in the gap of high current vacuum arcs: Origin and resulting effects. *IEEE Trans. Plasma Sci.* **2003**, *31*, 932–946. [\[CrossRef\]](#)
57. Heberlein, J.; Gorman, J. The high current metal vapor arc column between separating electrodes. *IEEE Trans. Plasma Sci.* **1980**, *8*, 283–288. [\[CrossRef\]](#)
58. Miller, H.C. A Review of Anode Phenomena in Vacuum Arcs. *IEEE Trans. Plasma Sci.* **1985**, *13*, 242–252. [\[CrossRef\]](#)
59. Shoeck, P. An Investigation of the Energy Balance on the Anode of High-Current Arcs Birning in an Argon Atmosphere. In *Sovremennye Problemy Teploobmena*; Energiya: Moscow, Russia, 1966; Volume 10.
60. Hajossy, R.; Morva, I. Cathode and Anode Falls of Arcs with Fusible Electrodes II. *J. Phys. D Appl. Phys.* **1994**, *27*, 2095–2101. [\[CrossRef\]](#)
61. Yamamoto, K.; Tanaka, M.; Tashiro, S.; Nakata, K.; Murphy, A.B. Numerical Simulation of Metal Vapor Behavior in Argon TIG Welding. *Trans. ICCES* **2008**, *7*, 1–6.
62. Zacharia, T.; David, S.A.; Vitek, J.M. Effect of evaporation and temperature—dependent material properties on weld pool development. *Metall. Trans.* **1991**, *22*, 233–241. [\[CrossRef\]](#)
63. Landau, L.D.; Lifshits, E.M. *Electrodynamics of Continuous Media*; Nauka: Moscow, Russia, 1982; p. 624. (In Russian)
64. Kaganov, M.I. Energy spectrum of a metal and its singularities. *Sov. Phys. Uspekhi* **1985**, *28*, 257–268. [\[CrossRef\]](#)
65. Zaiman, J. Electrons in metals (Introduction to the theory of Fermi surfaces). Part V. Construction of the Fermi surface. *Sov. Phys. Uspekhi* **1963**, *80*, 665–684. [\[CrossRef\]](#)
66. Fu, Y.H. Cathode Surface Effects and H.F.-Behaviour of Vacuum Arcs. Ph.D. Thesis, Electrical Engineering, Technische Universiteit Eindhoven, Eindhoven, The Netherlands, 1990. [\[CrossRef\]](#)
67. Balanovsky, A.E.; Nesterenko, N.A. The influence of the thermophysical properties of the cathode material on the magnitude of the cathode voltage in an arc discharge. *High Temp.* **1992**, *30*, 1029–1031.
68. Mamadaliev, R.A.; Bakhmatov, P.V.; Martyushev, N.V.; Skeebe, V.Y.; Karlina, A.I. Influence of Welding Regimes on Structure and Properties of Steel 12KH18N10T Weld Metal in Different Spatial Positions. *Metallurgist* **2022**, *65*, 1255–1264.
69. Duniyashin, N.S.; Khudoyorov, S.S.; Zairkulov, E.Y.; Martyushev, N.V.; Valuev, D.V.; Karlina, A.I. Study of the Effect of K₂O, Na₂O, MgO, Al₂O₃ Oxide Additions on Density, Viscosity, Separability and Covering Capacity of CaO–MnO–SiO₂ System Slag in Low Carbon Steel Automatic Submerged Arc Welding. *Metallurgist* **2023**, *67*, 1093–1102. [\[CrossRef\]](#)
70. Rezanov, V.A.; Martyushev, N.V.; Kukartsev, V.V.; Grinek, A.A.; Skeebe, V.Y.; Lyosin, A.V.; Karlina, A.I. Study of Melting Methods by Electric Resistance Welding of Rails. *Metals* **2022**, *12*, 2135. [\[CrossRef\]](#)
71. Kolosov, A.D.; Gozbenko, V.E.; Shtayger, M.G.; Kargapoltsev, S.K.; Balanovskiy, A.E.; Karlina, A.I.; Sivtsov, A.V.; Nebogin, S.A. Comparative evaluation of austenite grain in high-strength rail steel during welding, thermal processing and plasma surface hardening. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *560*, 012185. [\[CrossRef\]](#)
72. Kaganov, M.I.; Lifshits, I.M. Electron theory of metals and geometry. *Sov. Phys. Uspekhi* **1979**, *22*, 904–927. [\[CrossRef\]](#)

73. Trelles, J.P. Pattern formation and self-organization in plasmas interacting with surfaces. *J. Phys. D Appl. Phys.* **2016**, *49*, 393002. [[CrossRef](#)]
74. Trelles, J.P. Formation of Self-Organized Anode Patterns in Arc Discharge Simulations. *Plasma Sources Sci. Technol.* **2013**, *22*, 025017. [[CrossRef](#)]
75. Ebert, U.; Arrayás, M. Pattern Formation in Electric Discharges. In *Coherent Structures in Complex Systems*; Lecture Notes in Physics; Reguera, D., Rubí, J.M., Bonilla, L.L., Eds.; Springer: Berlin, Heidelberg, 2001; Volume 567. [[CrossRef](#)]
76. Yang, G.; Heberlein, J. Anode attachment modes and their formation in a high intensity argon arc. *Plasma Sources Sci. Technol.* **2007**, *16*, 529–542. [[CrossRef](#)]
77. Liang, F.; Tanaka, M.; Choi, S.; Watanabe, T. Investigation of the relationship between arc-anode attachment mode and anode temperature for nickel nanoparticle production by a DC arc discharge. *J. Phys. D Appl. Phys.* **2016**, *49*, 125201. [[CrossRef](#)]

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