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O.V. JARTOVSKY *,[1] and O.V. LARICHKIN [2]

[1] Donbass State Engineering Academy,
72 Akademichna Str., Donetsk Region, UA-84313 Kramatorsk, Ukraine
[2] JSC 'Novokramatorsky Machine Building Plant',
5 Oleksa Tykhy Str., Donetsk Region, UA-84305 Kramatorsk, Ukraine

* avpivras@gmail.com

PRESSURE WELDING THROUGH THE LAYER OF HYDROCARBON SUBSTANCE: PHYSICAL PROCESSES OF A DIFFUSION JOINT FORMATION

The article deals with the hypothesis on the diffusion-processes' activation mechanisms during pressure welding with a pulsed current through the hydrocarbon-substance layer. Despite the developing this welding method in the last century, this topic is still insufficiently studied and, thus, needs further research. In the time of developing this welding method, the required amount of scientific data on the physical and chemical processes accompanying the formation of the joint did not exist. The article overviews the physicochemical processes dealing with the subject of the study of interdisciplinary research. Experimental studies carried out by specialists in different fields enabled establishing data necessary to develop the hypothesis. The nanoscale carbon formations were discovered, and their properties were studied. The phenomena accompanying the electric current in micropinches, 'Coulomb explosions' with the shock wave formation, the anomalous mass transfer under the shock loading during diffusion welding of different materials were investigated. As experimentally proved, the electroexplosive and electromagnetic phenomena, shock waves affecting the surface metal layers activate the diffusion processes. Based on a large number of interdisciplinary studies, a hypothesis on the formation of a diffusion joint during pressure welding with a pulsed current through the layer of hydrocarbon substance is formulated. The time of formation of a joint at the same temperature is lesser than that required for diffusion welding in vacuum. The structure of the welded joint is similar to the structure obtained by diffusion welding in vacuum.

Keywords: pressure welding, hydrocarbon substances, electric explosion, electric current, nanotubes, diffusion.

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1. Introduction

In the fabrication of bimetallic work pieces, butt-welding and friction welding are used. In butt-welding, the connection of metals occurs because of heating by electric current and plastic deformation of the surfaces to be joined. The formation of the joint occurs under the influence of the upsetting force. This is accompanied by the removal of oxide films, molten and part of the solid metal from the welding zone. A thickening occurs at the welding point. In friction welding, the heat generated by the intense friction of the work-pieces' surfaces pressed against each other is used to heat the metal. When the welding temperature is reached, upsetting occurs. Upsetting is accompanied by the formation of a thickening at the welding point. Removal of the thickening by machining involves a significant waste of expensive metal into chips. Metal waste into chips when manufacturing, for example, tools from bimetallic work pieces is of about 55% of the work piece weight. Diffusion welding in vacuum during manufacturing of precision work pieces eliminates the possibility of thickening at the junction point. The low productivity and high cost of the vacuum diffusion welding process limited its application. Pressure welding through the layer of hydrocarbon substances provides a high-quality connection with minimal deformations in the joint area and high productivity of the process. The welding process takes place with simultaneous longitudinal impulse compression of the work pieces and the passage of the pulsed electric current of constant polarity. To obtain a welded joint, the joint surfaces of the junction are coated with a hydrocarbon substance before welding [1–4]. The height of microroughnesses on the surfaces to be welded is of 1.6 microns. The most important parameter of the process is the rate of the joint heating. There exists a range of the joint heating rates, at which welding can be carried out. At speeds below the lower limit, the welding process is not implemented. At speeds above the upper limit, a risk of explosive destruction in the zone of the welded joint is arisen. The choice of this mode parameter is carried out experimentally, when developing the welding technology of various pairs of metals. The connection formation temperature is lower than the melting temperature of the material to be welded. The value of the upsetting welding pressure is set depending on the properties of the materials to be joined. The value of transverse deformation in the junction zone does not exceed 0.5%. The state of the issue has been studied using domestic and foreign literary sources. Pressure welding with interlayers of hydrocarbon substances has been known since the last century. The main body of known publications falls on the eighties of the last century. Currently, publications are represented by patents and advertisements of welding equipment. Modern foreign publications testify the production of equipment and its application. The equipment is used in the manufacture of bimetallic tools and parts blanks. The materials to be welded are represented by tool and structural steels. Any publications on the physicochemical model of the process in the available literary sources were not presented. The goal of the work is to create a working hypothesis of the welded joint formation process during pressure welding with a pulsed current through the layer of hydrocarbon substance.

The tasks of the work are interdisciplinary search and selection of process analogues, finding the analogy of the analogue object under study (model), and transferring information from the analogue to the modelling object.

The subject of research is the physicochemical processes during pressure welding through the layer of a hydrocarbon substance, when heated by a pulsed unipolar electric current.

The relevance of the proposed work is that, for the first time, a hypothesis of the welded joint formation process during pressure welding with a pulsed current through the layer of hydrocarbon substance is proposed.

The working hypothesis assumes the presence of electrical explosions at the contact points of the surfaces to be welded. Heating and pyrolysis of the hydrocarbon substance occurs. Carbon nanostructures are formed in microvolumes between surfaces at high pressures and temperatures. These structures exist for a short period of time and are decomposed under the action of electric discharge. Electric explosions at the contact points and carbon nanoparticles in microvolumes between surfaces and accompanying electromagnetic phenomena stimulate the activity of diffuse processes of the surfaces to be welded.

2. Research Technique

In research, it is often impossible to perform an experiment on a real object. Obtaining experimental data can be impeded by the size and location of the investigated object, the lack of data on the investigated processes. The lack of appropriate equipment and the high cost of experimental work are important factors. In addition, the implementation of experimental studies on a real object is difficult because of the variety of physical phenomena and effects in microvolumes between the surfaces to be connected. This led to the use of the analogy method.

Analogy is one of the logical methods of scientific knowledge that are widely used in engineering. Traditionally, analogy is examined as an inference, in which, from the similarity of some features of objects, a conclusion is made about the similarity of some other features of these objects. The analogy is considered as an object, which is identical or corresponding to a given object in some parameters. The application of the analogy method in any scientific or industrial field involves sequential actions: search for an analogue; analyse an analogue of the investigated object; transferring information from an analogue to the object.

Known types of analogies are as follow: direct, indirect and conditional. Direct analogy defines a situation of comparison when the model (analogy) and the original are maximally similar to each other. Indirect analogy is established in the form of an indirect coincidence or sufficient proximity of the model and the original. The conditional analogy between the original and the model is established as a result of the conditional agreement. Direct and indirect analogies are most widespread in technical and scientific experiments.

Sources containing information on physical and chemical processes of electric explosion and accompanying phenomena have been studied. The data on physicochemical processes in an electric explosion, on the influence of the pinch effect on the electric discharge, on the temperature and pressures in the electric explosion shock wave, on the electromagnetic phenomena accompanying it, on the 'Coulomb explosion' and other phenomena are studied.

The analogy method was used in the development and formulation of a hypothesis about the formation of a diffuse joint during pressure welding through the layer of a carbohydrate substance when heated by a pulsed unipolar electric current.

Applying the analogy methods, a number of factors and processes were not taken into account due to the lack of the necessary information on their influences.

3. Results and Discussion

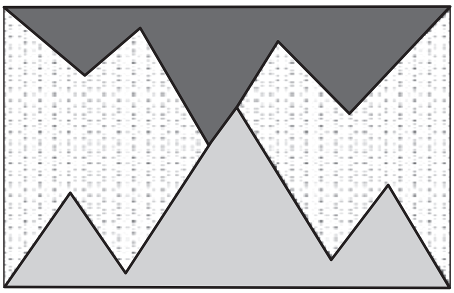
The contact surfaces of the work pieces to be welded have a structure due to the preliminary machining. The parameters of the microroughness height and waviness depend on the properties and parameters of the machining mode. Thin films of oxides, sulphides, chlorides, residues of cooling lubricants and other contaminants [5, 6] are always present on the surface of metals (like to various-type inclusions in the three- or two-dimensional materials [7–11]). Some of these films create additional resistance at the contact point. The value of the electric-current density at the contact points is of 10^3–10^4 times higher than the nominal one. This statement is true, when the contact surfaces are perfectly clean. However, the presence of films and dirty contributes to the increase of the electric current density and the manifestation of the associated physicochemical effects. There are prerequisites for high-speed heating of a small amount of material at the contact points of the surfaces to be joined [12, 13].

A schematic simplified representation of the contact point of the surfaces is shown in Fig. 1.

When the electric current propagates through the contact points of metal surfaces, the overheating and explosive evaporation of the metal occur. The duration of explosive processes and their rates were investigated on explosions of thin wires. The cross-sectional dimensions of the wires are comparable to the dimensions of the contact area of the microrelief protrusions of the surfaces to be joined [14]. According to the data in Ref. [14], the explosion time is from 120 to 300 nanoseconds, the speed of particle expansion is of $2.8 \cdot 10^3$ m/s. Researchers studied the energy balance of the conductor electrical explosion [15]. As found, up to 50% of the energy introduced into the conductor is spent on the generation of shock waves [15]. The energy is partially lost in electromagnetic radiation.

Researchers simulated the initial stage of the conductor explosion [16]. The authors of Ref. [16] proposed a study by the projection radiography. Explosions of flat foils with a thickness of 1–15 μm were carried out in a diode with a current of 40–80 kA. Foil explosion images were obtained with a spatial resolution of 3–4 μm in soft x-ray radiation (E = 2.5–5 keV) of hybrid X-pinch and temporal resolution better than 0.1 ns. Foils of aluminium and copper were used. For these foils, the estimate of the skin layer thickness is of 26 and 21 μm, respectively, for the current with a rise time of 100 ns. In experiments with a foil thickness up to 15 μm, the current flows through the entire foil thickness.

Experiments on the explosion of flat foils were carried out. Copper and aluminium foils with a thickness of 1 μm, 4 μm, and 15 μm were used. The research was carried out at the set parameters (250



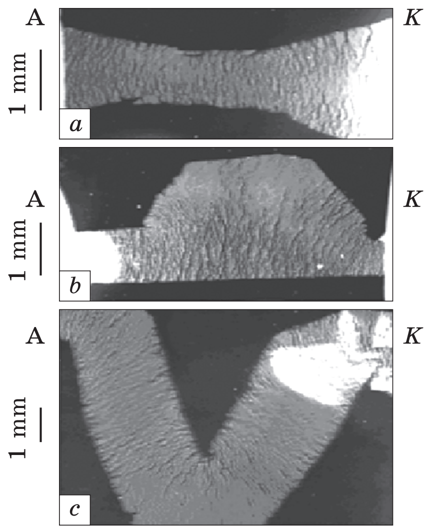


Fig. 1. Schematic view of the contact point of the surfaces

Fig. 2. Images of the explosion process of Al foil with a thickness of 4 μm of various shapes, obtained at 82 (*a*), 80 (*b*), and 65 ns (*c*) from the beginning of the current flow, which was of 52 kA (*a*), 72 kA (*b*), 48 kA (*c*). Here, electrode *A* is anode, *K* is cathode [16]

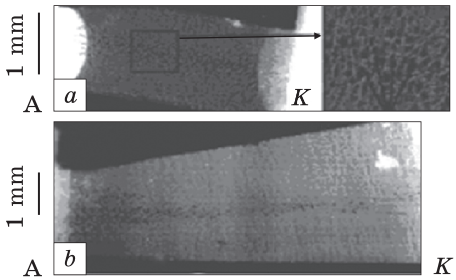


Fig. 3. X-ray diffraction patterns of the Cu foil explosion of 1 μm thick with different profiles, obtained at 62 (*a*) and 50 ns (*b*) from the beginning of the current flow. Electrodes: *A* is anode; *K* is cathode. Enlarged section of bubbles (*a*) and bubbles in the central part of the foil (*b*) are depicted [16]

kA, 100 ns, 300 kV). Experimentally, using projection radiography, the initial stage of foil explosion was recorded at different current values. It has been established that there are several stages, which the foil goes through, when the current flows. The structure arising at the initial moments of time and resulting from further heating and expansion of the substance were studied.

It has been shown experimentally that foil explosion begins with the formation of discontinuities perpendicular to the current direction. To confirm this assumption, experiments were carried out with foils. Figure 2 shows images of Al foil with a thickness of 4 μm. Figure 2, *a* depicts a foil that is tapered in the centre. Figure 2, *b* shows a foil with broadening in the centre. In Figure 2, *d*, the foil is of the *V*-like shape. The breaks occur to perpendicular to the edge of the foil and perpendicular to the direction of the current. These observations allow concluding that the formation of discontinuities is associated with the flow of current, and they arise under its influence. The images show that the current distribution changes with the different foil shape versions.

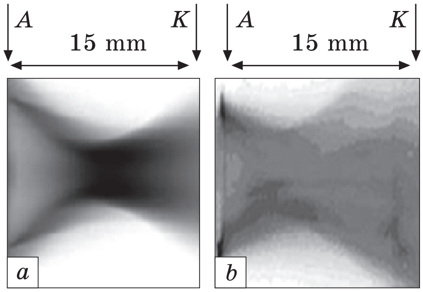
After the initial stage of foil explosion (breaks), the next stage is formation of bubbles inside the metal. The beginning of the boiling process of the substance is observed. X-ray diffraction patterns of the Cu-foil explosion with the image of bubbles are shown in Fig. 3.

In the above experiments, the initial stage of foil explosion at different currents is visualized. As shown, when the current flows, the foil passes through several stages. The foil explosion begins with the breaks formation perpendicular to the direction of the current. The breaks appear at the edge of the foil and represent destruction of its surface. After that, small bubbles begin to form in the centre. Thus, the boiling of the substance begins from the centre of the foil. The breakdown begins at the edge of the foil. The energy contribution to the central region turns out to be greater [16].

The images show that the explosion of the foil begins with the breaks formation. The direction of the breaks is perpendicular to the direction of the current. The breaks appear at the edge of the foil and represent destruction of the surface. Subsequently, the length and width of the breaks begin to increase. The number of breaks is also growing. The breaks cover the entire surface of the foil. Small bubbles begin to form in the centre. The images show that bubble nucleation starts from the centre and spreads to the rest of the surface. The bubble size varies from 4–6 to 20–40 μm. The boiling point of the substance starts from the centre of the foil. The energy contribution in the central region turns out to be greater.

The authors of Ref. [17] investigated explosions of a conductor in paraffin and wax without additives and with additives of nanosize particles of copper oxide. For this, cylindrical samples of various densities and percentage of additives were made. To simulate the explosion a copper wire with a diameter of 75–80 μm and a length of 100 mm was used. The wire was placed along the axis in collapsible containers of 20 mm in diameter and of 25–30 mm in height. The experiments made it possible to obtain the value of the dimensions of the channel formed in the wax samples during the conductor explosion. In the samples made of wax without a powder additive, the diameter of the channel formed by the products of the conductor electrical explosion is of 1.5–1.7 mm. Samples with the addition of 4.9% copper oxide have a channel diameter of 3.0 mm. Samples with the addition of 10.6% copper oxide have a channel diameter of 4.0 mm. The results of the experiments showed the possibility of the size determining of the zone of electric discharge plasma influence during the conductor explosion and further expansion. The authors of the research [17] estimated the value of the pressure of the electrical explosion products of a conductor in the plasma channel. According to their estimations, it can reach hundreds of MPa. This is close to the assessment of the authors of Ref. [18]. They indicate that the pressure of the conductor explosion products lies in the range of 120–175 MPa. In Ref. [19], the results of an experiment on the ultrafast electric explosion of microconductors during the discharge of a high-voltage voltage source with a subnanosecond pulse front are presented. The integral emission spectra of the electric explosion of microconductors were studied. It was found that the lines of neutrals and singly charged ions predominate in the spectrum of the Cu and W plasma. In the spectrum of Ni plasma, in addition to the lines of neutrals and singly charged ions, there are also lines of double and triple ions. The copper temperature estimate gives the core plasma temperature: $T = 6000$ K.

Thermionic emission from a metal conductor is one of the most important types of electron emission from a solid. This type of emission is caused by strongly pronounced thermal vibrations of the crystal lattice of a metal with positive ions at its nodes. This contributes to a significant increase in the energy of free electrons moving in the interatomic space of the conductor. As shown [20], an anomalous thermionic emission occurs during the electrical explosion of the investigated conduc-



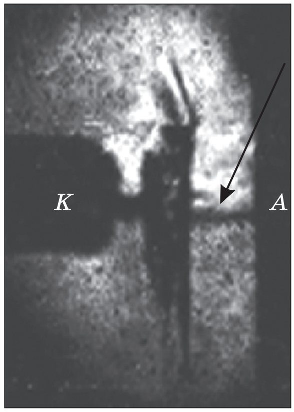


Fig. 4. The flow of the gas jet in the discharge gap (*a*) and photo of a discharge with a current of 10–15 A in the formed gas jet (*b*). The density structure is not completely stationary. The density maximum is not located on the axis, but at some distance from it [21]

Fig. 5. Discharge shadowgram, where *K* denotes cathode and *A* is anode. Arrow shows the channel of an optically dense medium extending from the pinching region to the external electrode surface [23]

tor. The maximum possible number of electrons is included in the emission process. The density of electrons can reach the concentration of atoms (positive ions) of its source material. The authors of Ref. [15] studied the electrical explosion. When the electric current flows in the place of an electric explosion and the formation of a plasma column, 'constrictions' are formed on it, *i.e.*, areas whose radius is less than the radius of the main column. The magnetic pressure in the 'constriction' area is increased due to the pinch effect. This leads to acceleration of the compression of the plasma column and to the outflow of substance from the constriction region in the axial direction. High initial temperatures of the plasma discharge of about 10^4 K and its decrease at rates of about 10^8 K/s are characteristic. The final stage of constriction development is the formation of a 'hot spot'. The authors of [21] presented the results of studies of the pinch radiation with initial gas density distribution with a maximum density in the centre of the discharge gap. A comparison of the calculated gas distribution with the visualized glow of a gas jet is presented. A qualitatively consistent is shown. The calculated form of halftones of the cross section of a neon gas jet is shown in Fig. 4, *a*. Comparison with Fig. 4, *b*, which shows a photograph of a discharge with a current of 10–15 A in the formed gas jet, shows a qualitative agreement.

The authors of Ref. [22] studied the processes in electric discharge. The processes in high-current vacuum diode with a cathode in the form of a single tip were investigated. The tips are made of metal wire with a diameter of 20–30 microns.

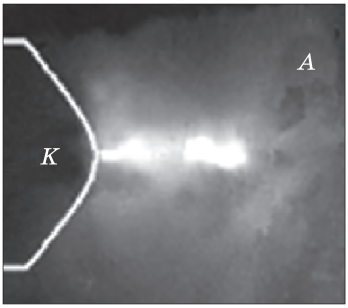
For the study, the method of projection radiography with a high-resolution in the hybrid X-pinch radiation was used. A strong inhomogeneity of the energy contribution to the wire material was found. The lowest energy contribution was observed in the region of the tip end where the electric field strength is maximal. Hard x-rays and the release of material from the anode were observed. This indicates the generation of the electron beam with parameters characteristic of explosive electron emission in a diode with this configuration. The experimental results [23] indicate the implementation of the mechanism of electrons 'runaway' in a longitudinal electric field in the axial region of micropinch discharge. The experiments were carried out on the high-current vacuum spark apparatus with a discharge current of up to 150 kA, the working medium of discharge was iron plasma. The shadowgraphs show the appearance of an optically dense medium channel extending from the pinch bunch of the discharge plasma to the surface of the external (flat) electrode along the axis of the discharge device symmetry (Fig. 5).

This structure is observed with a negative polarity of the charging voltage of the high-voltage capacitor bank. At the initial stage of the discharge, the current drift of electrons occurs in the direction from the inner electrode (cathode) to the outer electrode (anode). The analysis of shadow images allows concluding that the thin channel is not a product of the discharge plasma pinching [23].

This is confirmed by the nature of the x-ray source images in the spectral range $\lambda \leq 1.8$ nm (Fig. 6).

The images of radiation sources with $\lambda \leq 0.4$ nm show objects that cannot be interpreted otherwise than the traces of interaction with the discharge plasma and the electrode surface of the high-energy electron beam, which propagates in the region of micropinch formation towards the external electrode (Fig. 7).

The authors of the study [23] believe that, in addition to the pinching process, the trajectory of an electron beam in the peripheral low-density discharge plasma is recorded on shadowgraphs. Imaging occurs due to refraction and abnormal absorption of the probing laser radiation. The acceleration of the formation of the plasma electronic component occurs in the paraxial region of the discharge under conditions of a weak magnetic field [23]. This occurs in the longitudinal electric field during the micropinch formation because of an anomalous increase in the plasma resistance. In works [24, 25], the results of investigations presented in Ref. [23] are experimentally confirmed. Thus, it is clear that, during the welding process at the contact points of the micropro-



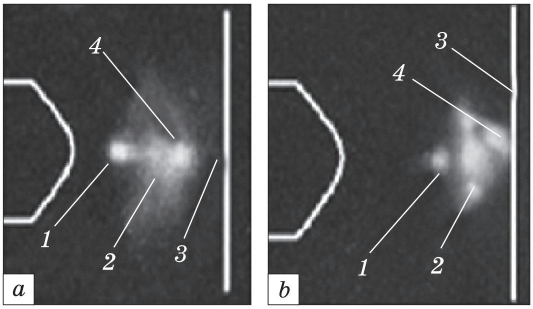


Fig. 6. X-ray obscurogram of the discharge in the range $\lambda \leq 1.8$ nm (*K* is cathode, *A* is anode) [23]

Fig. 7. X-ray obscurograms of the discharge in the range $\lambda \leq 0.4$ nm, recorded at negative polarity of the capacitor bank charging voltage, where *1* is image of the micropinch region, *2* is diffusely luminous peripheral plasma cloud, *3* is anode surface, *4* is electron-beam deceleration trace [23]

trusions during the passage of a high-density pulsed electric current, microexplosions accompanied by micropinches occur. As a result, 'hot spots' are formed. In the process of compression, the plasma column is deformed with the formation of constrictions, the radius of which is less than the radius of the main column. The magnetic pressure in the constriction region increases, which leads to the outflow of the substance from the constriction region in the axial direction. After the current starts to flow through the pinch, first (in a short time) an electrical explosion of the conductors occurs, then a micropinch (constriction) of several hundred microns in size is formed, then, a 'hot spot' of several microns in size is formed on the micropinch, which serves as a source of soft x-ray radiation. In the end, the 'hot spot' explodes and at this time an electron beam, hard x-rays and high-energy ions are generated, which appear a few seconds after the main pulse of soft x-rays [15]. Electric discharge according to I.V. Kurchatov [26] could be a source of thermonuclear reactions. The authors of Ref. [27] investigated by mass spectrometry methods. Scanning electron microscopy and x-ray fluorescence analysis are products that arise between carbon electrodes in aqueous glycerine solution because of low-energy electrical discharge. The formed precipitate has a different chemical composition and microstructure from the initial constituents. In the experiments, electric discharge was conducted between carbon electrodes of 0.6 mm in diameter (grade ОСЧ 7-2) in a 30% solution of PK-94 glycerine in distilled water. A diagram of an electric discharge cell with indication of the elements that automatically maintain the discharge is shown in Fig. 8.

Carbon electrodes *1* are located inside the Helmholtz coil *2*. Movement of the upper carbon electrode relative to the immovable lower

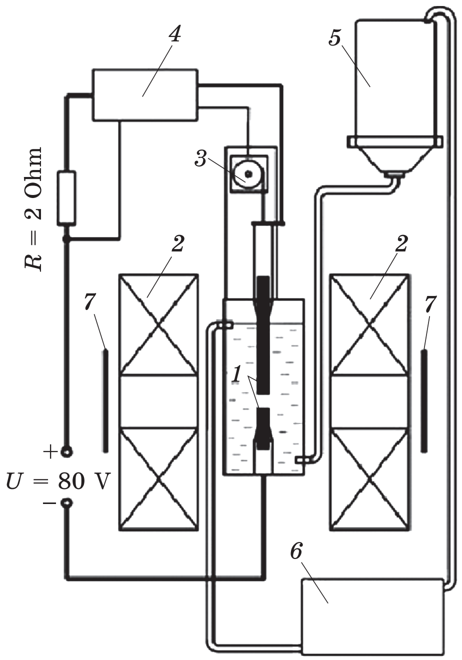


Fig. 8. Scheme of the electric discharge cell: *1* is carbon electrodes (upper electrode is mobile, while lower one is fixed), *2* are Helmholtz coils, *3* is device for the mobile electrode lifting and lowering, *4* is control unit for lifting and lowering device, *5* and *6* are drain and filling tanks, *7* are locations of x-ray films [27]

electrode is done by automatic device *3* designed to raise and lower the electrode.

Unit *4* provided the automatic mode of the device operation. When using the automatic discharge device, the current interruption frequency was of 5 Hz, and the maximum discharge current at a constant supply voltage of 80 V did not exceed 30 A. The Helmholtz coils are designed to separate the magnetic radiation that occurs, and photographic films *7* to register this radiation. The volume of the glycerine solution in the working chamber of the device was of 300 ml. The discharge cell has the flow-through system design with circulation and cooling of the working fluid. Filling *5* and drain *6* containers with a volume of 5 litters each. The liquid pumping rate in the range from 400 to 500 ml/min. The time of one cycle of the electric discharge ranged from 40 to 60 min. To determine the chemical composition and study the microstructure, the methods of mass spectrometry, electron microscopy and x-ray fluorescence were used. The study of the reaction products was carried out in samples of the substance from the sediment formed in the discharge zone. The change in the elemental composition of the electrodes used in the experiments was also studied.

To determine the amount of chemical impurities in carbon electrodes, mass spectrometry studies were carried out. In this case, the electrodes (anode and cathode) were investigated both before and after the discharge. The mass spectrometry study was also carried out on the precipitate that was formed directly in the glycerine itself during the electric discharge. Typical results of semi-quantitative analysis of the electrodes elemental composition and glycerine precipitate for one of the research options are shown in Table.

The qualitative composition of the new elements in all cases was the same, and the relative amounts of the elements formed in the precipitate varied in the range that significantly exceeded the measurement error limits of ±10%. The results given in Table 1 show that, on the surface of the electrodes themselves and in the precipitate as a result of the electric discharge in a 30% solution of PK-94 glycerine in a distilled water, new chemical elements appear in significant amounts. Similar studies were carried out in Refs. [28–32]. They investigated [28] the formation of new elements in arc discharge on graphite electrodes in air and water. As revealed [33], if the arc discharge on graphite electrodes burns in a gas and does not contain oxygen, then, no synthesis of elements occurs. The appearance of new elements was not detected in experiments, in which an arc discharge on graphite electrodes was carried out in a nitrogen atmosphere. In the studies of the authors of Ref. [34], the facts of the formation of high-pressure silicon from other elements in the O–Al–Si–P system were also experimentally established. The formation of chemical elements in electric arc discharge was recorded in basalt melt [35]. The survey article [36] is devoted to the transmutation of elements in arc discharge. The results of Ref. [27] coincide with the results of Refs. [32, 33]. In Refs. [27, 30], during electric explosion of metal in a liquid, the transformation of chemical elements and 'strange' radiation were simultaneously recorded. It is fixed on the nuclear photoemulsion in the form of unusual, peculiar, intermittent tracks. The experiments were carried out simultaneously within the same laboratory. The authors of Ref. [27] connect the transformations of synthesized elements during the electric discharge and the conditions for the appearance of magnetic monopoles on a nuclear photoemulsion in the form of tracks.

All chemical elements synthesized during experiments are stable isotopes. The authors of Refs. [28, 30] believe that there is enough experimental evidence in favour of the reality of the monopole and its role

Semi-quantitative analysis of the samples (error ±10%) [27]

Element	Initial electrode, μg/g	'Cathode' electrode, μg/g	'Anode' electrode, μg/g	Precipitate, μg/g
Mg	8	160	36	415
Al	8	13	14	189
K		36	36	566
Ca		36		274
Cr				19
Mn		14		85
Fe		58	11	2547
Ni				47
Cu		36	11	2264
Zn		36		387
Ag				57
Sn				26

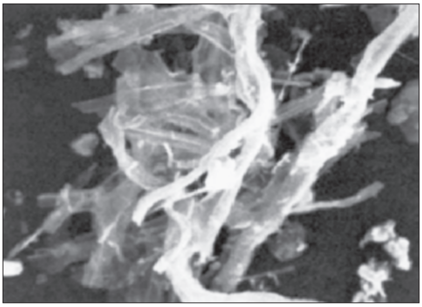


Fig. 9. Fibrous tubular structure formed by transmission of electric discharge through aqueous glycerine solution [27]

as a catalyst for the transformation of chemical elements in the electric discharge plasma. According to the article [36] (see also references therein), where the experiment on thermal pressing of garnet crystal at a pressure of 5000 MPa and a temperature of 850 °C is described (see also Refs. [37, 38]), the author explains the results as the transition Fe $\rightarrow$ Cr. In the experiments described earlier [27], the electric discharge was carried out between carbon electrodes of 0.6 mm in a 30% solution of glycerine grade PC-94 in distilled water. Figure 9 depicts a fibrous tubular structure that was formed during electrical discharge.

Its individual elements are elongated. Through the microprobe analysis, it was found [27] that the glomerular and tubular clusters are carbon structures with a low amount of impurities. During low-energy electric discharge in aqueous solution of glycerine, the creation of tubular carbon structures is observed [27]. The author of work [39] described an original technique for nanotubes growing and filling them with catalysts in active medium using gas-static conditions. The experiments were carried out using a 'gasostat' (HIP unit).

HIP unit is a high-pressure cylinder, in which a heating device is mounted. During the synthesis, the average temperature in the apparatus was of 570 ± 30 °C, and the pressure was of 50 MPa. A mixture of carbon monoxide CO and nitrogen N_2 in a ratio of 1:30 was used as a carrier gas. In the experiment, the maximum temperature was of 1400 °C, and the crucible temperature with the catalyst and precipitate was of 500–600 °C. The synthesis time was of 7 minutes. The study of the samples was carried out using the method of high-resolution electron transmission microscopy (microscope JEOL-2010, accelerating voltage 160 kV). It was found that the resulting material contains cylindrical nanotubes. Cobalt particles are inside the tubes. Frequent particles possess an f.c.c. lattice. Particles with a hexagonal close packing have been found. Cobalt carbide has also been found.

Figure 10 shows the cell of a high-pressure washer. A special feature of the work is the use of HIP unit for the synthesis of nanotubes. In the experiments of the HIP unit to obtain high pressures and temperatures, the emphasis is on the effect of high pressures in the processes of synthesis of nanotubes. The mechanism of the formation of carbon nanotubes in electrochemical processes has been studied [40].

The possible mechanism of the formation of carbon nanotubes under the conditions of electrolytic bath in the presence of small fragments of graphene planes in the medium of alkali metal and halogen atoms and ions has been analysed using the quantum chemistry methods. During the interaction of such graphene fragments 'burdened' with alkali metal and halogen atoms, the combined graphene configuration is twisted into a nanotube-type structure with open edges [40]. A technique is described [41], with the use of which the substances formed inside the microvolumes between the surfaces to be welded were experimentally isolated. Pressure welding was carried out through the layer of hydrocarbon material. Blind holes were drilled in the welded samples along the axis. Glycerine or uncured epoxy resin was applied to the surfaces to be welded. When the hydrocarbon substance was heated, it was pyrolized. The products of pyrolysis under the action of the pinch effect move into the cavity inside the sample and settle on its walls. Nanotubes and spherical carbon formations were detected. Nanotubes and nanoclusters [42–45] have high conductivity, heat resistance, various structures and properties. They depend on the nature and technology of obtaining. As shown in Refs. [46, 47], the process of Coulomb dissociation of carbon nanoclusters and fullerenes is possible when they are irradiated with picosecond pulses of high-intensity infrared laser of 10^{13}–10^{16} W/cm^2. Under irradiation, multiple ejections of electrons from the nanocluster atoms occur, and the Coulomb repulsion of positive ions is formed in them. This leads to the 'Coulomb explosion' of the nanocluster. The described processes are accompanied by the formation of a 'Coulomb explosion'. The mechanism of this phenomenon is described in Ref. [37]. The gas kinetic pressure in the Z-pinch and its temperature were estimated [48]. Based on the laws of conservation of matter and momentum to the left and right of the shock front, they were of about 1 Mbar and 300 eV, respectively. The effect of ambient pressure on the electrical explosion of conductors in a liquid dielectric has been investigated [49, 50]. As found, the presence of high pressure in the zone of the exploding conductor leads to a delay in the time of the electric explosion. This leads to increase in the energy contribution to the metal substance in the process of the electric explosion.

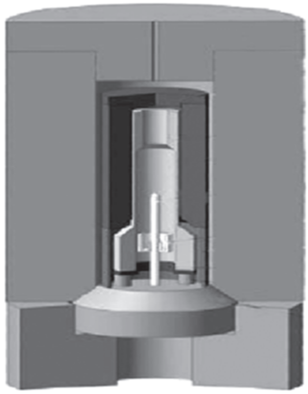


Fig. 10. High-pressure washer cell [39]

Electrical explosion is accompanied by the appearance of a pulsed shock wave. It interacts with the surface to be welded. Because of microexplosions and accompanying micropinches, 'Coulomb explosions' and 'hot spots' are formed. A thin surface layer is subjected to impulsive shock compression in a shock wave. In microvolumes between the surfaces to be connected under the influence of the pinch effect, carbon nanoclusters, which have electric charge, move from the periphery to the centre. When the critical mass of positively charged carbon clusters is reached, a 'Coulomb explosion' of carbon nanoclusters occurs. This is accompanied by ejection from the central part of the junction along the resulting channel. In addition to microexplosions, the process of junction formation can be significantly affected by several factors arising when a pulsed electric current is passed. An analysis [51] of the interaction mechanism of two dissimilar materials under the influence of plastic deformation and high-density pulsed current is presented to assess the connection strength of the considered metals. An assessment of the energy interaction of two metals under the influence of pulsed current and plastic deformation, the certain heating temperature of the contact layer and the depth of penetration of metals into each other are carried out. The technology of production of electrically conductive laminated materials using high-density pulsed electric current is considered. The authors of [51], as a result of the analysis, concluded that the creation of a welded joint occurs due to the transmission of current pulses through the deformation zone, mainly due to electroplasticity and the action of a pulsed current. The authors of works [52, 53] used the methods of radioactive indicators (^{63}Ni, ^{55}Fe) and ion mass spectrometry. Diffusion processes in copper and nickel were studied. The materials were subjected to high-speed compression at elevated temperatures. The compression was performed by imposing powerful pulses of electric current on the quasi-static deformed metals. The effect of this action on the mobility of atoms, the penetration depth, the shape of the concentration profile, the deformation rate, and the structure defectiveness has been studied. Assumptions are given in Refs. [52, 53] regarding a possible mechanism of matter transfer during the action of pulses of an electromagnetic field or electric current pulses. The results of theoretical and experimental studies in [54] of the effect of pulse current with a density of 10^3 A/mm^2, pulse duration of 10^{-4} s and frequency of 600–800 Hz on the microstructural characteristics during the implementation of multipass electroplastic rolling of magnesium are presented. The contribution of the ponderomotive factors of the intrinsic magnetic and electric fields to the modification of the microstructure under the conditions of the electronic subsystem excitation of metal under external electromagnetic influences is considered.

The electroplastic effect arises under the action of single current pulses during the tension and compression deformation of crystals; it manifests itself in a stepwise elongation of the samples when the current pulse passes through without any significant thermal effect. The authors of [54] claim that the electroplastic effect is due to the accel-

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eration of the plastic flow of metal by the flow of conduction electrons. Conduction electrons, in addition to the Joule effect, as free electrons are capable of producing a special specific electroplastic effect on metal under mechanical stress above the yield point [54]. A pulsed current passed through the metal loaded above the yield point realizes the phenomenon of electroplasticity and causes, in addition to electroplastic action, ponderomotive effects. These effects predetermine the occurrence of mechanical stresses, excitation of ultrasonic vibrations of the ion core of the metal crystal lattice with a frequency of current pulses due to the action of a transverse Hall field. The authors of Ref. [54] assert that, upon additional deformation of the sample due to ponderomotive factors, the magnetic field diffuses into the crystal, while the diffusion rate depends on both the metal conductivity and the current frequency. To achieve the maximum pinch effect, it is necessary to choose current pulses frequency, at which the magnetic field does not have time to penetrate significantly the sample surface. With the same sample geometry, the pinch effect is more pronounced for a material with a higher electrical conductivity. As was claimed by the authors of Ref. [54], it corresponds to the concept of the mechanism of electroplasticity described in the fundamental work [55].

There exist several models for the formation of diffusion bonding. The most meaningful is the model of the diffusion compound formation in a vacuum proposed by the authors [56, 57]. According to the provisions of this model, the compound formation occurs in three stages. At the first stage, the formation of physical contact occurs due to plastic deformation at a distance, at which physical interaction occurs due to Van der Waals forces, or at a distance, at which a weak chemical interaction is possible. In the second stage, the contact surfaces are activated. When welding dissimilar materials at this stage, active centres are formed on the surface of the harder material of the materials to be joined. When welding homogeneous metals, the first and second stages practically merge into one, since the activation of both contact surfaces begins already in the process of their convergence when individual microprotrusions are collapsed due to joint plastic deformation. At the third stage, volumetric interaction takes place. This stage occurs from the moment of the active-centres' formation on the surfaces to be joined. In the third stage, the development of interaction takes place. Metals are connected in the plane and in the volume of the contact zone with the formation of strong chemical bonds. When welding homogeneous metals, recrystallization can serve as a criterion for the end of the third stage that leads to the formation of common grains in the contact zone. When welding dissimilar (heterogeneous) materials, the need to develop or limit heterodiffusion is determined by the properties of the diffusion zone and the creation of phases in it (see also Refs. [6, 58]).

This model does not take into account the previously described processes, which occur in electrical explosions when exposed to pulse electric and magnetic fields. During the formation of a diffusion joint during pressure welding through the layer of hydrocarbon substances, many additional factors arise. These factors influence the formation of the bond.

4. Summary

The previously presented works of various authors, based on a large number of interdisciplinary studies, explain the processes occurring during the formation of a welded joint in pressure welding through the layer of hydrocarbon substances. Based on the studied analogues, it is possible to imagine a model of the process under study. Some processes can be identified that affect the formation of the welded joint. When passing a pulsed electric current at the points of contact of the surfaces to be welded, its density is high. The prerequisites for high-speed heating of a small amount of material appear. The heating of the microprotrusions substance of the welded surfaces is accompanied by thermionic emission. Cracks are formed on the surface perpendicular to the direction of electric current passage. Inside the metal, a microprotrusion occurs along with overheating of the metal with the formation of melt bubbles. Upon further heating, the electrical explosion occurs with the formation of a plasma gap and a micropinch. In the process of compression, the plasma column is deformed with the formation of constrictions, the radius of which is less than the radius of the main column. The magnetic pressure in the constriction region increases that leads to the substance outflow from the constriction region in the axial direction. Because of the pinch action, the overflow of electrons occurs with the formation of a 'hot spot' and a 'Coulomb explosion'. The 'hot spot' explodes and, at this time, the generation of the electron beam, hard x-rays and high-energy ions occurs. The electrical explosion is accompanied by the formation of a blast wave, high pressures and temperatures. It was found that the presence of high pressure in the zone of the exploding conductor leads to the time delay of the electric explosion. This leads to increase in the contribution of energy to the metal substance in the process of an electric explosion. High temperatures and pressures lead to pyrolysis of the hydrocarbon material. Carbon structures are formed. Carbon structures under the action of pinches move to the central part of the joint to be welded. They also explode under the effect of high temperatures and pulse electric current. A Coulomb explosion occurs in carbon structures. The welding process ends with the ejection and combustion of products from the joint zone. Forceful action on the surfaces to be joined and the action of electric pulse current activate the surface. Electromagnetic fluctuations affect the vibrations of the crystal lattice and clouds of conduction electrons. The electroplastic effect appears. The analysis of the phenomena in the studied analogues makes it possible to explain the small deformations of the joint formation zone and the short time required for welding. Electromagnetic effects, described as catalysts for the synthesis of elements in the electric discharge, are likely to influence the formation of a welded joint. However, there is no way to confirm this experimentally. No publications are available. The hypothesis does not contradict the outlined three-stage model of the diffusion joint formation.

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О.В. Жартовський[1], *О.В. Лaрічкін*[2]

[1] Донбаська державна машинобудівна академія,
вул. Академічна, 72, Донецька обл., 84313 Краматорськ, Україна
[2] ПрАТ «Новокраматорський машинобудівний завод»,
вул. Олекси Тихого, 5, Донецька обл., 84305 Краматорськ, Україна

ЗВАРЮВАННЯ ТИСКОМ ЧЕРЕЗ ШАР ВУГЛЕВОДНЕВОЇ РЕЧОВИНИ: ФІЗИЧНІ ПРОЦЕСИ УТВОРЕННЯ ДИФУЗІЙНОГО З'ЄДНАННЯ

Стаття стосується гіпотези про механізм активації дифузійних процесів при зварюванні тиском імпульсним струмом через шар вуглеводневої речовини. Незважаючи на розробку такого способу зварювання минулого століття, цю тематику все ще мало вивчено, що потребує подальших досліджень. Під час розробки цього способу зварювання не було необхідної кількости наукових даних про фізико-хімічні процеси, що супроводжують утворення з'єднання. У статті оглянуто фізико-хімічні процеси, що належать до предмету досліджень міждисциплінарного характеру. Експериментальні дослідження, виконані фахівцями у різних галузях, уможливили встановлення даних, необхідних для розробки гіпотези. Було відкрито карбонові наноутворення та вивчено їхні властивості. Досліджено явища, що супроводжують проходження електричного струму в мікропінчах, «Кулонові вибухи» з утворенням ударних хвиль, аномальне масоперенесення в умовах ударного навантаження при дифузійному зварюванні різнорідних матеріалів. Експериментально доведено, що електропідривні й електромагнетні явища, ударні хвилі при впливі на поверхневі шари металу активують дифузійні процеси. На основі великої кількости міждисциплінарних досліджень сформульовано гіпотезу про утворення дифузійного з'єднання при зварюванні тиском імпульсним струмом через шар вуглеводневої речовини. Час утворення з'єднання за однакової температури менше потрібного для дифузійного зварювання у вакуумі. Будова зварного з'єднання є аналогічною будові одержаного шляхом дифузійного зварювання у вакуумі.

Ключові слова: зварювання тиском, вуглеводневі речовини, електричний вибух, електричний струм, нанотрубки, дифузія.