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FEATURES OF FORMATION OF STRUCTURE OF COAXIAL JOINTS OF COPPER AND ALUMINIUM IN EXPLOSION WELDING WITH VACUUMING OF WELDING GAP

M.O. Pashchin, P.S. Shlonskyi, A.G. Bryzgalin, O.S. Kushnaryova and **N.L. Todorovych**
E.O. Paton Electric Welding Institute of the NAS of Ukraine
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine. E-mail: office@paton.kiev.ua

The results of the study of intermetallics formation in explosion welding of copper and aluminium coaxial joints depending on the length of the joint and the environment in the welding gap (air and vacuum) are presented. The metallographic analysis of the boundary of the coaxial joint in copper-aluminium rods showed that at different areas of bimetallic rods in welding under different conditions both in air as well as in the presence of vacuum in the gap, intermetallic layers of different thickness are formed. The growth, observed in the volume fraction and thickness of the intermetallic layer in the joint area, as it moves away from the initiation point, regardless of the environment in the welding gap (air or vacuum), is natural and is explained by the channel effect in explosion welding. 14 Ref., 1 Table, 9 Figures.

Keywords: *explosion welding, channel effect, intermetallics, contact point speed*

As is known, in aircraft industry, manufacturers seek to reduce the weight of aircrafts. Therefore, manufacture of conductive elements with a copper solid gap, which inspite of a high electrical conductivity at the same time has a high density, is irrational. In current-carrying elements (Figure 1) an alternating current of high frequency flows and, taking into account the skin effect, the current is distributed nonuniformly in the cross-section — mainly in a thin surface layer [1].

The length of the pipe cladding can be characterized by the coefficient of length in the form of the ratio of its length L_p to diameter d_p

$$K_l = L_p d_p^{-1}.$$

Among the reasons that cause the need in cladding long-length workpieces, two main reasons can be distinguished:

- producing or restoring standard products;
- increase in efficiency and economy of expensive materials.

Until now, the possibilities of technologies for explosive cladding pipes and rods were limited to short-length products (K_l < 5–10) [2] and the nomenclature of coating materials (stainless steel, titanium) [3–6]. These works show the need in further development and improvement of technologies, in particular, for the development of the range K_l > 5–10 and cladding with electrical materials.

In [7] the possibility of producing long-length coaxial joints (K_l ~ 30) is presented, but at the same time it is indicated that the continuity of the joint, on average, amounts to 50 % from the total contact area of welded surfaces, which may be quite acceptable for conductivity and unsatisfactory when a product is subjected to mechanical action (bending, flattening, etc.).

Despite numerous successes achieved in the field of studying the process of explosion welding of copper and aluminium, due to investigations by Ukrainian and foreign scientists Kudinov V.M., Dobrushin L.D., Petushkov V.G., Derybas A.A., Sedykh B.S., Lysak V.I., Trykov Yu.P., Kuzmin S.V., Pervukhin L.B., Crossland V., Bahrani, etc. most of the works are devoted to the problem of producing sheet bimetal or three-layer composite material produced according to the battery scheme (simultaneous cladding on both sides).

Figure 1. Appearance of conductive element of aircrafts

M.O. Pashchin — https://orcid.org/0000-0002-2201-5137, P.S. Shlonskyi — https://orcid.org/0000-0002-3566-1752,
A.G. Bryzgalin — https://orcid.ord/0000-0001-5886-3069, O.S. Kushnaryova — https://orcid.org/0000-0002-2125-1795,
N.L. Todorovych — https://orcid.org/0000-0002-3872-5790

The process of joint formation during explosion welding of coaxial joints of copper with aluminium is greatly influenced by an shock-compressed gas, which fills the gap between the welded surfaces and moves at a speed exceeding the speed of the point contact [8]. For combination (joining) of copper-aluminium, the atmosphere in the welding gap affects the formation of the joint structure because of a low melting point of aluminium and the eutectic $Al_2Cu + \kappa$, which has a melting point of 548 °C [9]. A high temperature of the gas before the contact point results in heating the welded surfaces [10–12]. An increase in the size of the eddy zones (up to the melts and destruction of the cladding layer) with moving away from the beginning of the welding process indicates an increase in the amount of energy absorbed by the metal in the zone of the welded joint formation. The abovementioned results of investigations allowed formulating the aim of this work.

The aim of this work was to study the effect of the length and vacuuming of the welding gap on the structure of the joint of copper with aluminium during explosion welding of long-length cylindrical products.

Materials and procedures of investigations. To determine the maximum length, at which it is possible to produce a high-quality welded coaxial joint of copper and aluminium, as well as the effect of vacuuming, explosion welding experiments were performed on the conditions mentioned in Table, with and without vacuuming of the welding gap.

As welded materials, M1 grade copper pipe with an outer diameter of 28 mm and a wall thickness of 1 mm and AD1 grade aluminium rod were used (Figure 2), and the welded area was ground to a diameter of 24 mm. The length of the welded workpieces was 1000 mm. Explosion welding was carried out on two conditions at collision speeds of 320 and 390 m/s, the speed of the contact point of 2000 and 2600 m/s, respectively, with and without vacuuming of the welding gap. Before welding, the copper pipes were etched in a 10 % solution of nitric acid to remove scale after annealing, and aluminium rods were cleaned by a sandpaper with a grain size of P120. During vacuuming of the welding gap, the value of vacuum was 20 kPa. For uniformity of loading, the container was used consisting of several parts (Figure 2, *b*).

Cutting out of specimens for the subsequent manufacture of sections from them was carried out mechanically by means of a corner saw, according to the scheme

Numbers of sections cut out from rods, welded on different conditions

Conditions	V_c = 2000, m/s	V_c = 2600, m/s
Air	No.1 — beginning 70–100 mm	No.7 — beginning 70–100 mm
Same	No.2 — middle 450–500 mm	No.8 — middle 450–500 mm
»	No.3 — end 870–900 mm	No.9 — end 870–900 mm
Vacuum	No.4 — beginning 70–100 mm	No.10 — beginning 70–100 mm
Same	No.5 — middle 470–500 mm	No.11 — middle 470–500 mm
»	No.6 — end 870–900 mm	No.12 — end 870–900 mm

Figure 2. Workpieces for explosion welding (*a*), loading of explosives into a folded container (*b*)

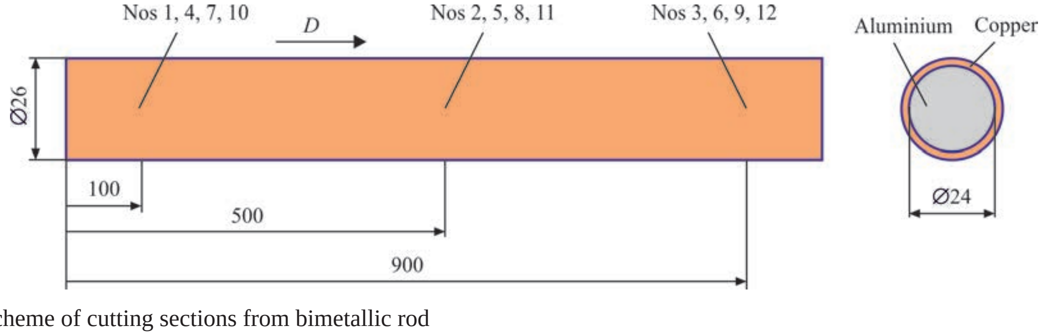

Figure 3. Scheme of cutting sections from bimetallic rod

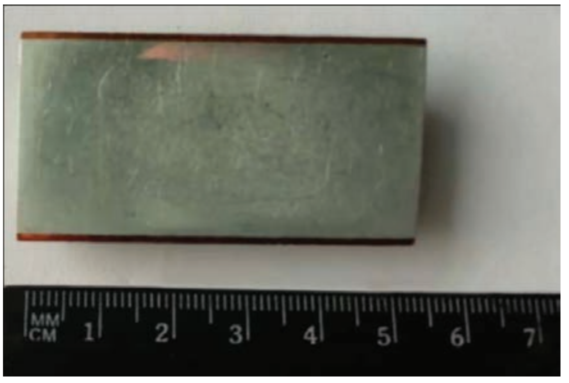

Figure 4. Specimen of microsection of bimetallic rod for metallographic examinations after explosion welding

presented in Figure 3. In all cases, the cut was made using coolant to prevent overheating of the joint area.

Table describes the place of cutting out of the specimen to study the microstructure and indicates the conditions, on which the explosion welding was carried out.

A specimen of a microsection of copper-aluminium joints after explosion welding is shown in Figure 4. To reveal the microstructure, copper etching was performed. Etching of microsections was performed in a mixture from 1 part of nitric acid (50 %) and 1 part of water (50 %).

The hardness tests were performed by the Vickers method. Into the surface of the material, a tetrahedral diamond pyramid with an angle at the apix $\alpha = 136°$ is pressed.

The measurements of microhardness were performed in a microhardness tester PMT-3. The measurements were performed by the method of reconstructed impression, which consists in applying the impression to the tested surface after application of a static load of 0.1 N for copper M1 and aluminium AD1 to the diamond tip. The measuring step was set in the range from 0.05 to 0.2 mm depending on the hardness of the material and the distance from the boundary of the joint *d* (with an increase in *d* the step increased) was investigated. Setting up of PMT-3 device on touch of the specimen was carried out at a load $P = 0.005$ N.

Results of experiments and their discussion. The produced specimens were subjected to metallographic examinations, the results of which are presented in Figure 5. The volume fraction of intermetallics and the width of intermetallic layer were studied. Based on their results the diagrams of dependence of the abovementioned parameters on the conditions of explosion welding and the presence or absence of vacuum in the welding gap were plotted (Figures 6, 7).

Figure 5, *a*, *b*, c shows the photos of the microstructure of different zones (beginning, middle, end) of the bimetallic rod produced at V_c = 2000 m/s in air, and in Figure 5, *d*, *e*, *f* in vacuum. The photos of microstructure of different zones of the bimetallic rod (beginning, middle, end), produced in air and in vacuum at V_c = 2600 m/s are presented in Figure 5 (*g*, *h*, *i*) and Figure 5 (*j*, *k*, *l*), respectively.

The carried out metallographic analysis of the boundary of the coaxial joint in copper-aluminium rods showed that at different areas of bimetallic rods in welding on different conditions and in air, and in the presence of vacuum in the gap, it is impossible to produce a joint without the formation of intermetallics.

In explosion welding of copper with aluminium at the speed of the contact point V_c = 2000 m/s, the joint line has a configuration close to a wave-like one with the presence of areas of molten metal near the base of the deformation mounds. Intensification of welding conditions (increase in the speed of the contact point to 2600 m/s) leads to the formation of a wave-like configuration of the joint with unstable parameters of waves and the formation of a continuous interlayer of intermetallics both in vacuum and without it.

In this case, an eddy is formed at the beginning of a wave formation, inside which looseness, copper particles and other inclusions are observed (see Figure 5).

The observed increase in the volume fraction (Figure 6) and thickness of the interlayer (Figure 7) of intermetallics in the joint zone as they move away from the initiation point, regardless of the environment in the welding gap (air or vacuum), has a natural character and is explained by the channel effect in explosion welding [13].

During welding in air on the conditions V_c = = 2000 m/s at the beginning of the specimen the volume fraction of intermetallics is equal to 60 %, during welding in vacuum on the same conditions it is equal to 48 % (Figure 6), which is 1.25 times lower. At the same time, the ratio of the volume fraction of intermetallics in air to the same fraction in vacuum at the beginning of the specimen in welding at V_c = 2600 m/s amounts to 1.08. This indicates the fact that with an increase in speed of the contact point, the transition of kinetic energy into heat energy occurs mainly due to plastic deformation of the metal of the near-weld zone, and to a lesser extent due to the channel effect, which is weak expressed at a short distance from the initiation of the explosion welding process.

In the middle and at the end of the specimen, the ratio of the volume fraction of intermetallics in air to the same fraction in vacuum during welding on the conditions V_c = 2000 m/s amounts to 1.05 and 1.03, respectively, i.e. they are almost equalized. This indicates the fact that at a distance of more than ten diameters of the workpiece in the welding with vacuuming gap, air «plug» of a shock-compressed air and parti-

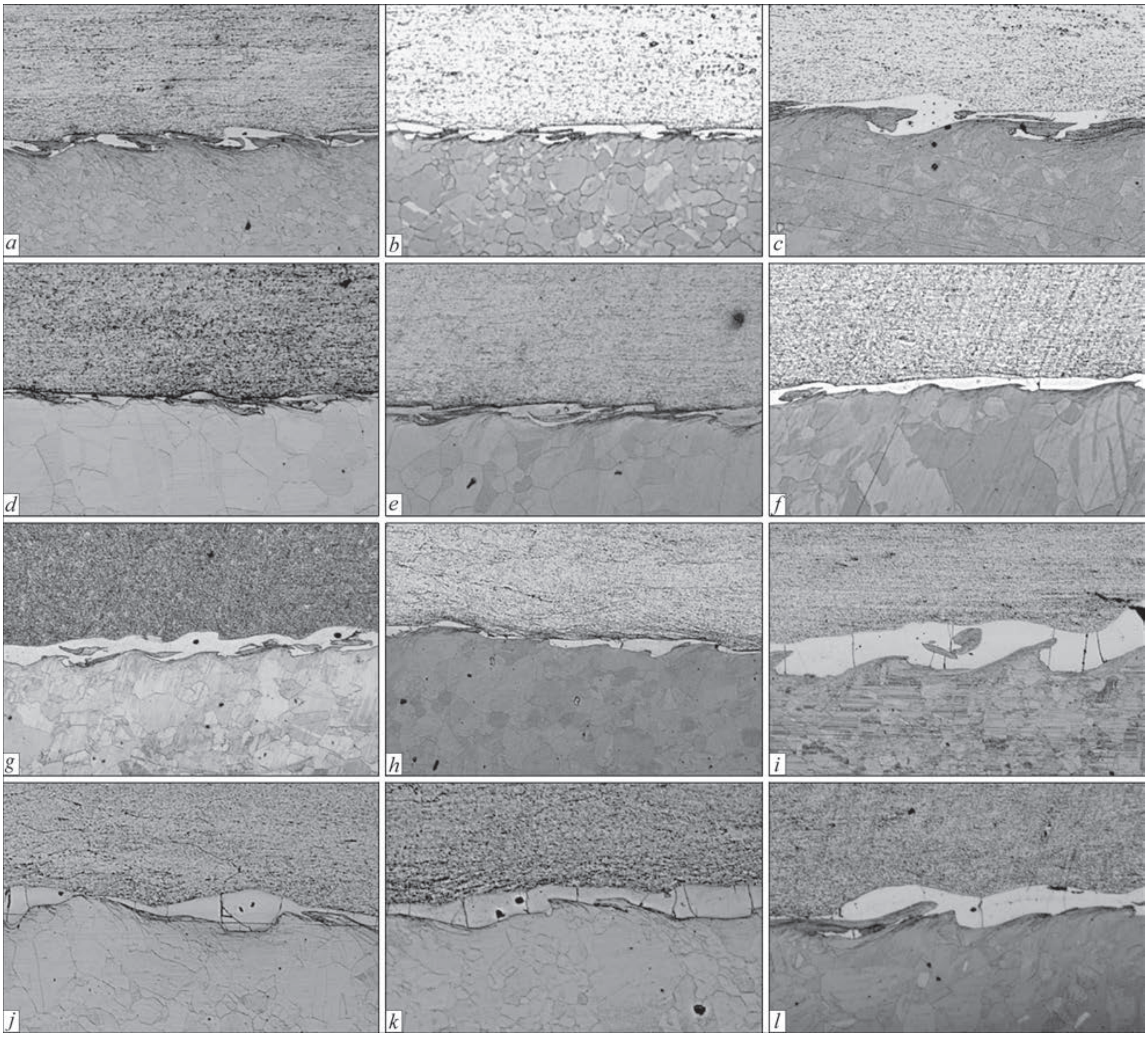

Figure 5. Change in the microstructure of the joint zone depending on the distance from the beginning of welding and environment in the welding gap at different speeds of the contact point (×150, aluminium is above): *a*, *b*, *c* — beginning, middle, end, V_c = 2000 m/s in air; *d*, *e*, *f* — beginning, middle, end, V_c = 2000 m/s in vacuum; *g*, *h*, *i* — beginning, middle, end, V_c = 2600 m/s in air; *k*, *l*, *m* — beginning, middle, end, V_c = 2600 m/s in vacuum

cles of welded materials is accumulated, which heats welded surfaces.

As is seen from Figure 6, the ratio of the volume fraction of intermetallics in air to the same fraction in vacuum in the middle of the specimen in welding on the conditions V_c = 2600 m/s, is equal to 0.61. Thus, the volume fraction of intermetallics produced by welding in vacuum is 1.5 times higher than during

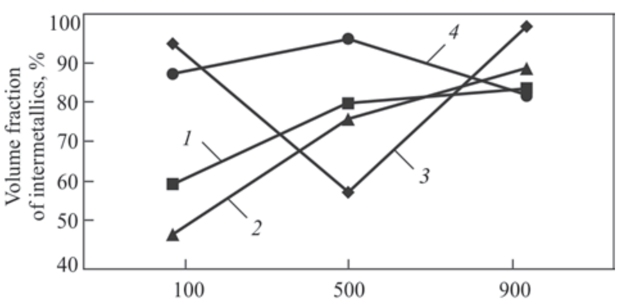

Figure 6. Dependence of the volume fraction of intermetallics on conditions and distance from the beginning of welding: *1* — V_c = = 2000 m/s — in air; *2* — V_c = 2000 m/s — in vacuum; *3* — V_c = = 2600 m/s — in air; *4* — V_c = 2600 m/s — in vacuum

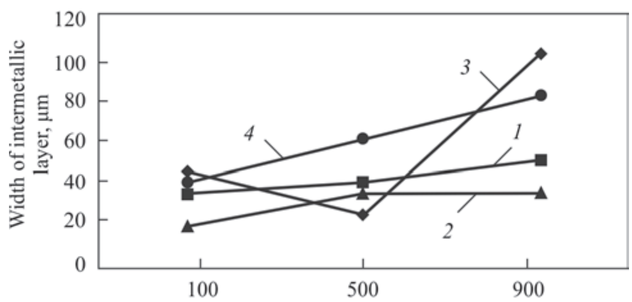

Figure 7. Dependence of width of intermetallic layer on the conditions and distance from the beginning of welding: *1* — V_c = = 2000 m/s — in air; *2* — V_c = 2000 m/s — in vacuum; *3* — V_c = = 2600 m/s — in air; *4* — V_c = 2600 m/s — in vacuum

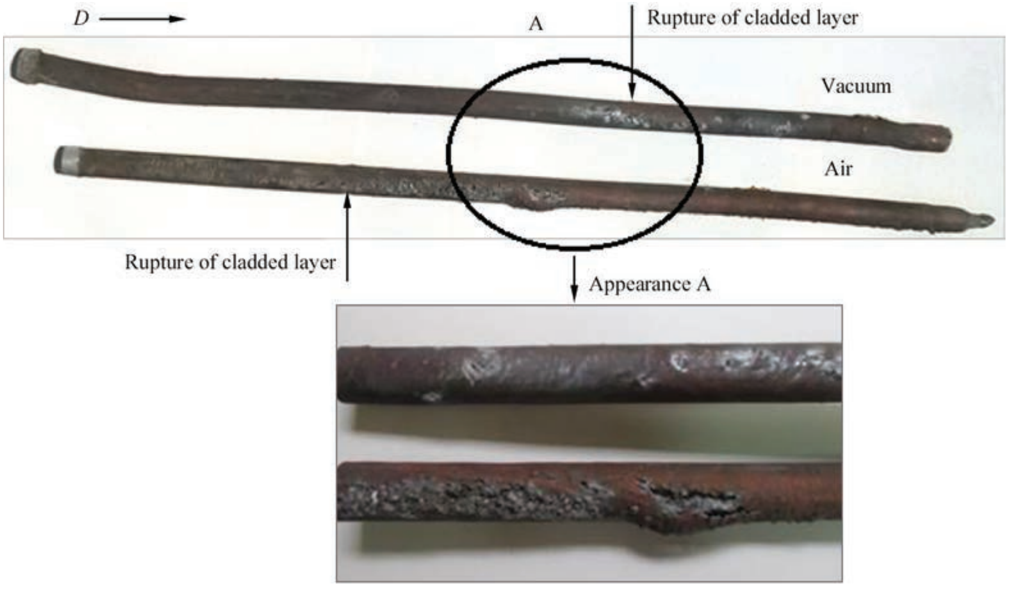

Figure 8. Coaxial workpiece after explosion welding. General appearance, above – with vacuum, below — without vacuum, detonation direction is from left to right. Appearance A — rupture of cladded layer, above — with vacuum, below — without vacuum

welding in air. This is explained by the fact that in welding on these conditions at a distance of 250 mm from the beginning of the process, a rupture of the cladded layer (Figure 8) occurs, which results in the leakage of a heated shock-compressed air. At the same time, on the workpiece, produced by vacuuming of the welded gap, the beginning of defects in the form of a rupture of the cladded layer is observed at a distance of about 500 mm from the closest to the point of initiation of the edge of the workpiece.

The dependence of the width of intermetallic layer on the conditions and the distance from the beginning of welding looks similar (Figure 7). It can be seen that at the initial area of the specimen the width of the intermetallic layer during welding in air at the conditions V_c = 2000 m/s is 35 μm, which is significantly (1.75 times) higher than during welding in vacuum of 20 μm. The width of the intermetallic layer during welding in air on the conditions V_c = 2600 m/s amounts to 45 μm, which can be compared with welding in vacuum — 40 μm. This indicates the fact that at the initial stage of welding, the main mechanism of transition of mechanical energy into heat energy is plastic deformation of the near-weld zone metal.

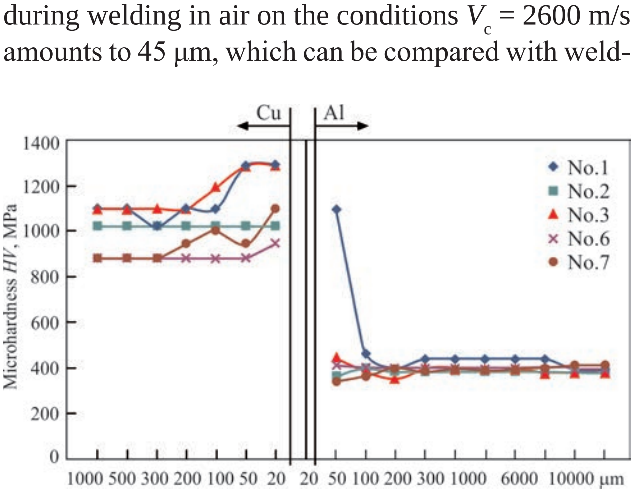

Figure 9. Change of microhardness in welded joint depending on welding conditions and presence of air in the gap (specimen numbers correspond to Figure 2)

In the middle area of the workpiece in welding on the conditions V_c = 2000 m/s, the width of intermetallic layer increases relative to the initial area during welding both in vacuum and in air. At this time the ratio of the width of the intermetallic layer produced in air to the width of the layer produced in vacuum, is up to 1.14 times reduced. At the end of the workpiece during welding in air on the conditions V_c = 2000 m/s a 1.25 times increase in the width of intermetallic layer is observed as compared to the middle area, and during welding in vacuum, an increase in the width is not observed.

Therefore, vacuuming of the welding gap in explosion welding of long-length coaxial joints allows reducing the width and volume of an intermetallic layer, but does not exclude the formation of intermetallics.

A smaller amount of intermetallics in vacuum welding indicates that the main energy input to the creation of intermetallics provides a channel effect, which is especially revealed in explosion welding of coaxial joints.

Studies of the microhardness of the welded joint zone of coaxial copper-aluminium workpieces (Figure 9), produced by explosion welding in vacuum and without it at different conditions (V_c = 2000 and V_c = 2600 m/s) showed that in the joint zone, the nature of microhardness distribution typical for explosion welding with the values of 946–1100 MPa is observed, which is by 10–15 % higher than the value of 860–940 MPa for a flat bimetal copper-aluminium [14].

A strengthening of the near-contact layers is observed, the microhardness of copper in explosion welding on the conditions V_c = 2000 m·s^{-1} in vacuum amounts to 1190 MPa, which is higher than the microhardness of the near-contact layers in welding on the same conditions in air by 150 MPa (specimens No.6 and No.3, respectively). The zone of maximum microhardness of copper (946–1100 MPa) reaches 0.05–0.15 mm. This is also a confirmation of the fact that the collision speed in vacuum welding exceeds the collision speed during welding in air.

The microhardness of aluminium in the near-contact zone is in the range of 336–413 MPa, which is by 5–12 % lower than the maximum microhardness of aluminium (400–460 MPa) for bimetal copper-aluminium produced by the two-dimensional circuit [14], while in the contact zone at a depth of 0.02–0.05 mm microhardness is lower than at a greater depth. This is probably associated with the fact that in explosion welding by a coaxial circuit a more intense heating of the surface layer occurs as compared to a parallel circuit and a thin layer of aluminium, which has a low melting point, is partially annealed and becomes softer.

Conclusions

1. It was experimentally established that in explosion welding of copper with aluminium according to the coaxial circuit with vacuuming of the welding gap, it is possible to produce a workpiece without cladding defects of up to 500 mm length with a diameter of 26 mm, and up to 200–250 mm with the same diameter in welding without vacuuming of the welding gap.

2. On the basis of metallographic examinations, it was established that vacuuming of the welding gap allows almost 1.4 times reduction in the width of intermetallic layer on average on the length on the conditions of V_c = 2000 m/s and in 1.2 times on V_c = = 2600 m/s and reducing the volume fraction of intermetallics by 1.1 times and 1.15 times in welding in the abovementioned conditions, respectively. This is explained by the fact that the main energy contribution to the formation of intermetallics provides a channel effect.

3. It was established that generation of vacuum (~ 20 kPa) in the gap during explosion welding of copper with aluminium, which were assembled coaxially, reduces the amount of intermetallics appearing after welding by 20 %.

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