PROBLEMS OF STIRRING AND MELTING IN EXPLOSION WELDING (ALUMINIUM–TANTALUM)

B.A. GRINBERG[1], **O.A. ELKINA**[1], **A.M. PATSELOV**[1], **A.V. INOZEMTSEV**[1], **A.V. PLOTNIKOV**[1], **A.Yu. VOLKOVA**[1], **M.A. IVANOV**[2], **V.V. RYBIN**[3] and **Yu.B. BESSHAPOSHNIKOV**[4]
[1]Institute of Metal Physics, Ural Division of the RAS, Ekaterinburg, RF
[2]G.V. Kurdyumov Institute for Metal Physics, NASU, Kiev, Ukraine
[3]St. Petersburg State Polytechnic University, St. Petersburg, RF
[4]OJSC «Uralkhimmash», Ekaterinburg, RF

The results of investigation of structure of transition zone of aluminium–tantalum joints, having different plane or wavy shape of the interfaces, are presented. Independently of the shape of boundaries, two types of fragmentation were revealed: one of them is similar to fragmentation in explosion, another one — at intensive plastic deformation. The same types of fragmentation were earlier observed also in joints of copper–tantalum having no mutual solubility unlike the aluminium–tantalum. Melting was observed in transition zone of joints being investigated. Structure of melted areas depends greatly on the availability of mutual solubility in metals being welded.

Keywords: *explosion welding, fragmentation, transition zone, local melting, mutual solubility, intermetallic*

Among the whole variety of materials and welding conditions the basic problem is stirring in the transition zone near the interface [1, 2]. It is the structure of transition zone that defines the possibility of adhesion of both materials. Stirring occurs as a result of strong external effect supposing large plastic deformation (including pressure, shear components, torque moments of stresses, deformation non-uniformity, etc.), friction of surfaces, influence of cumulative jet and other factors. However it is still unclear how stirring can occur at such a great external effect in a short time of welding procedure.

The explosion welding was carried out by CRSI of Structural Materials «Prometey» (St. Petersburg), Volgograd State Technical University, Ural Plant of Chemical Machine Building (Ekaterinburg). Depending on welding conditions different joints were produced having wavy or plane shape of interfaces.

Originally the welded joints of metal–intermetallic with normal mutual solubility were investigated [3–7]. In the capacity of metal the commercially pure titanium was selected, and as the intermetallic — orthorhombic aluminide of titanium (further named aluminide for briefness). Depending on welding conditions the different joints were produced which were called for convenience in different ways: A_w, A_p, B_w, B_p, where the low index designates the shape of an interface (plane, wavy). For joints A the orthorhombic alloy was used, containing 16 at.% Nb, for joints B — 23.5 at.% Nb. The molten areas of any of mentioned joints represent genuine solutions where stirring occurs at the atomic level.

To reveal the importance of mutual solubility of initial materials, the metals (copper–tantalum, iron–silver) were selected for explosion welding which have practically no mutual solubility both in solid and in liquid states, moreover they form non-mixed suspensions in liquid state. It was found that in joints C_p, C_w of copper–tantalum [8, 9] and D_p of iron–silver [10] the areas of local melting are filled with such colloid solutions.

Having used the obtained results the possible reasons for good quality of a copper–tantalum joint were revealed, due to which the explosion welding was successfully carried out on the large areas of plates [11] from which the chemical reactor was designed. The body of reactor was made of the carbon steel–copper–tantalum composite. The inner shell is composed of tantalum and on its corrosion resistance the whole structure is based. The colloid solutions have a risk of emulsion lamination [12]. However at the areas of local melting of joint C_w the lamination was not observed [9]. But the suspension, composed of tantalum particles in the copper matrix, on the contrary contributes to dispersion strengthening of the joint.

In the present work, which is the continuation of works [8, 9], the welded joints E_p and E_w of aluminium–tantalum with normal mutual solubility are investigated. The welding parameters (angle of collision γ, speed of contact point v_c) for these joints are given in Figure 1. With decrease of welding parameters of aluminium–tantalum ($\gamma = 7.5°$, $v_c = 1900$ m/s) the welding did not occur at all. The Figure shows also the welding parameters for the joints C_p, C_w of copper–tantalum. As is seen from Figure 1, the parameters for the joints E_p and C_p, having plane boundary surfaces, locate near the lower boundary of weldability. Comparing the joints E_w and C_w the welding parameters for the joint E_w are seen considerably higher. Basing on the comparison of results obtained for the mentioned joints, the authors tried to reveal the processes which are common both for the metals with mutual solubility as well as for the metals without it. Meantime the simultaneous use of both joints with different shape of an interface (plane, wavy) was successive for the same pair of metals.

The metallographic analysis was carried out using the optic microscope «Epiquant» equipped with the computational complex SIAMS. The microstructure was investigated using transmission electron microscopes JEM 200CX and CM-30 Super Twin and scanning electron microscope Quanta 200 3D. The X-ray shooting was performed in the diffractometer DRON-3M in monochromatic Co-K_α-radiation.

The images of interfaces, obtained using scanning electron microscopy (SEM), plane for the joint E_p (Figure 2, *a*) and wavy ones for E_w joint are given in Figure 2. For wavy interface the period is about 300 μm, the amplitude is 30 μm.

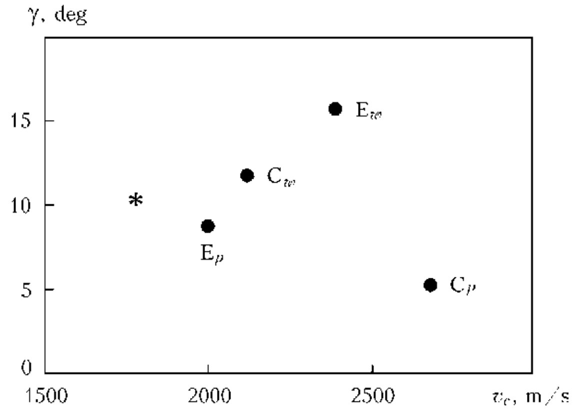

Figure 1. Welding parameters for joints being investigated (asterisk designates the mode accepted in the work [11])

Fragmentation during explosion. The phenomenon of fragmentation as a process of splitting of solid body into parts (fragments) occurring at the intensive outer influence was known long ago. It came even into the name of weapon: fragmentation warhead, fragmentation shell, fragmentation bomb. The description of fragments separation is connected with the name of N. Mott [13]. He together with other authors (see for example [14]) showed that using methods of simple geometric fragmentation the dynamic fragmentation of cylindrical shell can be described.

We suppose that fragmentation during explosion investigated by Mott occurs also during explosion welding. In the titanium–aluminide joints A_w the separation of micron particles of aluminide has a striking resemblance to separation of fragments occurring during explosion but of other sizes [15]. Here it should be noted that during explosion the separation of fragments occurs in the open space, whereas in explosion welding the fragments are separated at closed space limited by the material of plates.

For fragmentation observed in explosion welding we used previously the notion «fragmentation of crushing type» (FCT). Though in both

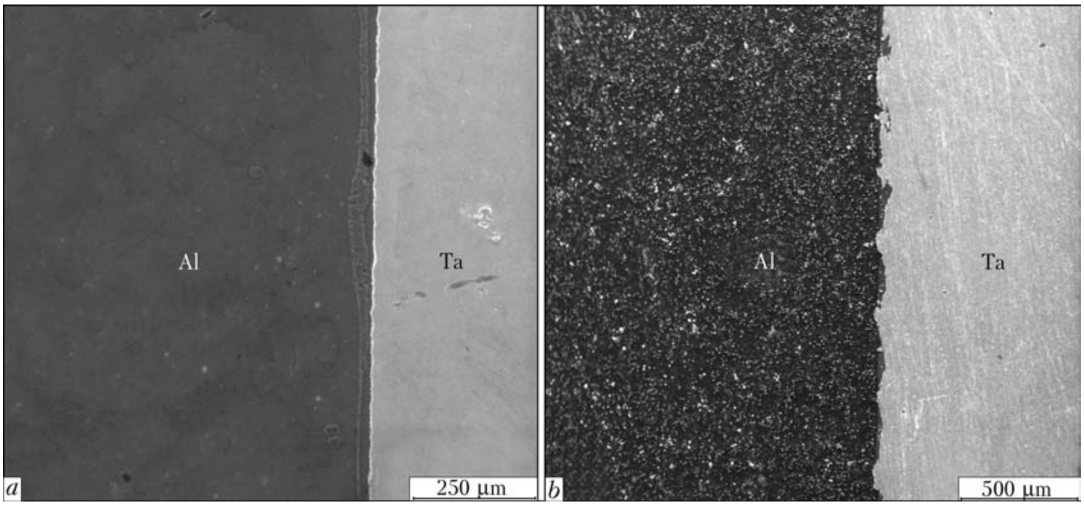

Figure 2. Interface (cross section) for the aluminium–tantalum joints: *a* — joint E_p; *b* — joint E_w

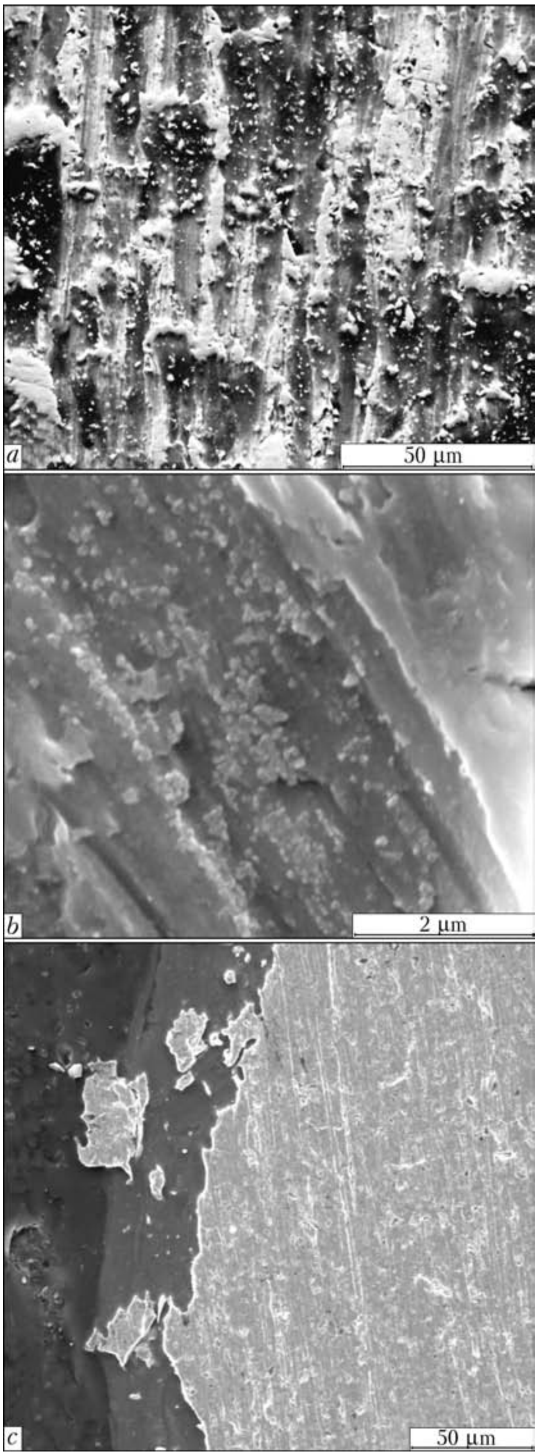

Figure 3. Microstructures of longitudinal section of transition zone (a, b) and cross section (c): a — joint E_p; b — joint E_p, aluminium is etched; c — joint E_w

cases the formation and separation of particles are observed, these types of fragmentation are not similar. FCT represents the process of splitting into particles which either separated or abutted each other. Similar to explosion fragmentation, FCT represents quick-running process which has time to occur during explosion.

Figure 3, *a* shows many particles of tantalum of arbitrary shape on the background of aluminium. We suppose that separation of tantalum particles observed in explosion welding as well as separation of aluminide particles mentioned above is similar to separation of fragments in explosion. In Figure 3, *b* after aluminium complete etching, the particles of tantalum were seen at the surface of tantalum, poured during aluminium removal. In Figure 3, *c* the coarse particles of tantalum are seen, reaching sizes of 20–40 μm which are much larger than those observed in the joint E_p. The possible reason for such difference is that joint E_w was obtained at more intensive outer influence than the joint E_p (see Figure 1).

The observation of particles separation in explosion welding proves the concept about fragmentation similar to fragmentation in explosion. FCT is observed both in the metal–metal joints, as well as in metal–intermetallic ones both at the normal solubility and also at the absence of mutual solubility of the metals being welded independently of the shape of interface. This is the evidence of dominating role of explosion in investigating welding method.

FCT provides a powerful channel for dissipation of induced energy, as the surface of separating particles has a large total area. FCT arises as a result of microfractures and is a process alternative to fracture. Instead of free surfaces, formation of which could result in fracture, the formation of surfaces due to microfractures is occurred, which either relate to separating particles or are «healed» at their consolidation. As a result, the FCT increases the «vitality» of material preventing its fracture even at such intensive outer influence as explosion welding.

Fragmentation at intensive deformation. In explosion welding the fragmentation of one more type is observed when the formation of new particles does not take place at all. It implies fragmentation [16], the existence of which is proved by many observations of material structure during strong deformation. Such, to the known extent, traditional fragmentation [15] includes pumping of dislocations (twins), formation of nodular, cellular and banded structures, and recrystallization.

In the present work for the joint E_p of aluminium–tantalum the TEM-images of strongly deformed structure of aluminium but not mixed with tantalum were given: regions with high dislocation density (Figure, 4, *a*) and recrystallized regions (Figure 4, *b*, *c*). Thus, in Figure 4, *b* the formation of triple butt is seen. The images of strongly deformed structure of tantalum are simi-

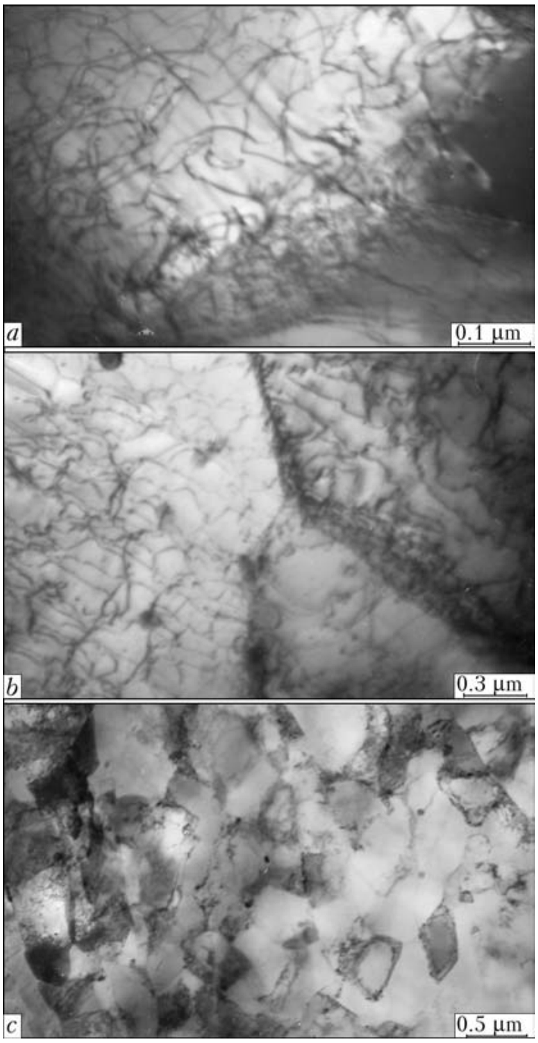

Figure 4. TEM-image of structure of strongly deformed aluminium: *a* — cold working; *b*, *c* — recrystallized areas

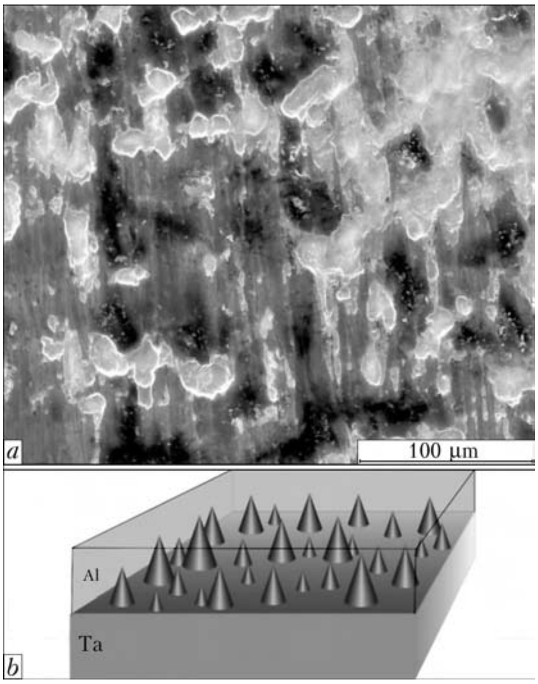

Figure 5. Transition zone for joint E$_p$: *a* — microstructure from the area of tantalum, aluminium and zone of local melting (longitudinal section); *b* — schematic image of projections (cones) at plane interface

lar to those observed for the copper–tantalum joint C$_p$ [15]. If to compare the images of deformed structure of aluminium and copper [15] it is seen that recrystallization of aluminium occurs more completely as compared to recrystallization of copper. It is connected with the fact, that, firstly, aluminium is fusible and, secondly, it has higher energy of packing defect.

Though the temperature in the contact zone in explosion welding can be extremely high, however at quick-running explosion effect the proceeding of thermally-active processes, defining the movement and restructuring of dislocations, is complicated and is hardly possible. It can be assumed that these processes the same as diffusion become possible only at residual temperatures and stresses. These are the processes that define the traditional fragmentation. As compared to the traditional fragmentation, the FCT occurs only in narrow area near the interface where outer influence is the most intensive. However the traditional fragmentation is observed somewhat further from the boundary surface. Respectively, the FCT is, by all means, the more rapid process than traditional fragmentation. The characteristic periods can be evaluated approximately as microsecond for FCT and 10^8–10^9 μs (time of structural relaxation) for traditional fragmentation.

Heterogeneities of interface surface: projections, zones of local melting. In Figure 5, *a* the image is composed of spots of three colors: white, black and grey. Respectively, the transition zone is composed of areas of three types which is the result of formation of projections at the interface surface. At the first time, the projections were revealed in the titanium–aluminide joints [5]. The data on chemical composition of mentioned areas forming the transition zone were obtained using SEM from repeated measurements. It was shown that area of tantalum corresponds to white color, aluminum area — to black, mixture of initial metals — to grey one.

The projections are formed most probably as a result of diffusion-free (due to quick run of welding) outburst of one metal into another (Figure 5, *b*). Actually, they certainly do not have perfect conic shape: the peaks are rounded and surfaces are not so smooth. Only by formation of projections it is possible to explain the pattern of transition zone for joint E$_p$ in Figure 5, *a*. As a result, the surface represents chaotic relief with a large number of projections of one material into another one, similarly to that observed in work [8].

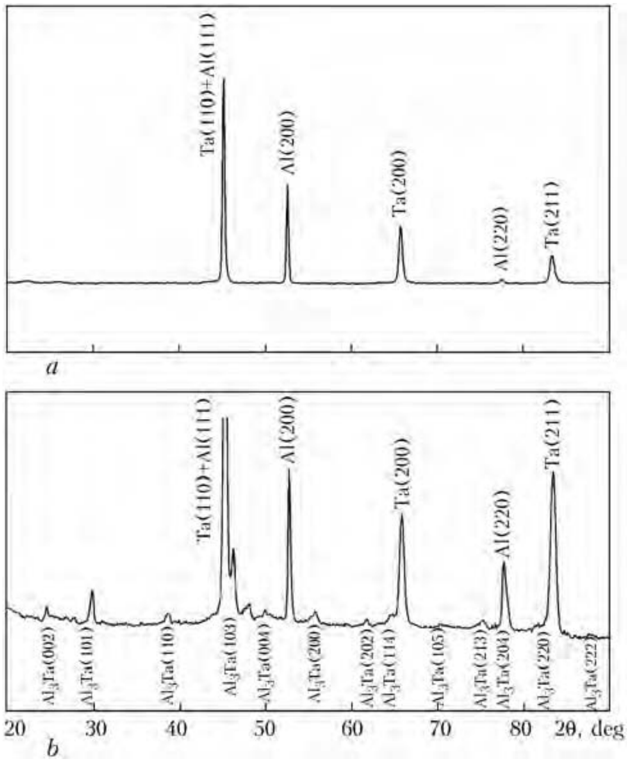

Figure 6. Diffractogram of transition zone (longitudinal surface of section): *a* — joint E_p; *b* — joint E_w

In the both joints E_p and C_p the drawing up of projections along some marked direction is clearly seen. It can be assumed that there is a connection between self-organization of projections and wave-formation, however it requires special investigations.

If the interface was smooth, then the problems with adhesion could arise and either reconstruction of metallic links or transportation of spot defects would be required. However presence of projections solves this problem: here the projections play role of «wedges», linking the contacting materials with each other. The friction on the surface of projection, strengthened due to the fact that the projection itself is not smooth, contributes to adhesion of surfaces.

There is a point of view [17] that strength of bimetal produced by explosion welding can be increased due to preliminary profiling of surfaces of a fixed plate, which can be performed, for example, due to longitudinal cavities and projections oriented approximately parallel to the direction of detonation spreading. A.Z. Bogunov et al. [17] consider that at the presence of projections it can be spoken about explosion riveting, which in case of profiling accompanies the explosion welding.

We suppose that the similar situation occurs in explosion welding due to projections forming in natural way, though their sizes are less than in preliminary profiling. In our investigated cases the sizes of projections are changed from micrometer to hundreds of micrometers, whereas after profiling the sizes of projections varied in the limits from several millimeters to dozens of millimeters [17].

Moreover, it can be assumed that existence of lower limit of weldability is connected indeed with impossibility to form projections on the plane interface. Below the indicated limit the projections either are not formed at all or appear to be rather small. There is obviously some critical height of projections when they provide adhesion of surfaces. With increase in external effect the projections are growing and lining up. Further, the wavy formation begins.

The X-ray diffractogram of transition zone (Figure 6, *a*) contains lines of tantalum and aluminium, and does not contain lines of other phases. The results of spot measurements of chemical composition of grey zone obtained using SEM showed that concentration of tantalum does not exceed 5 at.% here, therefore grey zone represents a zone of local melting of aluminium alloyed with tantalum. However it requires melting of narrow edge of tantalum.

It is grey zone, being the zone of mixing, that is sensitive to the fact whether materials being welded have mutual solubility or not. At normal solubility they form natural solutions. At the absence of mutual solubility the colloid solutions arise as in case of copper–tantalum [8].

Melting along the interface. Near the wavy interface, in contrast to plane one, the interface is corrugated, therefore, its longitudinal section represents a set of alternating bands of both materials with almost parallel boundaries. The longitudinal section of transition zone near the aluminium–tantalum joints E_w, given in Figure 7, *a*, represents really a slightly inclined section due to small amplitude of wavy surface. At the longitudinal section of transition zone at the same joint after the aluminium was etched (Figure 7, *b*) the bands of tantalum are seen and also particles which poured after aluminium dissolution.

For comparison, Figure 8, *a* shows the longitudinal section of transition zone for the copper–tantalum joint C_w. The system of bands in Figures 7, *a* and 8, *a* is not regular. If we restore the interface according to given images, then in both cases it will be not perfect. In Figure 8, *a* the numerous zones of local melting are clearly seen having the vortex structure. As is seen from Figure 8, *b*, for the both joints C_p and C_w of copper–tantalum the zone of local melting is

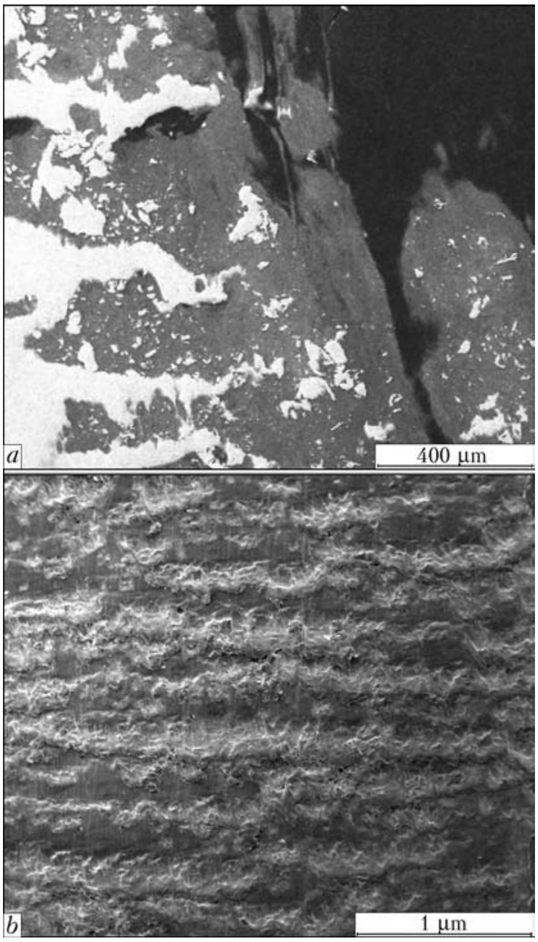

Figure 7. Microstructures of transition zone for joint E_w (longitudinal section): *a* — bands of aluminium and tantalum; *b* — aluminium is completely etched

filled with colloid solution, independently of the interface shape.

In Figure 8, *a* many projections of different sizes from several micrometers to 100–150 µm are seen. Some of them begin in one band, intersect another one and form adhesion between the bands. The role of projections, promoting the formation of joints was mentioned above during analysis of the joint E_p.

As is seen from Figures 7 and 9, in the joint E_w, in contrast to C_w, the zone of local melting, i.e. isolated melted areas, are not observed. Instead of them, in Figure 9 while moving from the solid phase of aluminium the layers of molten aluminium are seen, first not containing and then containing particles of other phase (with small and then large density of particles). The sizes of particles are changed within wide range: from 50 to 500 nm. Quite sharp cut of particles is particularly noticeable. Further the edge of tantalum is followed, observed in Figure 9, *a*, *b* as illuminating line. Such illuminating boundary («braid»), which represents a molten film, was observed by the authors before in the titanium–aluminide joints A_p [5].

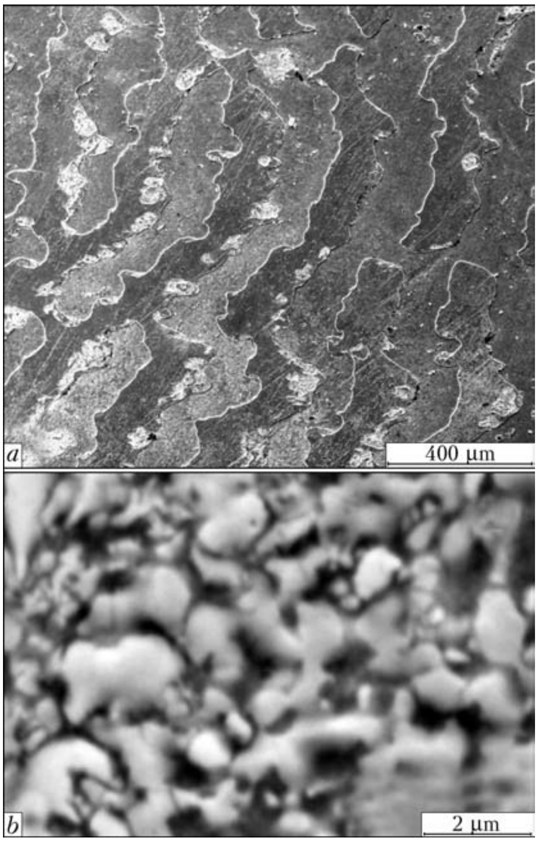

Figure 8. Microstructures of longitudinal section of the interface for joint C_w: *a* — bands of copper and tantalum; numerous zones of local melting are seen; *b* — zone of local melting

The diffractogram taken from the longitudinal surface of the section (see Figure 6, *b*) shows clearly how X-ray peaks are recorded not only from tantalum and aluminium, but also from intermetallic phase Al_3Ta. Compound Al_3Ta has tetragonal crystal lattice, spatial group 14/mm, structural type — Al_3Ti. Namely the particles Al_3Ta are seen in Figure 9, *b*. It is obvious that melting of tantalum is required for running of intermetallic reaction. In fact in Figure 9, *c* the spherolites are seen which are the evidence of tantalum melting. The above-mentioned molten film for the titanium–aluminide joint A_p has a similar structure, where the spherolites were also observed (see Figure 5, *e* in work [5]).

In Figure 9, *d* the structure of layer is given containing intermetallic inclusions after annealing at 500 °C for 1 h. It is seen that the structure is heterogeneous but in general the coarsening of particles occurred as compared to those observed in Figure 9, *b*.

In the joint E_w the film includes edge of tantalum of 2.0–2.5 µm width and above-mentioned molten layer of about 40 µm width (30 µm with particles, 10 µm — without). The observed structure of transition zone is formed in the following

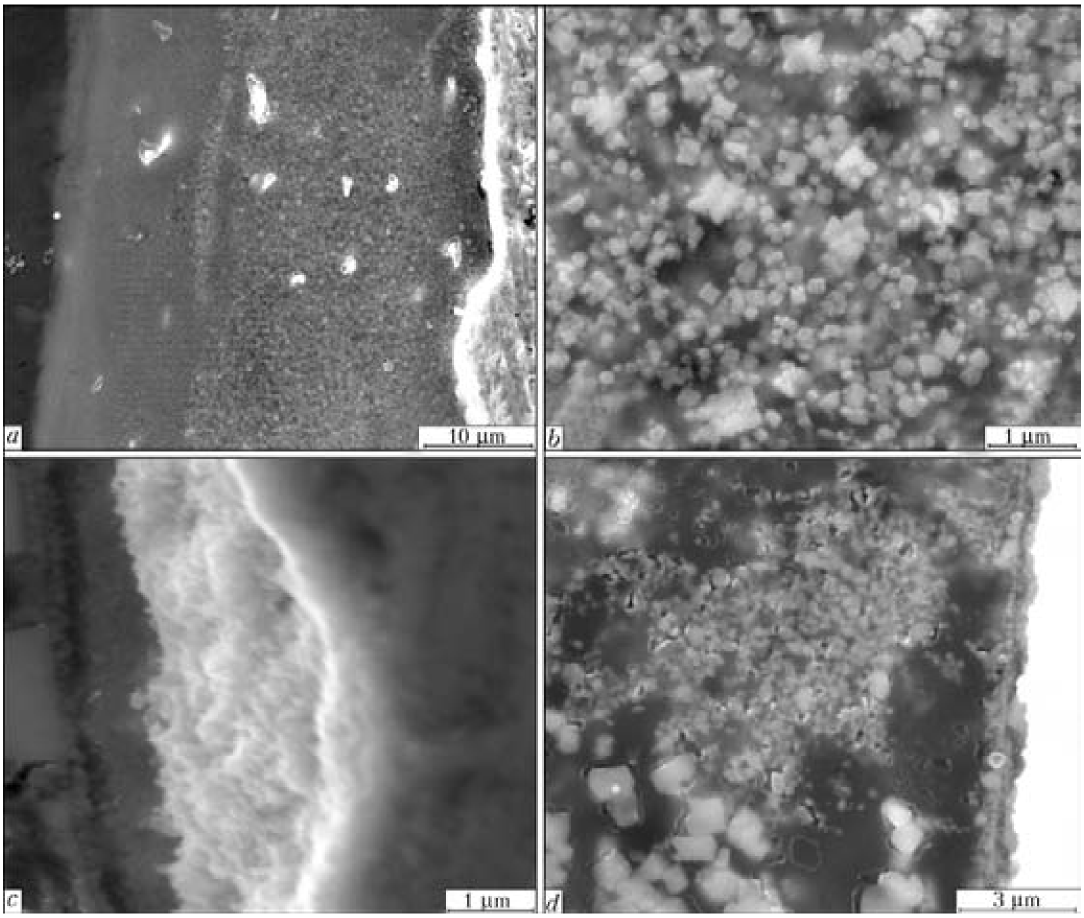

Figure 9. Microstructures of the transition zone cross section for joint E_w: *a* — layers of melted aluminium without and with particles; *b* — particles of intermetallic Al_3Ta in the melt of aluminium; *c* — spherolites; *d* — after annealing

way: at first, the melting of aluminium as more fusible one is occurred, then followed the partial melting of tantalum surface, formation of solid solution based on aluminium, and formation of intermetallic phase at achieving the certain concentrations. The mentioned particles are retained during dissolution of aluminium and observed together with tantalum particles (see Figure 7, *b*).

However, before melting begins in accordance with the scenario offered above, the most quick-running process takes place: separation of solid particles of tantalum which are seen in Figures 3, *c*; 7, *a*; 9, *a*.

The fact is that the molten zone in the joint E_w represents a film at the interface, while in the joint E_p the isolated zones are coordinated with intensification of welding condition used to produce joint E_w as compared to the joint E_p (see Figure 1). Here the observation of intermetallic inclusions in the joints E_w and their absence in the joint E_p is also related to this.

Melting and adhesion. Strong explosion effect during producing of the joint E_w evidence of approaching to the upper limit of weldability. In this case the melting becomes dangerous for integrity of the joint. However, as authors suppose, in favorable case (at not very high values of parameters of explosion effect) the melting, on the contrary, facilitates the formation of joint due to adhesion of surfaces. In this relation, microphotography is very convincing (see Figure 9, *a*), demonstrating transition from aluminium to tantalum, occurring due to melted aluminium, aluminium with particles, and melted tantalum. It is obvious that such a transition facilitates the adhesion of aluminium and tantalum comparing with abrupt solid-phase transition.

For other materials, namely polymers, the best adhesive substance is solution or melt of the given polymer [18]. It gives a certain prove to the possibility of adhesion also the investigated materials due to their melting in explosion welding, as far as during melting the problems of wetting, adhesion and protection from contact corrosion are instantly solved. Let us pay attention to the following fact. Aluminium is one among few metals, the adhesion of which is impossible without preliminary chemical treatment of surface [19]. Only mechanical treatment turned to be not sufficient. However aluminium plate was not subjected to chemical treatment before welding. Nevertheless welded joint with tantalum was produced. Here, most obviously, the remarkable feature of explosion welding was manifested, i.e. self-cleaning of surfaces to be welded due to cumulative effect [1, 20].

It is known that a film of adhesive substance should not exceed the specified value for thickness [18]. As applied to welded joints it can mean the restriction for thickness of melted area. During intensification of welding condition and approach to the upper limit of weldability the critical thickness of melted area will be reached, at which the adhesion becomes impossible.

Thus, explosion welding comprises to a definite extent also another method of joining materials, namely their adhesion by formation of melted areas.

The electron-microscopic investigations were carried out in the Center of collective use of electron microscopy of Ural Division of the RAS.

The work was carried out at financial support of RFFI grant No. 10-02-00354, project of Presidium of the RAS No. 12-P-2-1053, projects of the RAS UrD Nos. 12-U-2-1011 and 12-2-006-UT and State Purposeful Program of Ukraine «Nanotechnologies and nanomaterials» No. 1.1.1.3-4/10-D.

1. Deribas, A.A. (1980) *Physics of strengthening and explosion welding*. Novosibirsk: Nauka.
2. Lysak, V.I., Kuzmin, S.V. (2012) Lower boundary in metal explosive welding. Evolution of ideas. *J. Mat. Proc. Technol.*, **212**, 150–156.
3. Rybin, V.V., Semenov, V.A., Sidorov, I.I. et al. (2009) Bimetallic joint of orthorhombic titanium aluminide with titanium alloy (diffusion bonding, explosion welding). *Voprosy Materialovedeniya*, 59(**3**), 17–31.
4. Rybin, V.V., Grinberg, B.A., Antonova, O.V. et al. (2009) Formation of vortexes in explosion welding (titanium–orthorhombic titanium aluminide). *Fizika Met. i Metallovedenie*, 108(**4**), 371–384.
5. Rybin, V.V., Grinberg, B.A., Ivanov, M.A. et al. (2010) Structure of zone of titanium joint with orthorhombic titanium aluminide in explosion welding. *Deformatsiya i Razrush. Materialov*, **11**, 27–33.
6. Grinberg, B.A., Ivanov, M.A., Rybin, V.V. et al. (2010) Structure of zone of titanium joint with orthorhombic titanium aluminide in expolsion welding. II. Localized vortex melted zones. *Ibid.*, **12**, 26–34.
7. Rybin, V.V., Greenberg, B.A., Ivanov, M.A. et al. (2011) Nanostructure of vortex during explosion welding. *J. Nanosci. and Nanotechnol.*, 11(**10**), 8885–8895.
8. Grinberg, B.A., Elkina, O.A., Antonova, O.V. et al. (2011) Peculiarities of formation of structure in the transition zone of the Cu–Ta joint made by explosion welding. *The Paton Welding J.*, **7**, 20–25.
9. Grinberg, B.A., Ivanov, M.A., Rybin, V.V. et al. (2012) Nonuniformities of interface in explosion welding. *Fizika Met. i Metallovedenie*, 113(**2**), 187–200.
10. Grinberg, B.A., Ivanov, M.A., Rybin, V.V. et al. (2012) Explosion welding: Stir processes of metals without mutual solubility (iron–silver). *Ibid.*, 113(**11**) (in publ.).
11. Frey, D., Banker, J. (2003) Recent successes in tantalum clad pressure vessel manufacture: A new generation of tantalum clad vessels. In: *Proc. of Corrosion Solutions Conf.* (2003, USA), 163–169.
12. Gelfman, M.I., Kovalevich, O.V., Yustratov, V.P. et al. (2004) *Colloid chemistry*. St.-Petersburg: Lan.
13. Mott, N.F. (1947) Fragmentation of shell cases. *Proc. Royal Soc. A*, 189, Jan., 300–308.
14. Grady, D. (2006) *Fragmentation of rings and shells*. The legacy of N.F. Mott. Berlin, Heidelberg: Springer.
15. Grinberg, B.A., Ivanov, M.A., Rybin, V.V. et al. (2012) Fragmentation processes in explosion welding. *Deformatsiya i Razrush. Materialov*, **8**, 2–13.
16. Rybin, V.V. (1986) *High plastic deformations and fracture of metals*. Moscow: Metallurgiya.
17. Bogunov, A.Z., Kuzovnikov, A.A. (2009) Production of aluminum–steel bimetal with profiled interface. *The Paton Welding J.*, **11**, 65–68.
18. Frejdin, A.S., Turusov, R.A. (1990) *Properties and design of adhesive bonds*. Moscow: Khimiya.
19. Kapelyushnik, I.I., Mikhalev, I.I., Ejdelman, B.D. (1972) *Technology of gluing of parts in aircraft construction*. Moscow: Mashinostroenie.
20. Zakharenko, I.D. (1990) *Explosion welding of metals*. Minsk: Navuka i Tekhnika.