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Examination of reasons for the formation of defects of the type of burns and air holes in explosion welding

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When using explosion welding for cladding metallic elements (plates, components, sections, etc.) with thin metal sheets, defects of the type of burns or air holes with the edges bent upwards and with traces of melting[1] sometimes appear in the components. These defects have a negative effect on the quality of joints and, consequently, result in complete rejection of the joints. Individual investigators have assumed that the formation of these defects is possible if the cladding element is not straight, i.e. in the presence in the element of the so-called local 'concavities' or 'depressions'.[2] This assumption can be confirmed or rejected by examining the process of collision in explosion welding taking place in the zones of rapid variation of the initial (setting) gap h, i.e. in the zones of the given local concavities or compressions of the flyer (cladding) plate. In order to simplify analytical analysis, the zones can be regarded as identical with the conical surfaces with the diameter of the base of the conical surface on the cladding sheets d_k and the height of the cone h_k.

Investigations will be carried out into the collision of a flyer (cladding) plate, with local concavities, with a stationary plate in the zone of the concavities, modelled by a conical surface, where the setting gap in the middle section changes from h to $h+h_k$ and from $h+h_k$ to h (Fig. 1). It will be assumed that the detonation front behind the boundary of the concavity is flat, tangential and propagates through the charge of the explosive substance (ES) along the axis X from left to right with velocity D. It will be assumed that the parameters characterising ES (density ρ_{ES}, the height of the charge H, detonation speed D, etc.) did not change in the concave zone and that the detonation front in exit to the conical surface, and also during the passage of the surface through the tip of the cone and in exit outside the limits of the cone, is always rotated (in the XOY plane) through a certain angle and tries to occupy the perpendicular position in relation to the section of the flyer plate situated below the detonation front.

The shape of the sections of the flyer plate beyond the detonation front is described by the equation[3]

$$Y = X\left[1+\frac{\theta-1}{\eta\theta}\right]-H, \qquad [1]$$

and the speed by the equation[3]

$$v = D\left(1+\frac{\theta-1}{\eta\theta}-\frac{H\theta}{Dt}\right), \qquad [2]$$

where

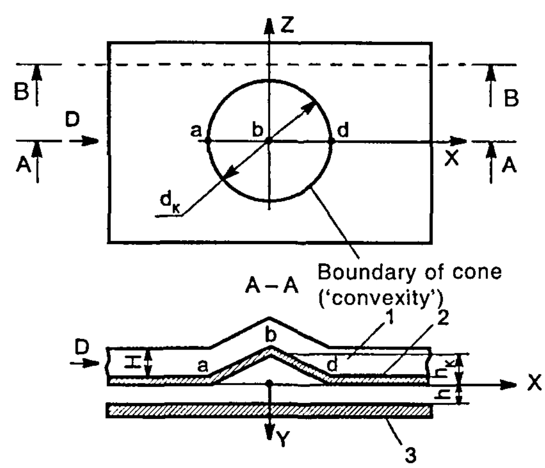
$$\theta=\left[1+2\eta\left(1-\frac{H}{Dt}\right)\right]^{-1/2},$$

$$\eta=\frac{16}{27}\frac{\rho_{ES}H}{\rho\delta},$$

δ is the thickness of the flyer plate; ρ is the density of the material of the flyer plate.

The method of determination of the position of the points, forming the contact line, in relation to the detonation front, coinciding with the ZOY plane, for any moment of time $t > H/D$, is described in Ref. 3.

Special attention should be given to the behaviour of the flyer (cladding) plate in the vicinity of bends resulting from forming (see Fig. 1, points a, b) because the detonation front, leaving these areas, is instantaneously rotated (in the XOY plane) through a certain angle, and



1 *Principal diagram of assembling for explosion welding (a, b, d – the points of technological bends of the flyer plate): 1) ES charge; 2,3) The flyer and stationary plate.*

tries to maintain the previous position in relation to the section of the flyer plate which is situated below it at the examined moment of time (Fig. 2). Consequently, the section of the flyer plate beyond the detonation front is characterised by the formation of a second dynamic bend (Fig. 2, points f), if the first dynamic bend is represented by the bend formed immediately behind the detonation front (see Fig. 2, point O'). The position of the point of the second dynamic bend f of the section of the flyer plate behind the detonation front can be determined by solving jointly the equation [1] and $Y' = f(X')$.[3] For this purpose, it is sufficient to have the equation linking Y with Y' and X with X'. The derivation of these equations is not associated with any large problems, if the angle r at the point of the technological bend of the flyer plate and the position of this point in the coordinate system $X'O'Y'$, associated with the detonation front, 'sliding' on the flyer plate, are known. For the case of movement of the point of the technological bend of the flyer plate on the detonation front a the equations can be derived on the basis of the analysis of the only possible case (for the given case and the logically justified geometrical pattern, Fig. 2):

$$Y = h - (A - X')\sin\alpha - Y'\cos\alpha, \quad [3]$$

$$X = X'\cos\alpha - (Y' + H)\sin\alpha, \quad [4]$$

where A is the distance from the detonation front of the hypothetical point of intersection of continuation of the inclined section $O'a$ and the concave region with the stationary plate; α is the angle of the technological bend at point a.

Analysis of Fig. 2 and equations [3] and [4] shows that the shape of the flyer plate behind the detonation front has the form of a broken curve, consisting of the branch $O'f$, described by the equation $Y' = f(X')$, and fK, described by equation [1]. With an increase of the distance of the detonation front from point a (i.e. with an increase of distance A), the points K (the actual point of contact), K' (the apparent point of contact) and f continuously move towards each other and at some moment of time t_i merged into a single point. The latter is the point of intersection of the curves $Y' = f(X')$, describing the shape of the flyer plate in the section with an increase in concavity, and the straight line $Y' = (A-X')\tan\alpha$, describing the position of the stationary plate in the $X'O'Y'$ coordinate system.[3] This results in a sudden increase of the angle of collision by the value α and in a decrease of the speed of the contact point by

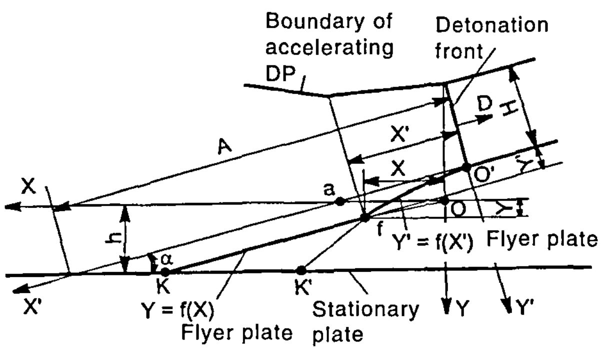
$$\Delta v'_k = \frac{\Delta'_{i+1} - \Delta'_i}{\Delta t}, \quad [5]$$

Where Δ'_i, Δ'_{i+1} is the delay of the contact point, situated in the zone of increase of the concavity, in relation to the point of contact situated behind the boundary of the concave region, at the moment of time t_i and $t_i + t_{i+1}$, respectively; Δt is the increase of time (time step).

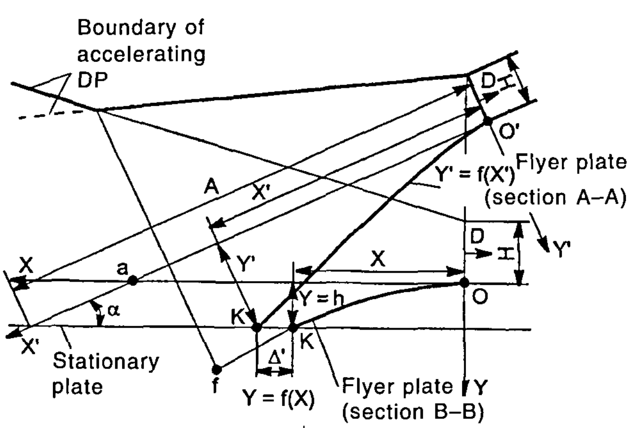
The values of Δ' for any moment of time can be calculated from the equation, derived on the basis of comparison of the pattern of movement of the detonation surface (DS) and the flyer plate in the sections A–A and B–B (see Fig. 1 and 3):

$$\Delta' = (X' - Y'\tan\alpha)\cos\alpha - (X + H\sin\alpha). \quad [6]$$

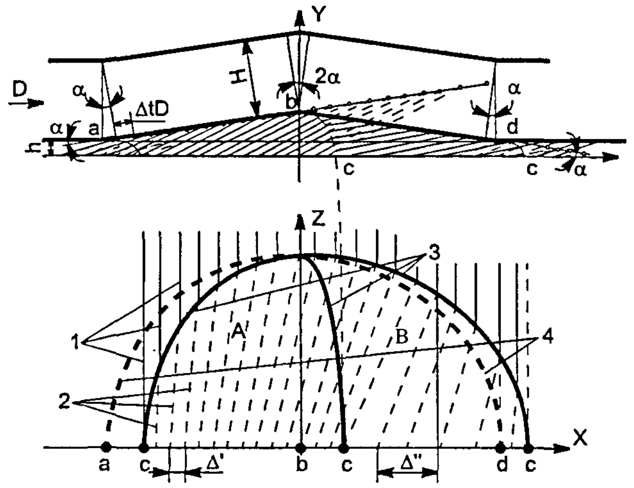
After passage of the detonation front through the second point of the technological bend b (through the tip of the concave area-cone), the so-called second dynamic bend forms again behind the detonation front in the section of the flyer plate but the sign of the second dynamic bend is reversed and its value is higher because the angle of the technological bend in these areas in the coordinate system $X'O'Y'$ is -2α. The upper branch of the broken curve $O''f$ is described by the formula $Y'' = f(X')$ (Fig. 4), and the lower branch fK by the formula $Y' = f(X')$; the point K' is the true contact point, and point K'' is the apparent contact point.[3] With movement of the



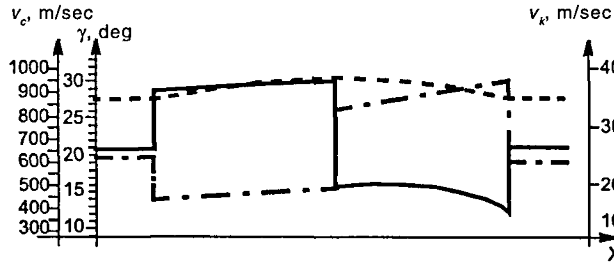
2 *Diagram of movement of the detonation surface (DS) of the flyer plate in the vicinity of the point of the technological bend a (O, O' are the points of the first bend of the section of the flyer plate behind the detonation front; K, K' are the points of contact of the section of the flyer plate with the stationary plate; A is the distance from the detonation front to the hypothetical point of intersection of continuation of the inclined section of the concave region with the stationary plate).*



3 *Combined diagrams of movement of the detonation surface and the flyer plate in the section A–A, B–B, corresponding to the moment of time t_i (Δ' is the delay of the contact point in the section A–A in relation to the contact point in the section B–B).*



4 Diagram of the collision process in the concave zone (A, B in the region of increase and decrease of γ and v_k, respectively): 1,2) The lines of contact outside the limits and within the cone, respectively; 3) The boundaries of sudden variation of Δ and v_k (boundaries of the 'shadows'; 4) The boundary of the technological bend of the flyer plate (the base of the cone).



5 The nature of variation of the parameters of explosion welding in the concave zone (solid line y = f (x), broken line v_c = f (x), the dot-and-dash line v_k = f (x)).

detonation front away from the tip of the concave region (from point b) the points K'', K' and f continuously come closer to each other and at a moment of time merge into a single point representing the point of interaction of the curve $Y'' = f(X'')$, describing the shape of the flyer plate in the section with a decrease in concavity, and the straight line $Y'' = f(A + X'')\tan\alpha$, describing the position of the stationary plate. At this moment the collision parameters also change abruptly: the angle of collision decreases by 2α, and the speed of the contact point v_k (in comparison with the speed of the point of contact in the sections where h = const) increases by

$$\Delta v_k'' = \frac{\Delta_{i+1}'' - \Delta_i''}{\Delta t}, \qquad [7]$$

The delay of the contact point in the zone with a decrease in concavity is

$$\Delta'' = (X'' + Y''\tan\alpha)\cos\alpha - (X - H\sin\alpha). \qquad [8]$$

When the detonation front has gone past the point d (see Fig. 1), the angle of collision increases, and the speed of the contact point decreases to the values realised outside the limits of the concave zone (where h = const, and Δ = 0).

Thus, it is possible to predict the development of specific processes in the concave zone. It will be assumed that aluminium sheet with a thickness of 0.8 mm, containing a concave region (d = 50 mm and h = 3.5 mm) should be welded to a 10 mm thick sheet of AMg6 aluminium alloy. The explosive substance will be represented by ammonit No.6ZhV, and H = 10 mm, h = 2 mm. The results of the solution to this problem in the form of graphs and schema are presented in Fig. 4 and 5. In zone A (where γ increases from 21 to 29°, and v_k decreases from 2500 to 1700 m/sec) the process of formation of waves is unavoidable, especially in the middle section A–A, in which the wavelength may increase 2–3 times and reach approximately 2 mm.[3] In this case, the existence of any cumulative jet is unlikely because of the dominance of the wave formation process in relation to the jet formation process. In zone B, the sudden decrease of γ from 30 to 14° and the increase of v_k from 1700 to 3300 m/sec result in the suppression of the wave formation process, and in the creation of suitable conditions for the formation of the cumulative jet,[3] whose effect may be regarded as controlling.

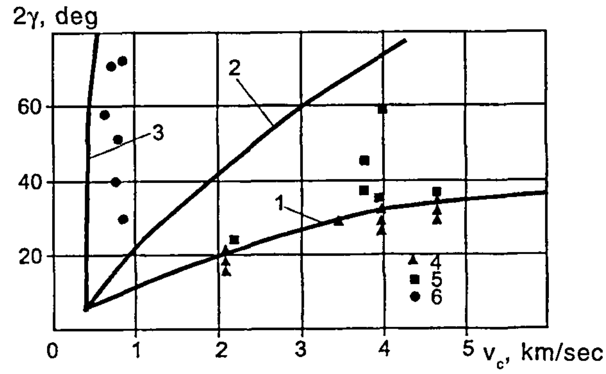
According to the hydrodynamic theory, describing the cumulation effect, the cumulative jet forms in any collision geometry, but experiments indicate the reverse situation (Fig. 6). For example, in Ref. 4, the authors observed the interaction of jet formation at collision angles smaller than specific values (Fig. 6, curve 1) and they formulated a jet formation criterion in oblique collision of the plates: if the speed of the jet v in the jet problem, corresponding to the given type of collision, is subsonic, the reversed (cumulative) jet always forms at $\gamma > \gamma_1^*$ and there is no jet at $\gamma < \gamma_1^*$. For real metals with the known shock adiabates, this critical angle of jet formation γ_1^* can be determined solving the equation of dynamic compatibility at the front of the oblique jump of density.

In Ref. 6, the experimental results show the deceleration of the cumulative jet and even complete 'closure' (absence) in a wide range of the variation of the collision angle, but at relatively low speed v_c. This boundary (Fig. 6, curve 3), will be described by the expression[7]

$$\gamma_3^* = \arccos\sqrt{\frac{2\sigma}{\rho v_c^2}}, \qquad [9]$$

where σ is the dynamic limit of yielding of the material; ρ is the density of the material; v_c is the collision speed which should be accepted to be equal to or slightly higher than $v_c^*\sqrt{2\sigma/\rho}/\cos\gamma$.

Thus, the presence of the critical conditions $\gamma_1^*(v_c)$, $\gamma_3^*(v_c)$ make it possible to estimate the region (in the parameters γ, v_c) of the existence of the cumulative jet



6 Critical curves of the plane of possible parameters of collision of the aluminium sheets: 1,3) The boundaries of the jet formation region; 2) The interface of the region of realisation of continuous and dispersed cumulative jet; 4) Jet forms;[4] 5) No jet;[4] 6) Jet forms.[5]

but not its qualitative state (the jet can be only continuous or have the form of a cloud of dispersed particles). In Ref. 8, the authors determine the condition of formation of a continuous cumulative jet. In the planar case and on the condition that v_c is directed along the normal to the colliding particles, the critical angle γ_2^* is determined by the expression[7]

$$\gamma_2^* = \arctan\left(\frac{v_c}{C_0}\right), \qquad [10]$$

where C_0 is the speed of sound in the material of the welded plates.

Thus, on the plane (v_c, 2γ) it is possible to draw another critical curve 2 (see Fig. 6) which divides the already determined region of collision of the jet into two regions: solid jets form above the curve, dispersed jets appear below the curve.

Taking these data into account, it may be concluded that in zone B, where v_c changes from 950 to 800 m/sec, γ from 16 to 13°, and v_k from 1700 to 3800 m/sec, a continuous flat cumulative jet forms in front of the contact point. The speed of the top part of the jet (in the laboratory coordinate system)

$$v_j = \frac{v}{\cos\gamma} + v = \frac{v_c}{\sin\gamma} + \frac{v_c}{\tan\gamma}, \qquad [11]$$

where v is the speed of discharge of the jet in the coordinates system connected with the point of deceleration of the jets; v_c is the speed of collision (throwing) of the plate (incident flows) in the laboratory coordinates system.

The first term in equation [11] – the speed of the contact point v_k – is the speed of movement of the coordinate system in which the flow pattern is stationary. The second term is the speed of the jet in the coordinate system, connected with the contact point. The selection of the direction of the actual throwing speed v_c along the normal to the surface of the fly element (incident flow) is not very important because for any direction of the vector of the speed v_c the values of these two speeds changed correspondingly, but the speed of the cumulative jet in the laboratory system of the coordinate is always determined by the sum of the speeds.

Taking these considerations into account, it is possible to determine the extent by which the top part of the cumulative jet outstrips the contact point (the length of the cumulative jet) at a certain period of time Δt after the formation of the jet, assuming that v_j = const and v_k = const. Using the equation

$$l_j = \Delta t \frac{v_c}{\tan\gamma}. \qquad [12]$$

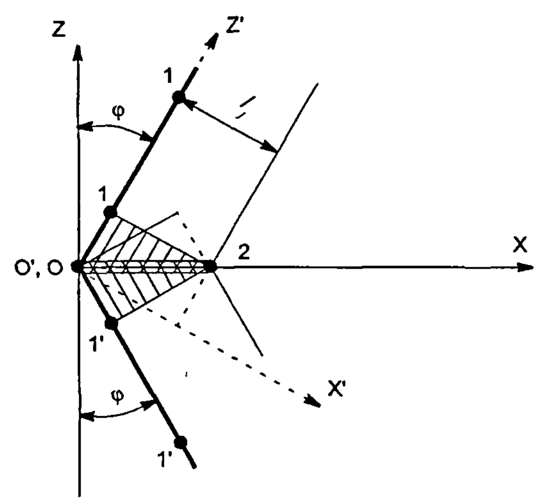
If it is assumed that $t = 10^{-6}$ sec, v_c = 950 m/sec, and γ = 16°, the length of the jet l_j is 3.3 mm. In this case, the thickness of the jet is[9]

$$\delta_j = \delta_1 \sin^2\left(\frac{\gamma}{2}\right), \qquad [13]$$

where δ_1 is the thickness of the flyer plate (incident flow).

Substituting into equation [13] δ_1 = 0.8 mm, γ = 16°, gives δ_j = 0.016 mm. With time, the value of l_j increases and the thickness of the jet does not change (in fact, the thickness of the jet decreases because there is a gradient of mass velocity along its length). This behaviour is typical of the flat cumulative jet in sections of the contact line in which there are no deflection points. It is evident this the jet of this type is not capable of causing any large damage to the flyer plate or even piercing it.

A completely different situation is observed in the section of the contact line containing a bend. The schema shown in Fig. 7 will now be examined. The meeting line (convergence line) of flat cumulative jets coincides with the X axis. This means that they transform to a conven-



7 The contact line and the front of cumulative jet in the vicinity of the inflection point 0: 1–1, 1'–1' – sections of the contact line with no bends; 1) 0–1' is the section of the contact line with the inflection of the point O; 0–2 is the line of contact (conversions) of the flat cumulative jets.

tional 'cylindrical' jet (in fact, the shape of this jet is close to a cone whose tip coincides with point 2 in Fig. 7). The volume of metal of the flat jets, transformed into the 'cylindrical' jet during time t, elapsed from the moment of their formation, can be described as $\delta_j l_j^2 \tan\varphi$. Knowing this volume and the length of the 'cylindrical' jet $l_j/\cos\varphi$, the diameter of the jet is calculated using the equation

$$d_{cj} = \sqrt{\frac{4\delta_j l_j \sin\varphi}{\pi}}. \qquad [14]$$

The velocity of this jet is

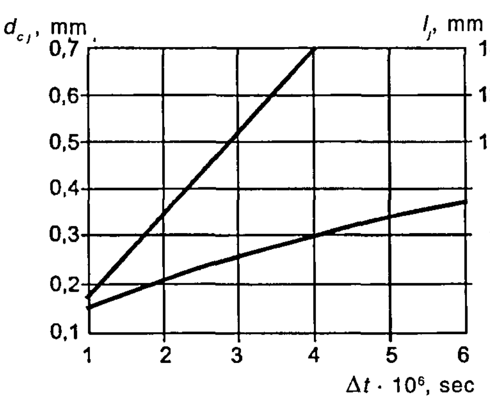
$$v_{cj} = v_j \cos\varphi, \qquad [15]$$

where v_j is the velocity of the flat cumulative jet in the laboratory coordinate system.

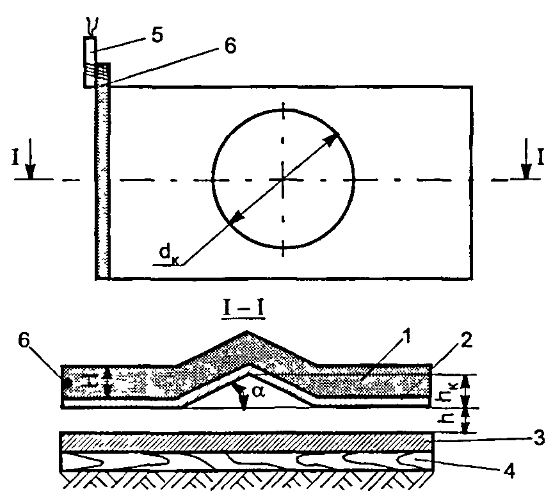
If the calculated values of δ_j and l_j are substituted into equation [14], we obtain $d_j \approx 0.15$ mm (which is an order of magnitude higher than δ_j). Analysis of the equations [12]–[14] shows that with an increase of time Δt from the moment of formation of the flat jets, the length and diameter of the 'cylindrical' jet will increase (Fig. 8), and already after 4×10^{-6} sec (at this moment, the detonation wave has already passed through the point d in Fig. 1) reaches the values of 14 and 0.3 mm, respectively. The jet with the dimensions, characterised by high velocity ($v_{cj} \approx 3100$ m/sec) and the density approximately equal to the density of the material of the flyer plate is capable, by spreading the internal surface of the flyer (aluminium) sheet with a thickness of 0.8 mm (this is possible because the gap in which it forms is 4–6 times smaller than the length of the sheet), of inducing extensive damage in the sheet and even piercing through it.

When the contact line has passed by the point of inflection on the section with a decrease in concavity (point d in Fig. 1) and the value of v_k changes abruptly from 3800 m/sec to the level of the speed of the point of contact in the sections of parallel distribution of the welded sheets (2500 m/sec), the 'cylindrical' cumulative jet starts to expand (under the effect of the initial forces) and, finally, separating from the contact line (points O, O' in Fig. 7) will move by inertia along the difficult-to-predict trajectory, until its kinetic energy is completely transformed to dissipative losses, determined by the deformation processes taking place during collision of the jet with the flyer and stationary plates. Within the framework of the proposed model of the process of collision, the path, travelled by the 'cylindrical' cumulative jet, separated from the contact point, after complete stoppage is difficult to calculate. Nevertheless, it is justified to assume that this path can be 2–3 times greater than the length. Thus, it may be assumed that the quality of the welded joint in zone B is greatly affected by the processes associated with the cumulative effect.

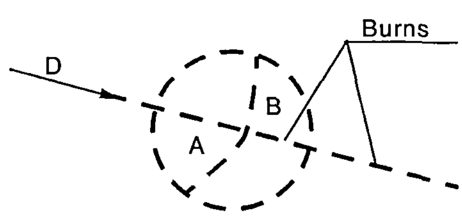
To verify these considerations, experiments were carried out with the explosion loading of 10 mm sheets of AMg6 aluminium alloy with thin (0.8 mm) aluminium sheets which contained specially produced local contained areas in the form of cones with the diameter d_k = 50 mm, and height h_k = 3.5 mm (Fig. 9). The explosive substance was ammonite No.6ZhV, H = 10 mm, h = 2 mm. The charge was primed using an electric detonator through a section of a detonating cord ensuring the formation of a flat tangential detonation front. As expected, the controlling process in the collision of the welded plates in region A was the wave formation process, and in region B it was the jet formation process, resulting in the burn-through of the cladding element (Fig. 10).



8 The dependence of the variation of the diameter d_{cj} and length l_j of the 'cylindrical' jet on time from the moment of formation of a flat cumulative jet.



9 The diagram of assembling for explosion welding: 1) The charge of explosive substance; 2,3) The flyer and stationary plate; 4) The substrate made of DSP material; 5) Electric detonator; 6) The section of the detonating cord.



10 External appearance of the section of the bimetallic sheet Al + Al-alloy on the sign of the cladding layer in the zone of the local concavity with a diameter 15 mm (the arrow indicates the direction of movement of the flat tangential detonation front).

Conclusions

1 The main reason for the formation of burn-through defects in the explosion welding is the presence of the local contained areas of the cladding element, with the height of these areas h_k being larger than the setting up gap h, and the diameter $d_k \leq (10–15)\ h_k$.

2 The nature of the processes, taking place in the zones with the changing gap, is not affected by the size of the gap but by the gradient of the gap (the rate of variation), which determines the size and sign of the technological bend in the flyer element, resulting in a sudden change of speed of the contact point and the collision angle with a small variation of the collision speed.

3 The sudden variation of the speed of the contact point and the collision angle behind the technological bend (depending on the sign of the bend) results in the process of either high-speed wave formation or distinctive jet formation (accumulation), accompanied in some cases by the formation of a continuous axisymmetric (conventional 'cylindrical') cumulative jet.

4 The continuous axisymmetric cumulative 'cylindrical' jet forms during convergence (merger) with the flat cumulative jets in those areas of the contact line which contained points of inflection (or breaks) characterised by the angles smaller than π. The formation of such a cumulative jet may result in extensive local damage of the cladding (flyer) sheet and even in its continuous burn-through.

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