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Influence of Pyrolysis Products on the Formation of a Joint During Pressure Welding Through a Layer of Hydrocarbon Substance

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The work is concerned with the study of the process of joint formation during pressure welding by pulse current through a layer of hydrocarbon substance. During the development of this welding method, there was no necessary amount of scientific knowledge about concomitant physicochemical processes. Interdisciplinary experimental studies performed by different authors have allowed establishing scientific facts necessary for the formation of a hypothesis about the mechanism of formation of a welded joint. Carbon nanoformations are found and their properties are studied. The phenomena accompanying the passage of pulse electric current through them are studied. The phenomena of anomalous mass transfer under the action of shock loading during diffusion welding of dissimilar materials are studied. It is experimentally proved that electroexplosive and electromagnetic phenomena as well as shock waves activate diffusion processes, when applied to the surface layers of metal. The hypothesis assumes that, when a pulsed electric current of constant polarity is passed, an electrical explosion of contacting metallic microblasts occurs. The formation and subsequent microexplosions of conductive carbon particles occur. Microexplosions and shock waves activate diffusion processes on the surfaces to be joined. The process is completed after the 'Coulomb explosion' and the release of pyrolysis products from the central part of the joint of the welded surfaces. It is experimentally proved that the formation of the joint occurs at temperatures below the melting point of the materials to be welded. The time of joint formation at the same

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temperature is much shorter than during diffusion welding in vacuum. The structure of the welded joint is similar to the structure obtained by diffusion welding in vacuum. The methodology is developed, and experimental studies are carried out. The obtained results confirm the put forward hypothesis and correspond to the previously performed interdisciplinary studies of specialists.

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

Робота стосується дослідження процесу формування з'єднання під час зварювання тиском імпульсним струмом через шар вуглеводневої речовини. На момент розробки цього способу зварювання не було необхідного обсягу наукових знань про фізико-хемічні процеси, що перебігають водночас. Міждисциплінарні експериментальні дослідження різних авторів дали змогу встановити наукові факти, необхідні для формування гіпотези про механізм утворення зварного з'єднання. Виявлено вуглецеві наноутворення та вивчено їхні властивості. Вивчено явища, що супроводжують проходження через них імпульсного електричного струму. Досліджено явища аномального масопереносу під дією ударного навантаження під час дифузійного зварювання різнорідних матеріялів. Експериментально доведено, що електровибухові й електромагнетні явища, а також ударні хвилі активізують дифузійні процеси під час дії на поверхневі шари металу. Гіпотеза припускає, що під час проходження імпульсного електричного струму постійної полярности відбувається електричний вибух контактувальних металевих мікровибухів. Відбувається утворення та подальші мікровибухи струмопровідних частинок вуглецю. Мікровибухи й ударні хвилі активують дифузійні процеси на поверхнях, що з'єднуються. Процес завершується після «Кулонового вибуху» та виділення продуктів піролізи з центральної частини стику зварюваних поверхонь. Експериментально доведено, що формування з'єднання відбувається за температур нижче температури топлення матеріялів, що зварюються. Час формування з'єднання за тієї ж температури значно коротший, аніж за дифузійного зварювання у вакуумі. Структура зварного з'єднання подібна до структури, одержаної за дифузійного зварювання у вакуумі. Розроблено методику та проведено експериментальні дослідження. Одержані результати підтверджують висунуту гіпотезу та відповідають раніше виконаним міждисциплінарним дослідженням фахівців.

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

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1. INTRODUCTION

Pressure welding is widely used in industry. One of the types of pressure welding is vacuum diffusion welding. In vacuum diffusion welding, the joint is formed because of deformation effect on the surfaces of the materials being welded to be joined. Joint formation occurs with the formation of a transition zone and joint grains at the contact points. There is a model for the formation of a diffusion compound [1]. It involves three stages. First, physical contact is formed based on interatomic interaction. Further, the contact surfaces are activated with the formation of active centres on the surface of the harder of the metals to be joined. After that, volumetric interaction takes place on the active centres. This is accompanied by stress relaxation. The formation of a joint with minimal deformation in the welding zone with high productivity is an urgent task and is solved in different technological processes in different ways. One of the methods for intensifying the diffusion welding process is the use of intermediate layers. Known technologies [2–5], which use various kinds of tapes and foils, powder layers. The processes occurring during the formation of 'material–layer–material' contacts are determined by the properties of all substances in the contact zone. The use of intermediate layers [4, 6–8] of submicron and nanosize powders makes it possible to exclude macroplastic deformations in the zone of the welded joint. The use of an activating Ni sublayer and a powder layer of submicron Ni powder made it possible [6] to obtain a high-quality diffusion joint of steel samples at temperatures of 0.5–0.6 of the melting temperature of the material being welded. Researchers have carried out work to study the factors that accelerate diffusion processes in the zone of formation of a welded joint. The phenomenon of anomalous mass transfer under shock loading of dissimilar materials during welding has been experimentally proved [9]. The method of radioactive isotopes on commercially pure metals (Fe, Ni, Cu) and steels (steel3, 12Kh18N10T) was used to study diffusion processes during high-speed plastic deformation of metals [10–16].

The occurrence of an electric current pulse during high-speed plastic deformation of metals has been established. There is a dependence of the current strength on the nature of the material and the rate of deformation of the metal. Electric potential and anomalous mass transfer are observed only because of pulsed plastic deformation. The phenomena are interconnected and occur simultaneously. Experimental studies were carried out [17] to study the simultaneous effects of double and triple effects. Three processing schemes were investigated. According to the first scheme, alternating deformations with an ultrasonic frequency were used at elevated temperatures. The second scheme involved the use of ultrasonic shock treatment together with pulsed plastic deformation. According to the third scheme, ultrasonic vibrations, a constant magnetic field and quasi-static deformation were simultaneously applied without heating. The results of experimental studies [17] indicate that the use of double and triple effects is promising for obtaining diffusion layers on metals and alloys. Experimental studies [18] on welding metals in the solid phase using high-density current pulses have shown the possibility of high-quality welding with various pulse shapes. The authors of [19] presented an analysis of the mechanism of interaction of two dissimilar materials under the influence of plastic deformation and high-density pulsed current for assessing the strength and quality of metal joining. An assessment of the energy interaction of two metals under the influence of a pulsed current and plastic deformation is carried out. The studies carried out confirm the effect of pulsed current on diffusion processes. The presented works confirm the possibility of stimulating diffuse processes by pulsed electric current, pulsed plastic deformation and combined action. There are data on the study of the influence of elastic waves on the rate of chemical transformations in a solid. The work [20] describes low-temperature solid-phase detonation. The author has proposed a probable mechanism for this phenomenon. The initiator and driving force of ultrafast low-temperature chemical transformations in solids is an elastic wave. The authors of Ref. [20] argue that from a combination of compressive, tensile, and shear deformations, shear deformations are more effective. They are primarily responsible for superfast conversions in the system.

The authors of works [21, 22] proposed to introduce hydrocarbon substances into the space between the surfaces to be welded, and to carry out heating by passing a pulsed electric current. The introduction of a hydrocarbon substance into the space between the surfaces to be welded when heated by a pulsed electric current makes it possible to accelerate the formation of a joint. The literary sources do not describe the processes occurring during the formation of welded joint using interlayers of hydrocarbon substances. The task is urgent and of great practical importance. The previously described studies by various authors suggest a special role for a number of factors affecting the acceleration of diffusion processes. These factors include the dispersion of substances in microvolumes between the contacting surfaces [4, 6–8], the electromagnetic effect of a pulsed electric current [17–19], a pulsed force [9–16, 20] on the surfaces of materials to be welded.

When a pulsed electric current of constant polarity is flowing, local overheating occurs at the contact points of the metal surfaces in contact with each other and electrical explosions occur. In the space between the surfaces to be welded, pyrolysis of hydrocarbon substance occurs with the formation of nanosize carbon formations. The resulting conductive carbon particles explode to form a multitude of micropinches. Shock waves activate diffusion processes on the surfaces to be joined. The proposed hypothesis is based on a large number of interdisciplinary experimental studies. In the literature, there is no model of joint formation in pressure welding through a hydrocarbon layer.

The aim of this paper is experimental verification of the provisions of the proposed hypothesis.

The objectives of this work are to develop an experimental technique to prove the formation of carbon structures in the microvolumes between the surfaces to be welded, to show experimentally the presence of electric charge of carbon structures, to show experimentally their movement to the centre of the cross-section of the welded surfaces under the action of the magnetic field of the pulse electric current of constant polarity. An accumulation of charged carbon structures is formed there. When a critical mass of charged particles accumulates, a 'Coulomb explosion' occurs.

2. METHODS, EXPERIMENTAL RESULTS AND DISCUSSION

To accomplish the set task, an experimental setup was developed and used, consisting of a power supply with a pulsed electric current of constant polarity, devices for fastening samples and longitudinal compression. Experiments were carried out to isolate the substance formed during the pyrolysis of the hydrocarbon substance. Cylindrical specimens with an axial circular cylindrical hole were used. The surfaces were coated with a hydrocarbon material (uncured epoxy) prior to welding. Welding temperature was of 1180–1200°C. The heating rate of the welded joint did not exceed 120–200°C/sec. The duration of the welding process did not exceed 10–12 seconds. The nature of the destruction of the samples was studied during mechanical tests of the welded joint. The structure of the welded joint was investigated by metallography methods. The nature of the release of the substance from the welded joint was studied visually.

In pressure welding with the use of hydrocarbon interlayers of homogeneous and dissimilar steels, the process always ended with the release of a substance from the joint zone with a specific sound and flash. This allowed us to assume the nature of the movement of the substance at the junction between the surfaces to be joined.

First, the pyrolysis products moved to the central part of the joint. Then, because of the 'Coulomb explosion', the substance was ejected. Figure 1, *a* show a diagram of the movement of products during heating of the welded surfaces and pyrolysis of hydrocarbon layers. Figure 1, *b* shows a diagram of the movement of products during an explosion of a substance.

Such motion of substance in the joint is possible at formation of charged particles because of explosion of metal in the contact points and microexplosions in products of pyrolysis of hydrocarbon material. This does not contradict the known data [23]. Pressure welding using hydrocarbon interlayers is characterized by the movement of pyrolysis products into the central part of the joint. This assumption was confirmed by physical experiment. A special sample design was used to

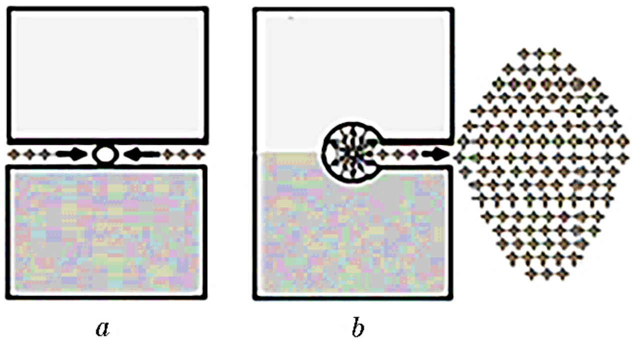

Fig. 1. Diagram of the movement of products at the joint during welding.

isolate the formed substances. Cylindrical samples with an axial round cylindrical hole were prepared. The ends of the samples were coated with the hydrocarbon substance under study. They were placed in a fixation device, subjected to compression and passed a pulsed current of constant polarity. The scheme of the experiment is shown in Fig. 2.

The experiment was conducted according to two schemes. According to the first scheme, the surfaces of the samples to be joined were coated with a hydrocarbon substance. The samples were placed in a fixing device, subjected to longitudinal compression. The joint was heated to the welding temperature and was welded. Then, the specimens were opened by milling parallel to the specimen axis. The nature of the release of the substance from the welded joint was studied visually. There were studied the structure of the substance inside the sample chamber. The substance inside the sample is shown in Fig. 3.

According to the second scheme, the samples were placed in a fixing device. The surfaces to be joined were coated with a hydrocarbon mate-

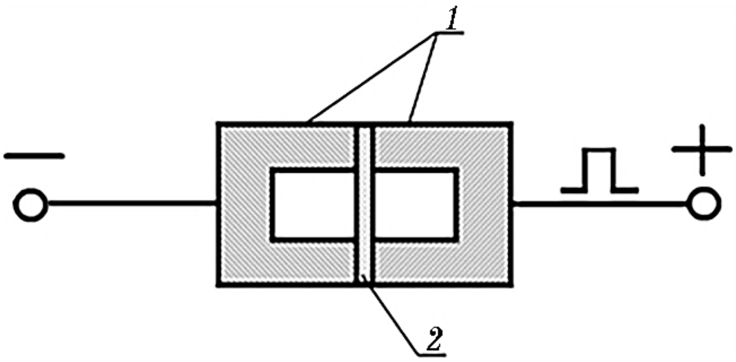

Fig. 2. Scheme of the experiment: steel cylinders with holes (*1*), hydrocarbon substance (*2*).

Fig. 3. Carbon layers inside the sample chamber.

rial. By passing a current, they were heated to the welding temperature. The samples were not subjected to longitudinal compression. After heating to the welding temperature, the samples were opened perpendicular to the axis at the place of heating. The placement of the products of pyrolysis of the hydrocarbon substance inside the sample chamber was studied. The effectiveness of the effect of pyrolysis products of the investigated hydrocarbon substance during welding was checked. The results of displacement of carbon structures are shown in Fig. 4. This figure shows the uneven distribution of carbon particles.

The matter inside the chamber is represented by carbon structures. Both parts of the chamber have different amounts of carbon on the walls. Part of sample 1 has a thin layer on the surface. Part of the layer is missing. Part of sample 2 contains dense deposits of carbon particles. The presented experimental results confirm the presence of charged particles in the space between the surfaces to be joined. Charged carbon particles under the pinch effect move deep into the sample. There they settle on the sample walls. The distribution of the particles is not uniform. The particles settle on the surface with opposite electrode charge. This confirms the presence of electric charge on

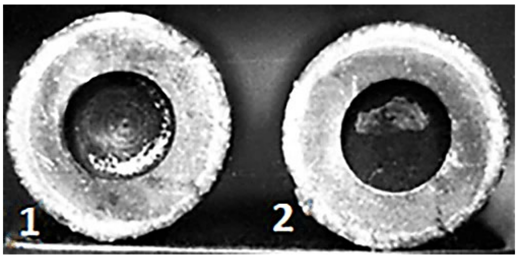

Fig. 4. Uneven distribution of carbon formations in different parts of the sample.

the carbon particles. Cylindrical steel specimens without cavities were welded. When opening the solid cylindrical welded specimens without internal cavities, capsules were found, in which carbon particles accumulated during welding according to the scheme in Fig. 1, *a*. As a result of a 'Coulomb explosion', these carbon particles are ejected from the weld and are visually observed as a flash in Fig. 1, *b*. Figure 5 shows a fragment of a capsule with a product exit channel.

Obtained experimental results are in agreement with the available experimental data [24] on the synthesis of carbon nanotubes at high pressures and temperatures. The experimental results also confirm the presence of high pressure and temperatures in the space between the surfaces to be welded. The creation of high pressure occurs due to multiple micro explosions. The source of this kind of explosion is the contact points of the surfaces to be welded. During passing an electric current through the surfaces to be welded, its value in the initial period of the process is 10^3–10^4 times higher than the nominal value due to the fact that the contact area is from 0.01% to 0.1% of its nominal value [25]. The explosion time is about 120–300 ns [26]. The pinch effect is a factor contributing to multiple manifestations of the 'Coulomb explosion' in the environment of carbon nanoformations between the surfaces to be welded. The existence of both the 'Coulomb explosion' and the charge of carbon nanoparticles coincide with the conclusions in [27, 28]. Shock waves increase diffusion activity on the surfaces to be welded. Due to the electromagnetic effect and the action of shock waves, diffusion processes are accelerated. The increase in the diameter of the cylindrical specimens at the point of formation of the joint after welding did not exceed 0.5%.

Mechanical tensile and toughness tests of homogeneous steels showed characteristics that did not differ from those of the base metal.

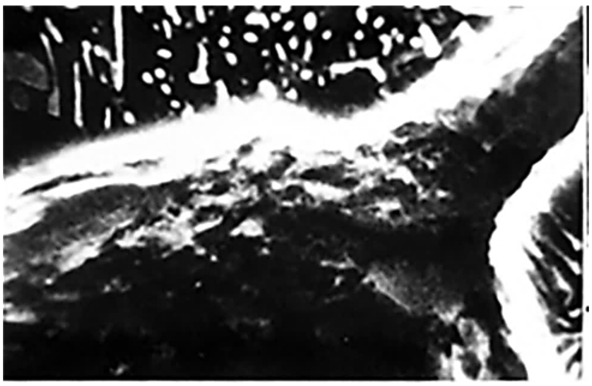

Fig. 5. Fragment of the image of the capsule with the product outlet channel (increase of 5000).

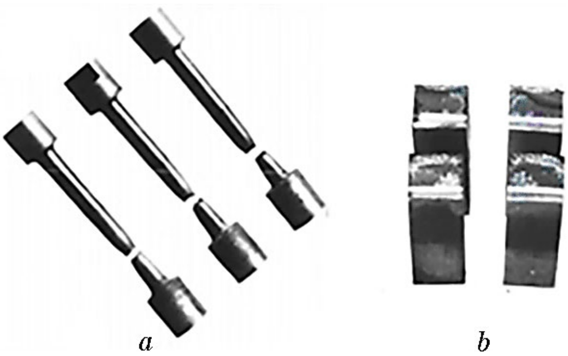

Fig. 6. The nature of the fracture of the sample during tensile tests (*a*) and the impact toughness of the KCU joint (*b*) according to GOST 6996-80 of R6M5 steel with steel 45 of the welded joint obtained by pressure welding through hydrocarbon interlayers.

In tensile tests of a welded joint of dissimilar metals, fracture occurred on a less strong material. Specimens for impact toughness fractured in brittle material. The nature of the destruction is shown in Fig. 6.

The microstructure of the welded joint of steel R6M5K5 with steel 45 is shown in Fig. 7.

The structure of the welded joint obtained by the investigated method is similar to the structure of the joint by diffusion welding in vacuum. The duration of the process of formation of a joint in vacuum without the use of intermediate layers and during welding by the investigated method was compared. According to Ref. [29], diffusion welding in vacuum under various conditions can be from 20 to 60 minutes. During welding with pressure through a layer of hydro-

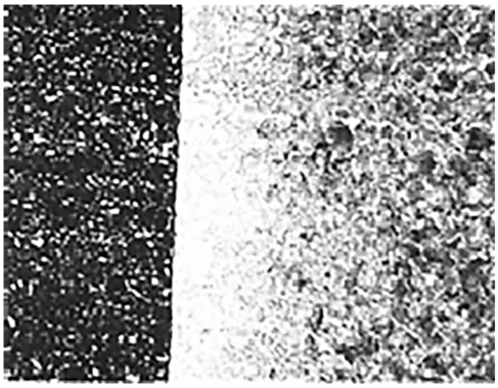

Fig. 7. Microstructure of welded joint of steel R6M5K5 with steel 45 (increase of 200).

carbon substance for welding samples with a diameter of 16 mm, it takes 10–12 sec.

3. CONCLUSION

Based on the results of a large number of interdisciplinary experimental studies, the hypothesis [1] about the influence of hydrocarbon interlayers on the formation of a welded joint was first put forward and experimentally confirmed. When passing a pulsed electric current of constant polarity, an electric explosion occurs at the contact points of the welded metal surfaces. In the space between the welded surfaces, pyrolysis of hydrocarbon substance occurs. This is accompanied by multifactor pulse force and electromagnetic impact. These impacts contribute to the activation of diffusion processes.

The methodology of experimental studies has been developed and realized. The experiment confirmed the formation of carbon structures in the microvolumes between the surfaces to be welded. The formation of charged particles from hydrocarbon pyrolysis products has been proved. It is proved that, under the action of magnetic field, the charged particles move to the central part and a critical mass of charged particles is formed there. This leads to a powerful 'Coulomb explosion' with the release of pyrolysis products into the surrounding space. The mechanical properties and structure of the welded joint of steel billets have been investigated. The structure of the welded joint is similar to the structure of the joint obtained by diffusion welding in vacuum.

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