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PRODUCING OF COAXIAL JOINTS OF DISSIMILAR METALS BY EXPLOSION

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ABSTRACT

Explosive welding allows joining metals and alloys in almost any combinations unlike various types of fusion welding. It provides the ability of manufacturing products with a combination of service properties of applied materials with a high level of strength, tightness, fatigue strength, etc. In addition to bimetals produced in fairly large volumes for chemical and oil equipment, explosive welding is used to manufacture products with special characteristics for different industries. Producing coaxial joints (welding is performed along generatrices of axisymmetric coaxial tubes) can be attributed to a special class of tasks, since they are more economical than alternative methods of their production. In some cases, a permanent joint can be created by explosion compression without welding of elements to be joined. This work presents a number of technological processes for manufacturing coaxial products developed at the PWI, which use both welding and explosive compression. The presented developments testify that a wide range of practical tasks can be solved with the help of explosion.

KEYWORDS: coaxial joints, explosive welding, bimetal, adapter, rod, coupling, permanent joint

INTRODUCTION

Coaxial explosive welding (EW) of cylindrical products is used in a smaller volume compared to EW of sheet metal on a parallel flow chart, but it is used to solve very important practical tasks. First of all, it deals with corrosion-resistant bimetallic tubes of chemical and oil engineering, in which strength is provided by a tube of carbon steel, and resistance to the medium is provided by appropriate metals or alloys (stainless steel, copper, brass, aluminium, niobium, etc.).

Bimetallic tubes and adapters are also used in cryogenic, space, aircraft engineering, elementary particle accelerators and other high-tech industries. Analysis of publications on the topic shows that from the moment when EW was discovered as a technology for bimetal production (1959), a large volume of research on coaxial welding was conducted in the USA and the USSR, the main flow charts of welding were proposed and tested, the features and differences from EW of plane sheets were determined. An overview of flow charts of coaxial explosive welding of tubes and tubes with tube plates of units for chemical production apparatuses is given in [1, 2]. However, since the mid-1960s, a number of publications has shortened sharply and began to bear mostly an informational nature with references to previously published works. This is probably associated with the development of industrial technologies and, accordingly, the lack of interest from producers to publishing their technological developments.

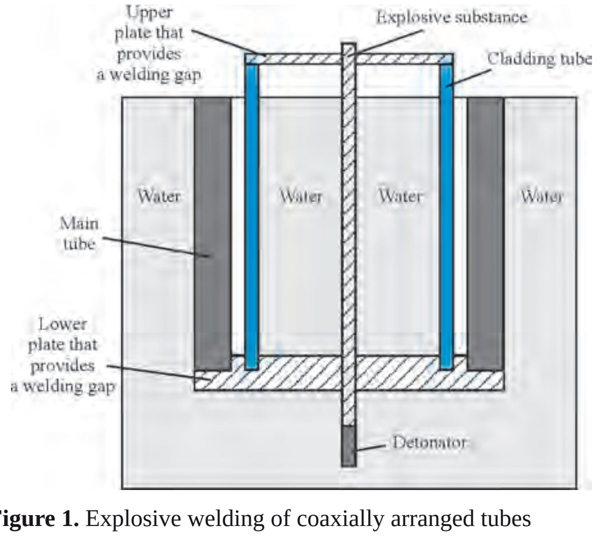

Figure 1. Explosive welding of coaxially arranged tubes

At the same time, it is worth noting some publications that differ in a new technical approach to solving tasks of coaxial welding.

In [3], it was proposed to perform EW with the use of water as a medium that transmits working pressure (Figure 1).

A mixture of hexogen with potassium nitrate was used as an explosive substance (ES). The mixture was placed in a cylindrical aluminium shell. The charge detonation velocity varied depending on the shell diameter but was always close to 7000 m/s. Considering that the detonation velocity in EW is 2000–3000 m/s, the mentioned chart is of interest to research. The works [4, 5] propose the method of theoretical prediction of the collision velocity of the metal of tubes to be welded — the main EW parameter, which determines the power parameters of the process in underwater explosive welding and welding in air, respectively.

However, determination of coaxial EW modes is a rather difficult problem and it is currently realized for each type of joints separately by using the calculation-experimental method. The methods of producing permanent joints (which are not disassembled on components without their partial fracture) with explosion without mandatory welding are also of interest.

In this work, technological solutions for various tasks are presented, which use the methods for producing coaxial joints developed at the PWI.

PRODUCTION OF COAXIAL COPPER-ALUMINIUM RODS BY EXPLOSIVE WELDING AND DRAWING

The conductive busses of a critical electrical equipment are made of copper, which has high electrical conductivity and at the same time high density [6]. In case of its operation at high current frequency (for example, in aircraft engineering), replacement of solid copper busses with aluminium, which are cladded with a thin layer of copper, provides a significant reduction of mass of products while maintaining their electrical conductivity.

At the PWI, the technology for manufacturing bimetal copper-aluminium rods by explosive joining of a copper shell with an aluminium rod and subsequent drawing was developed [7].

The margin of the joint did not exhibit a wave formation characteristic of explosive welding, which indicates that welding was performed on the lower limit of admissible modes, that is, with a minimum energy input [8]. This allowed minimizing (by an order of 10 % along the joint length) the amount of intermetallics formed during welding.

Producing rods with the required diameter of 8.0 and 9.0 mm was carried out by drawing bimetallic billets with a diameter of 26 mm. Here, heat treatment of billets at all stages of drawing operation is not required.

The specific electrical resistance of a bimetal rod to direct current in terms of the temperature of 20 °C amounted to $0.027 \cdot 10^{-6}$ Ohm/m.

The air in the gap forms a shock wave, the front of which moves at a speed higher than the detonation velocity, the speed of this front is constantly reduced due to an increase in the resistance of the air in the gap. At some length of coaxial elements assembled for welding, the rate of air leakage from the gap becomes lower than the detonation velocity. A certain volume of air remains between the elements to be welded, forming bubbles. The movement of the shock wave leads to a significant heating of the element surfaces [9] to be welded, up to boiling aluminium. This has a significant impact on the quality of produced welded joints. In order to prevent this, it was suggested to vacuum a welding gap. Experiments with similar, but longer specimens on the same modes with vacuuming and without a welding gap were conducted. The final pressure at vacuum was 1 Pa [10].

After explosive welding without vacuuming was performed at a distance of approximately 250 mm from the edge of a billet, which is closer to the initiation point, a beginning of defects in the form of a cladding layer tear and a damage to the aluminium surface is observed, which acquires a torn form, there are also defects in the form of bubbles that appear at a distance of 100 mm from the specimen edge. On the specimen with vacuuming, a similar picture is observed, but defects appear at a distance of about 500 mm. The formation of defects in the specimen with vacuuming is explained by the presence of air in the gap, though more rarefied.

A typical feature of both specimens is that most bubbles and all defects in the form of tears are concentrated on a one generatrix. Obviously, this is associated with the fact that as a result of the uneven detonation front, it will always lag behind on one of the generatrix. Such unevenness will depend, first of all, on the shift of the charge initiation center of an explosive substance (ES) from the center of the welding assembly, as well as on the uneven detonation velocity and the charge thickness along the specimen length. It should be noted that in welding with vacuuming, the formed intermetallics had a smaller size. Apparently, this is associated with the fact that in welding with vacuum, there is no heating due to the air flowing from the gap (Figure 2).

It can be concluded that vacuuming of the gap in explosive welding of coaxial billets by external charge improves the quality of welded joint, which consists in an increase in the length of welded billets, on which defects of the type of bubbles and external layer tear are absent, as well as a decrease in the size and amount of intermetallics during welding of copper + aluminium pair. It should be noted that in welding of more strength materials with a higher melting point, no visible defects are formed, the integrity of materials is preserved, the rod produced by explosive welding has less deformation in length. Figure 3 shows a photo of a steel-copper rod for manufacture of a copper refining cathode, produced at the PWI.

TUBE ADAPTERS OF BIMETALS

are widely used in shipbuilding, metallurgy, pipeline transport and nuclear power engineering.

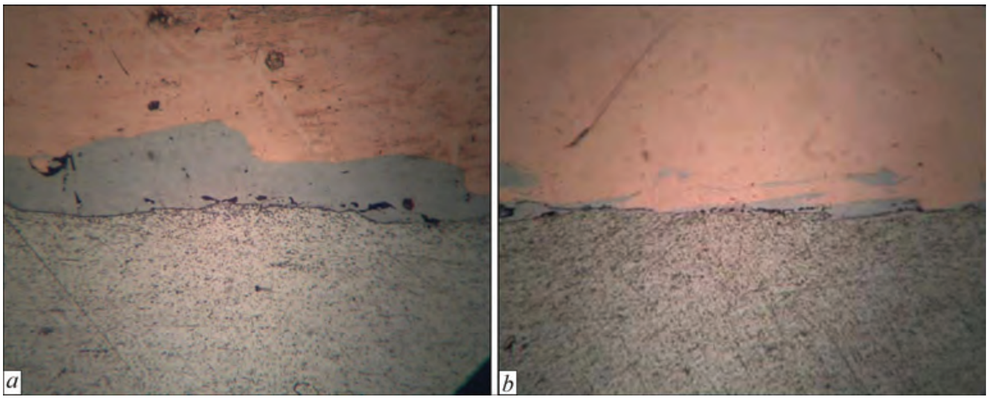

Figure 2. Intemetallics on the copper-aluminium joint interface after explosive welding: *a* — without vacuuming; *b* — with vacuuming

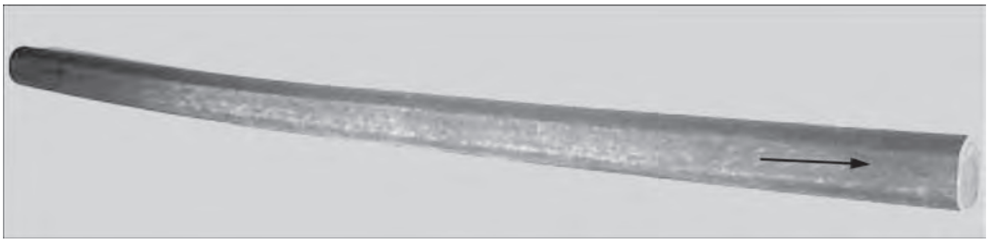

Figure 3. Bimetallic rod produced by explosive welding of copper base with steel tube

At the PWI, the technology for manufacturing the so-called quasi-butt tube transitional element was developed [11]. It represents a branch-pipe with the same geometry of the cross-section along its entire length, but has different materials at its ends, which are joined with each other by explosion (Figure 4).

The further attachment of the pipeline elements to the adapter is performed by fusion welding of similar materials, which allows achieving the high service properties of welded joints. The adapter length is almost unlimited and allows preventing the thermal impact from the arc butt welding of the pipeline extension for the joint produced by explosive welding.

The variants of joining almost any metals are possible with explosive welding. At the PWI, adapters from the following metals: aluminium + copper; copper + steel; stainless steel + steel 20 are manufactured.

The layer adhesion strength was studied by tensile tests of bimetallic tube specimens and those that were cut out along the adapter generatrix. The specimen width was 5–10 mm, depending on its diameter. The length was equal to the adapter length. The clamps of the tensile machine were mounted so that the distance from them to the closest butt edge was at least 20 mm. From each adapter, 3 tensile specimens were cut out.

In all cases, the specimen fracture occurred on weaker metal. There were no cases when a specimen fractured in the joint zone.

The general appearance of steel-copper tube adapters is presented in Figure 5.

Adapters successfully passed tensile tests, high pressure resistance and vacuum and helium tightness.

Such a butt joining of tubes by explosive welding was produced for the first time in the world practice.

In the electrotechnical industry, joining of copper and aluminium conductive elements is quite frequently used. A direct contact of such elements without welding is accompanied by electrochemical corrosion and burnout of expensive materials, resulting in an increase in the transitional resistance, growing during operation. Any kind of welding of these materials

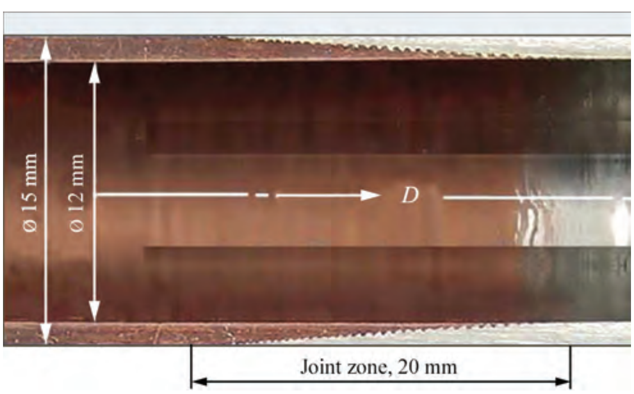

Figure 4. Quasi-butt tube adapter

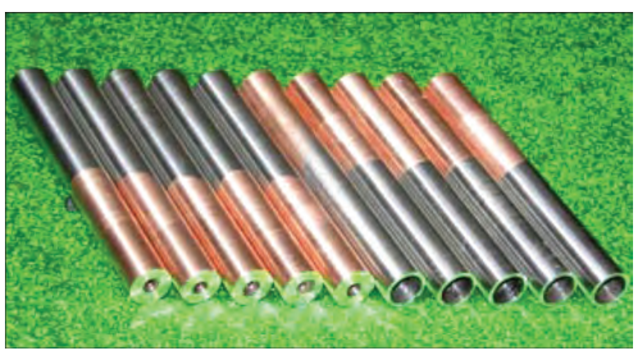

Figure 5. General appearance of tube Cu-steel adapters

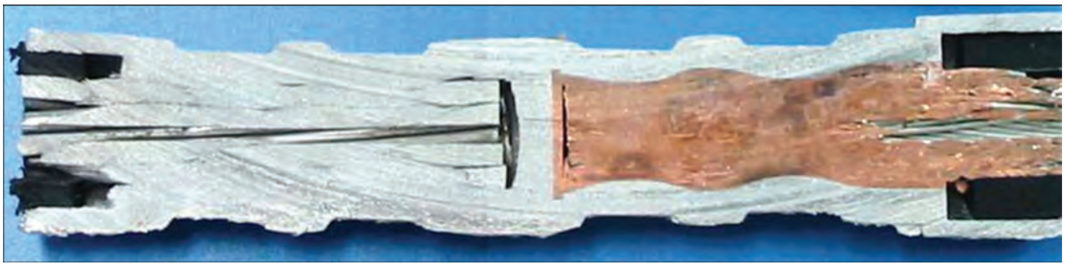

Figure 6. Joining of copper and aluminium cables by crimped couplings

leads to the formation of $A1_nCu_m$ type intermetallics, which can affect electrotechnical properties of a joint. Explosive welding is the most effective method of producing copper-aluminium electrical conductors with increased service properties. The efficiency of introducing designs of composite conductive assemblies produced by explosive welding is confirmed by 1.7–2.5 times decrease in the transitional resistance and by 5–7 times increase in the service life [8].

In particular, bimetallic couplings are used to join copper and aluminium multiconductor cables. They represent a hollow aluminium cylinder, half of which length is cladded with an explosion of copper layer from the inside. The copper cable is inserted into the coupling on the side of cladding and aluminium one is on the back side. Joining is performed by mechanical crimping of the coupling (Figure 6).

From the technological point of view, in some cases, explosive welding has to be performed by an external charge. Therefore, in this case, thicker aluminium is cladded, which is not characteristic of explosive welding [12]. A thin copper tube is a supporting one and should be reinforced from the inside to avoid its deformation during the explosion.

Studies of different variants of the copper tube reinforcement showed that the most rational option is the following: a rigid, for example, steel rod, is inserted inside a vertically mounted copper tube. A gap between the rod and the tube wall is filled with the Wood alloy, which has a melting point of approximately 70–90 °C. Such a rod at room temperature is not deformed by external pressure of detonation products. To remove the support from the copper tube after EW, it is enough to heat the produced billet to 80–90 °C, for example, in boiling water.

Microstructure of a copper-aluminium joint has a slight wave profile with a small quantity of intermetallic inclusions.

Since standard procedures for evaluation of the tear strength of the layers of the bimetallic ring, cut out from the tube billet are absent, a well-known procedure of testing bimetallic rings for flattening was used to qualitatively evaluate the adhesion strength of the layers [13]. The tests were conducted to detect cracks and delaminations in the joint zone under the action of loading.

The lack of delaminations at the joint interface indicates a high quality of EW and the preservation of plastic properties of both metals at the high level.

In the manufacture of products of complex configuration, a combination of EW with fusion welding can be used. The creation of a linear collider adapter can be a typical example [13, 14].

An adapter serves for joining separate cryomodules into one whole. Cryomodule elements to be joined is a niobium supra-conducting resonator, that has to be welded-on by electron beam welding to a niobium adapter branch-pipe, and the casing coaxially arranged to a niobium resonator of stainless steel has to be welded-on to the adapter disc manufactured of the same stainless steel. A niobium resonator is located inside a stainless steel casing, a vacuum is created in it and a liquid helium is poured under the casing. Thus, an adapter should provide the vacuum and helium tightness and operability of the unit in the conditions of high-frequency electromagnetic loads at cryogenic temperatures. The scheme and photo of an adapter is shown in Figure 7.

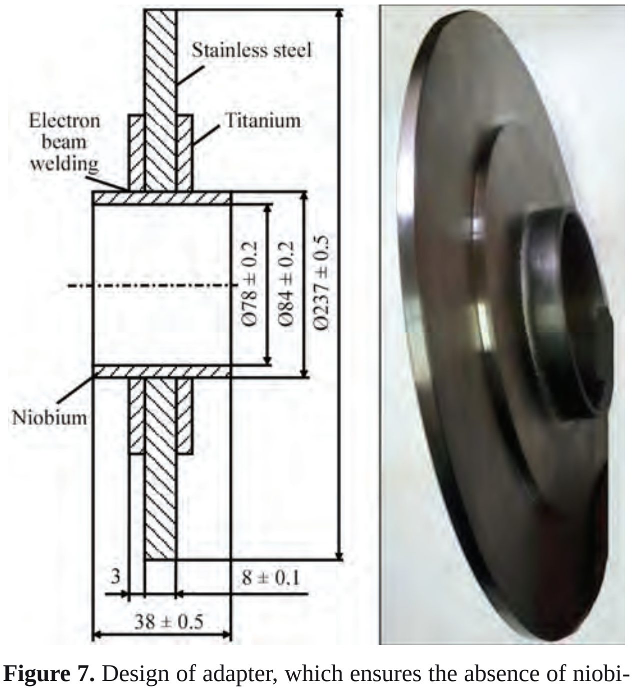

Figure 7. Design of adapter, which ensures the absence of niobium intermetallics formation during welding

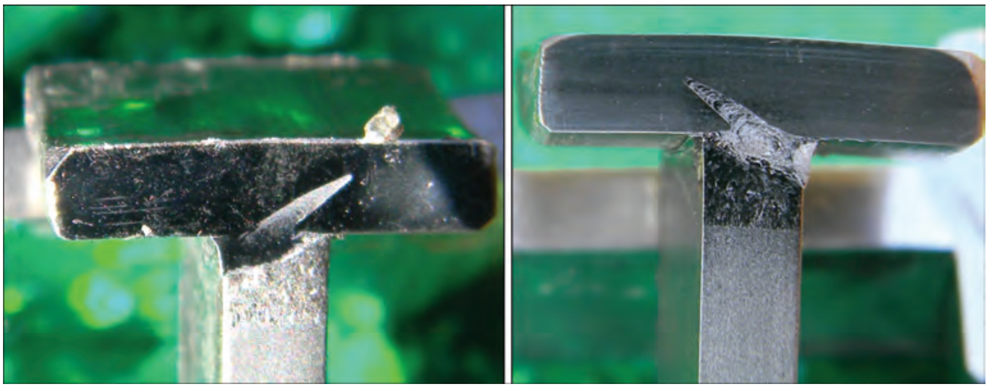

Figure 8. Sections of place of joining niobium with titanium by electron beam welding

It is known that welded joints of the highest quality are produced during welding of similar materials. I.e., an adapter should provide producing of welded joints of niobium with niobium, and stainless steel with stainless steel. Therefore, an adapter should be composed of at least two metals — niobium and stainless steel. The use of any methods of fusion welding to produce a joint of niobium with stainless steel, including electron beam welding, is unacceptable for solving the specified task due to the formation of Nb_xFe_y type intermetallics, which do not allow providing the required tightness of a joint. Manufacture of an adapter by explosive welding of a niobium tube with a steel disc appeared to be a fairly expensive process due to high consumption of niobium at subsequent mechanical treatment.

Previously conducted experiments showed that in electron beam welding of niobium with titanium, no intermetallics are formed and the required tightness of joints is provided on helium and vacuum. In this regard, the following option of manufacturing an adapter was proposed.

The stainless steel disc is first cladded with titanium on both sides by explosive welding, then, after rendering the required shape to the produced trimetal (by straightening and turning in size), a hole for a niobium tube is cut out. The branch-pipe is inserted into the hole and welded-on to titanium by electron beam welding. The possible formation of intermetallics in joining of titanium with steel, which is produced by explosive welding, does not affect the adapter serviceability, because helium cannot get into the cavity of the niobium tube through the adapter.

Mechanical tests of the produced EW joints on tear of layers showed satisfactory strength (375 MPa), the bending of bimetal at 180° did not detect the formation of delaminations or cracks. The optimal modes of electron beam welding of titanium with niobium (Figure 8) were experimentally selected.

The specimens produced by combined technology were cooled with liquid helium to a temperature of 4.2 K, and then quickly heated to room temperature with dryers. The specimens after thermal cycling carried out in such a way provided a helium and vacuum tightness [15].

The existing methods of joining rebars when constructing reinforced concrete objects [16] have a number of disadvantages. Development of high-performance, economic and ergonomic methods of joining thermal reinforced rebars, providing strength properties of joints at the level of the base metal, is a very urgent task for today.

One of such methods can be joining of rebars by couplings crimped by explosion. The advantages of explosive technology are absence of strength loss of the base metal, ability to join metals that cannot be welded by fusion methods without deterioration of service properties, for example, thermally strengthened or bimetal rebars, coated with an external anticorrosion layer, lack of need in using special equipment, independence of power supply sources, ability to conduct works with high performance.

Figure 9. Principal scheme and macrosection of rebar joint made by explosion: *1* — rebar; *2* — charge shell; *3* — initiating detonating cord; *4* — coupling; *5* — explosive substance

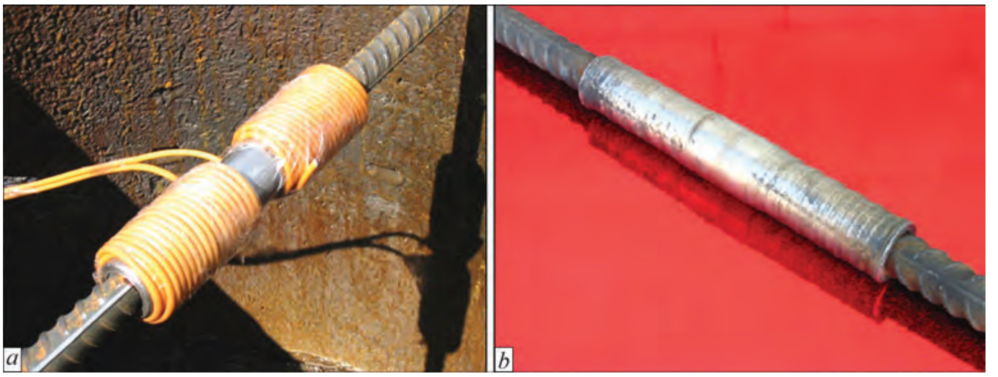

Figure 10. Example of coupling compressed by a charge from the detonating cord before charge explosion (*a*) and after explosion (*b*)

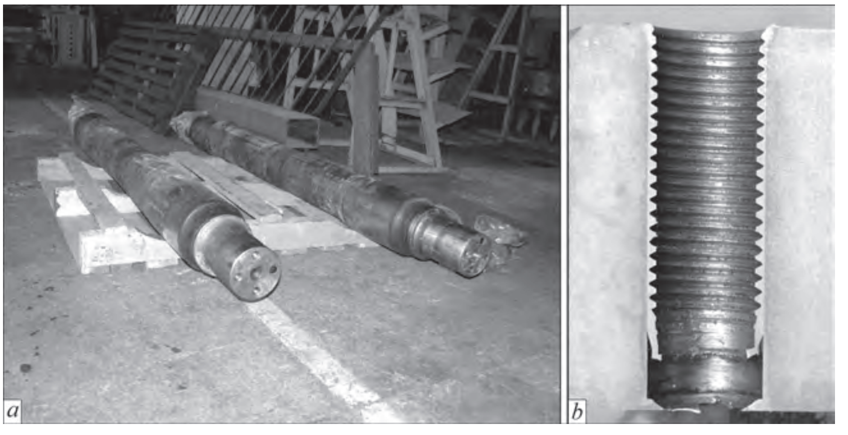

Figure 11. Repair of threaded holes by means of explosive welding: *a* — general appearance of wheel pair axle with four threaded holes; *b* — macrosection of threaded hole restored by explosion

The essence of the technology consists in the fact that a steel coupling (tube) with a charge of explosive substance located on its outer surface is put on the ends of the joined rebars symmetrically relative to the butt. The pressure created by the charge explosion, crimps the coupling metal so that it tightly touches with the bar metal. The presence of transverse projections on the bar surface ensures the formation of a permanent mechanical joint (Figure 9).

The strength of a joint when adding tensile load will be determined by the strength of the coupling metal, the strength of transverse projections of the rebar, working for creasing, and the strength of the rebar itself. The method of calculating the coupling and charge parameters that provide an equal strength of the joint and rebar metal was developed.

The tests on tear and cyclic fatigue life of the bar joints of different sizes and strength class were conducted. The couplings were compressed with charges from a detonating cord that was wound on a coupling in several layers (Figure 10).

All specimens that were tested on tear fractured on the base metal.

The fatigue tests were performed in accordance with the requirements of DSTU [17] in the laboratory conditions of the PWI at the mode of the axial harmonic tension in the area of multicyclic fatigue life at a frequency of 5 Hz and a stress ratio of 0.4. The criterion for completion of the tests was a complete fracture of the specimen. The specimens were fractured inside the coupling at a distance of 10–35 mm from its edge.

Analysis of the obtained data shows that in terms of fatigue resistance, such joints are not inferior to other methods of joining rebars widely used in industry.

Wheel pairs of cars are subjected to increased wear of threaded holes for fixing bearing caps in the axles of wheel pairs [18]. The existing methods of their restoration with the use of arc welding are either unacceptable because of inadmissible thermal deformations (sealing of holes by fusion and application of new thread) or not reliable due to the dynamic nature of working loads (inserting of the tube into the hole, its welding with the base metal along the upper edge and cutting new thread). At the PWI, it was proposed to weld-on a repair tube to the base metal of the axle in the worn threaded holes by the method of explosive welding and cutting new thread (Figure 11).

As ES, a mixture of ammonite with nitrate was used. Lack of fusion on the edge, characteristic of EW, was absent at the upper part, and at the lower part, it did not affect the quality of the joint in general, since the length of a newly cut thread exceeded the length of the working turns of the bolt. Gas formation from the explosion did not affect the quality of welding and did not create defects in the hole.

The minimum value of the cyclic fatigue life of the axles with threaded holes, restored by the method of explosive welding, amounted to 122,000 load cycles, which is only by 4 % lower than the basic value for new axles.

Two wheel pairs with the holes restored by explosion were mounted on a car and passed working tests at the test site of Ukrzaliznytsia. After the run of 100,000 km without defect formation, the tests were stopped.

CONCLUSIONS

1. The strength and fatigue life of coaxial joints made by explosive welding is usually not lower than that of the same joints produced by other methods.

2. Manufacturing of complex products by combination of explosive and fusion welding allows avoiding the formation of undesired intermetallics and providing the necessary service properties of a product.

3. Explosive technologies can be effectively used to create coaxial joints of different purposes.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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