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Critical conditions of the formation and failure of welded joints in explosive welding

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Explosive welding, like any other process of joining of metals, should guarantee the formation of full-strength welded joints. The main advantage of this method in comparison with other currently available welding methods is that it makes it possible to weld efficiently almost any combination of metals and alloys of different thickness and dimensions. One of the special features of explosive welding is the problem of retaining the already produced welded joint which may be weakened or completely fractured as a result of the effect of tensile stresses formed in the weld zone due to the arrival of unloading waves. The problem of the effect of these waves on the strength of explosive-welded joints has been studied in a number of investigations[1–4] where the results were presented of the qualitative evaluation of the shockwave effect on the zone of bonding of metals. Nevertheless, the parameters ensuring the formation of full-strength welded joints have not as yet been determined. This is especially important in the explosive welding of metals with greatly differing physical-mechanical properties, and also in joining thick-plate materials. Therefore, the problem of determination of the critical conditions of formation and possible failure of the joints in explosive welding is very important.

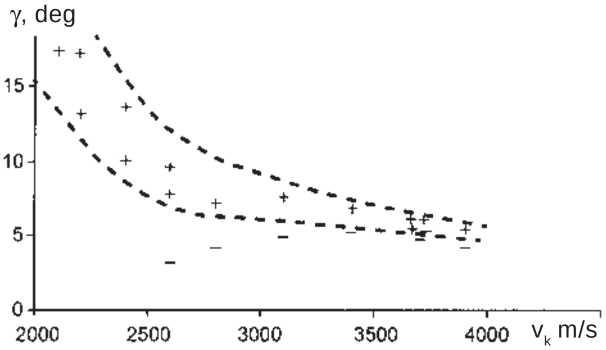
The aim of this article was the determination of the optimum method of explosive loading and the parameters of resulting in the formation of full-strength welded joints.

Investigations were carried out on aluminium and steel which greatly differ not only in the physical–mechanical properties but also in the parameter R which is very important in explosive welding, i.e. the acoustic stiffness, equal to ρc (ρ is the density of the material, c is the speed of propagation of sound in the metal). In addition to this, the joining of aluminium to steel belongs to the group of difficult welding processes characterised by a narrow weldability range[5,6] even in the production of bimetals of small and medium thickness. In transition to thick bimetals, where it is necessary to use the flyer plate thicker than 10 μm, the problem of producing high-quality welded joints is even more urgent.[3,7,8] At the same time, industry (electrometallurgy, power engineering, etc) urgently requires thick-plate steel–aluminium composite materials.[9,10]

The experiments were carried out using the most rational methods of explosive welding with the parallel distribution of plates. The thickness of the flyer aluminium plate was varied in the range 1–20 mm, the thickness of the stationary steel plate was 22 mm. The welding conditions were selected in such a manner as to ensure, for every combination of welded thickness, the maximum possible strength of the welded joint.

The experimental results are presented in Fig. 1 and in Table 1. Analysis of the experimental results obtained for the explosive welding of aluminium with steel St3 shows the following special feature. The range of weldability of aluminium to steel, presented in the traditional kinematic coordinates 'collision angle γ – the speed of the contact point v_k' (Fig. 1) is characterised by the narrow range of the formation of high-quality welded joints. It has also been established that the increase in the thickness of the flyer aluminium layer results in a large decrease of the strength of the welded joint: from 95 MPa to 0 for the identical kinematic conditions of the collision (Table 1). At a thickness of $\delta_1 = 20$ mm, it was not possible to produce joints between the layers. This can be explained on the basis of energy considerations[11,12] and, in addition to this, the literature contains a relatively large number of experimental data indicating that no consideration was made in the investigations of the effect of the shockwaves on the produced welded joint, as confirmed by the present experimental results.

The results of metallographic examination of the contact boundary of the separated specimens show that



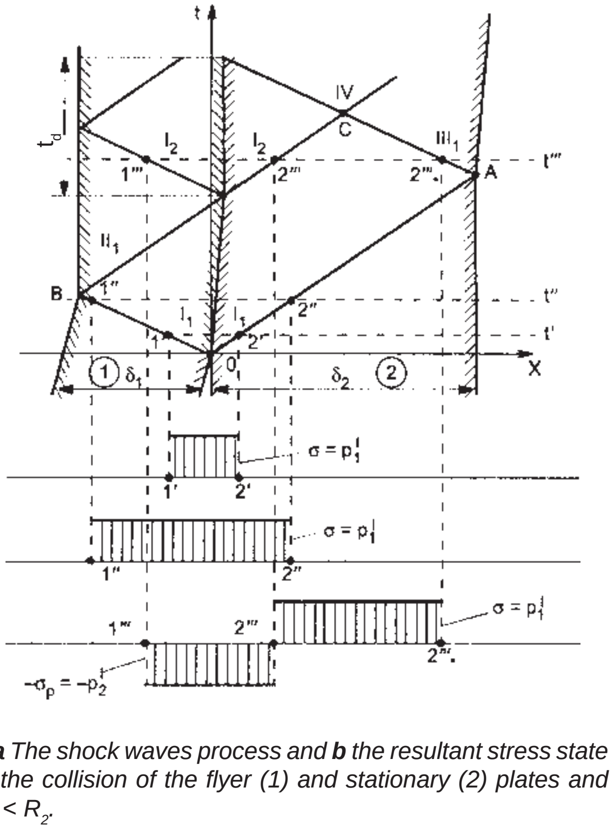
1 *Region of explosive welding the Al+St3 pair.*

Table 1

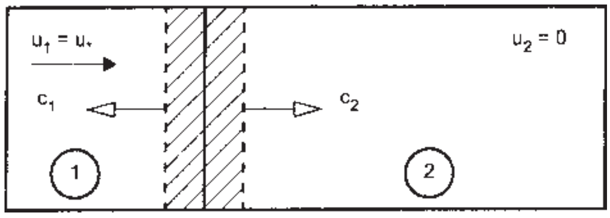
Number of experiment	Flyer plate thickness δ_1, mm	Stationary plate thickness δ_2, mm	Collision angle γ, deg	Collision speed v_c, m/s	Time of arrival of unloading waves τ_p, μs	Solidification time τ_s, μs	Kinetic energy of separation W_{sep}, MJ/m^2	Joint strength σ_p, MPa
1	5	22	5.4	350	1.06	0.51	0.195	95
2	10				2.16	1.91	0.39	70
3	15				3.24	3.22	0.585	20
4	20				4.32	4.44	0.780	0
5	20	1 + 22–			4.32	1.05	0.780	114

the experiments 3 and 4 are characterised by extensive plastic deformation with the development of wave formation on the contact surfaces. This also resulted in the failure of the produced welded joint.

In order to explain the results, it is necessary to examine in detail the shockwave mechanism and the stress state, formed in the high-speed collision of the plates for different methods of explosive loading.



3 ***a*** *The shock waves process and* ***b*** *the resultant stress state in the collision of the flyer (1) and stationary (2) plates and* $R_1 < R_2$.



2 *Diagram of collision of the flyer plate (1) with the stationary plate (2) at* $R_1 < R_2$.

Attention will be given to the main loading mechanism used in explosive welding in which an aluminium sheet is ‘thrown’ onto a thick stationary steel plate, i.e. $R_1 < R_2$. Prior to collision, the sheets have the following parameters (Fig. 2):

- the flyer sheet – δ_1, ρ_1, c_1, $p_1 = 0$, $R_1 = \rho_1 c_1$, $u_1 = u_*$,
- the stationary sheet – δ_2, ρ_2, c_2, $p_2 = 0$, $R_2 = \rho_2 c_2$, $u_2 = 0$,

where δ_i is thickness; ρ_i is density; c_i is the speed of sound in the metal; p_i is pressure; R_i is acoustic rigidity; u_i is mass velocity; $u_* \approx v_c$ (v_c is the collision speed).

After collision of the sheets, shock waves will propagate with the speed of sound from the contact boundary through the layers of both metals (Fig. 3 **a**). The law of movement of the shockwave in the stationary plate (straight line *OA*) is described by the equation $x = Dt$, and in the flyer sheet (straight line *OB*) $= (u_* - D)t$ (D is the speed of the shockwave; t is time).[13]

In order to determine the parameters of the shock waves, propagating through the flyer and stationary plate, it is sufficient to find the point of intersection I_1 of their shock adiabates (Fig. 4 **a**).

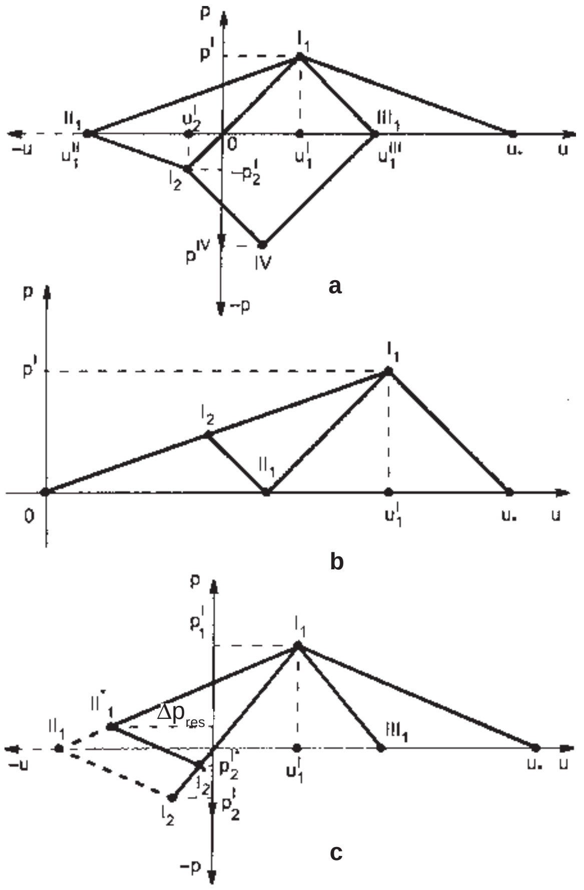
In this case, the pressure and mass velocity may be determined from the following equations:[1]

$$p_1^1 = \frac{R_1 R_2}{R_1 + R_2} u_*; \qquad [1]$$

$$u_1^1 = \frac{R_1}{R_1 + R_2} u_*; \qquad [2]$$

According to Ref. 1, the values of pressure, determined using equation [1], are characterised by good convergence with the values calculated from the shock adiabates[4] for the collision speeds similar to the conditions of explosive welding (the difference does not exceed 7.5 %).

When the shockwave, propagating through the flyer plate, reaches the free surface, the unloading wave will propagate in the direction to the boundary of the joint (Fig. 3 **a**). The state at this moment for the flyer plate corresponds to the *p*,*u*-diagram at point II_1 (Fig. 4 **a**) with



4 *p,u-diagram of collision of the flyer plate with the stationary plate at* ***a*** *$R_1<R_2$,* ***b*** *$R_1>R_2$, and* ***c*** *$\Delta p_{res} \neq 0$ and $\Delta p_{res} = 0$.*

the following coordinates:

$$u_1^{II} = \frac{R_1 - R_2}{R_1 + R_2} u_*; \qquad [3]$$

$$p_1^{II} = 0. \qquad [4]$$

It should be mentioned that at $R_1 < R_2$ the value of the speed u_1^{II} will be negative, i.e. the speed is directed away from the weld boundary.

When the shockwave reaches the free surface of the stationary plate, the unloading wave will propagate in the opposite direction, also to the weld boundary (Fig. 3 **a**). The condition at this moment for the stationary plate corresponds to the *p,u*-diagram at the point III_1 (Fig. 4 **a**) with the coordinates:

$$u_2^{II} = \frac{2R_1}{R_1 + R_2} u_*; \qquad [5]$$

$$p_2^{II} = 0. \qquad [6]$$

Comparison of equations [2] and [5] shows that when the shockwave reaches the free surface of the stationary plate, the speed of movement of the wave (of the surface) is doubled. This is in agreement with the data published in Ref. 13 and 14 in which investigations were carried out into the processes of movement of the shock waves to the free surface of the target and, consequently, this is also applicable for the case of explosive welding.

The unloading wave, moving on the flyer plate from its free surface, reaching the weld boundary, is transformed into a tensile wave which, correspondingly, results in the formation of tensile stresses at this boundary (Fig. 3). This condition corresponds to the *p,u*-diagram at the point I_2 (Fig. 4 **a**) and is described by the following equations:

$$u_2^{II} = \frac{R_1 (R_1 - R_2)}{(R_1 + R_2)^2} u_*; \qquad [7]$$

$$p_2^{I} = -\sigma_{\mathrm{p}} = \frac{R_1 R_2 (R_1 - R_2)}{(R_1 + R_2)^2} u_*. \qquad [8]$$

It should be mentioned that as the difference between R_1 and R_2 increases, the level of the tensile stresses σ_{p} also increases and, consequently, the probability of weakening of the welded joint and even of its complete failure becomes greater, if the values of these stresses exceed the dynamic ultimate strength of the metal of the pair with the lowest strength $\sigma_{\mathrm{d.p.}}$. If this is not the case, i.e. the first tensile wave does not weaken the welded joint, the risk of failure or weakening of the joint will no longer exist. This is caused by the fact that after a certain period of time, the stationary plate is characterised by the formation of a second tensile wave due to the contact (at point *C* in Fig. 3 **a**) of the first tensile wave with the unloading wave travelling from the back surface of the stationary plate. The formation of the second tensile wave leads to the appearance of even higher tensile stresses (Fig. 4 **a**). These tensile stresses can be calculated from the following equation:

$$p^{IV} = -\sigma_p^{IV} = -\frac{2R_1 R_2^2}{(R_1 + R_2)^2} u_*. \qquad [9]$$

Thus, at $R_1 < R_2$ after high-speed collision of the welded plates they are characterised (including the weld boundary) by the appearance of tensile stresses which may not only weaken but even fracture the already produced welded joints.

To prevent the formation of tensile stresses, it is recommended to use the so-called reversed method of explosive welding, i.e. steel should be ‘thrown’ on aluminium, fulfilling the condition $R_1 > R_2$. As indicated by the *p,u*-diagram in Fig. 4 **b**, in this case it is possible to prevent completely the formation of tensile stresses.

However, it should be mentioned that the ‘reversed’ method of explosive welding is not suitable for joining metals with greatly different properties, such as steel and aluminium. This is associated with the fact that the density of aluminium is almost three times higher than the density of steel and, consequently, in throwing the steel plate it is necessary to use a more powerful charge of the explosive substance which, in turn, increases the kinetic energy and this results in the formation of a large number of brittle molten zones at the boundary of the joint between aluminium and steel greatly decreasing the strength of the bimetal.

Therefore, in exposing welding certain combinations of metals, such as aluminium and steel, it is sufficient to use the conventional method of explosive welding, and to reduce the negative effect of tensile stresses on the external surface of the flyer plate it is recommended to generate the residual pressure Δp_{res} of the products of detonation of the charge of the explosive substance. Figure 4 **c** showing the *p,u*-diagram indicates that by increasing Δp_{res} it is possible to reduce greatly the level of tensile stresses.

Thus, selecting the dynamic and technological parameters of exposing welding, it is possible to generate a high residual pressure Δp_{res} and, consequently, greatly decrease the level of tensile stresses and, therefore, reduce the detrimental effect of this stress on the welded joint.[15]

The effect of the unloading waves must be taken into account in the determination of the upper boundary of the range of explosive welding by calculating the time, t_p, of arrival of these waves into the welding zone and the time of formation of the first tensile wave:[5]

$$t_p = 0.5 + 0.66\left(\rho\, v_k^2 / G\right)\frac{\delta_1}{v_k}, \qquad [10]$$

where ρ_1 is the density of the flyer plate; v_k is the speed of the contact point; G is the shear modulus of the metal; δ_1 is the thickness of the flyer plate.

In Ref. 3, 5, 7 and 16 it was reported that the strongest effect of unloading waves, up to complete failure of the welded joint, is observed when the formation of the welded joint at the moment of arrival of the waves into the weld zone is not yet complete, i.e. the molten areas have not yet solidified. In order to evaluate the solidification time of molten metal t_s it is recommended to use, for example, the relatively approximate equation:[16]

$$t_s = \frac{1.15 \cdot 10^{-3} \rho_1 v_k^4 \delta_1^2 \left(\dfrac{\delta_2}{\delta_1 + \delta_2}\right)^2 \sin^4 \dfrac{\gamma}{2}}{\pi c \lambda T_1^2}, \qquad [11]$$

where c, λ, T is the specific heat capacity, the heat conductivity coefficient and of the melting point of metal, respectively.

The calculations carried out using equations [10] and [11] for explosive welding of aluminium to steel show that an increase in the thickness of the flyer plate increases the solidification time t_s and the time of arrival of the shock waves t_p and appearance of tensile stresses σ_p in the weld zone, and the increase of t_p is linear and that of t_s quadratic (Fig. 5).

Analysis of the experimental results shows that in explosive welding metals with greatly differing properties, such as aluminium and steel, there is a critical thickness of the flyer element at which the resultant welded joint is in the completely fractured state or its strength will greatly decrease. For example, to produce high-quality joints between aluminium and steel, the optimum ratio should be $\frac{t_p}{t_s} \geq 1.2 \div 1.5$ and, in this case, the critical thickness of the flyer aluminium plate is $\delta_{cr} = 16$ mm.[8]

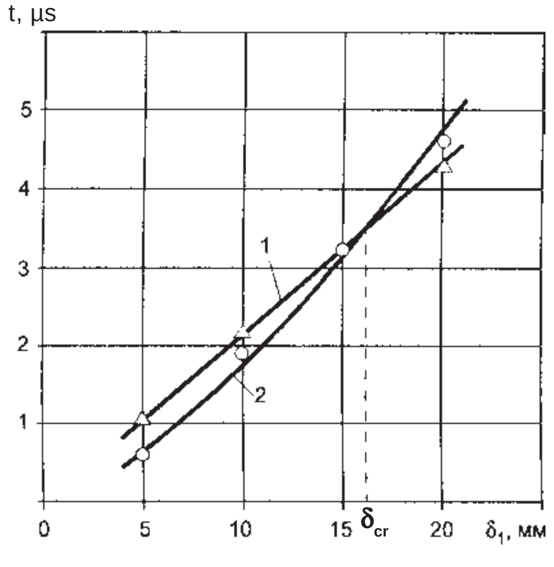
Thus, taking the above considerations into account, in explosive welding of aluminium to steel it is necessary to reduce the time t_s. This may be achieved by consecutive explosive welding using two methods: in the first stage a thin aluminium layer is welded and, in the second stage, the main the aluminium layer is welded (Patent No. 217-0289, Russian Federation). In this case, t_s decreases by almost a factor of 4 and, consequently, the strength of the joint rapidly increases to approximately 114 MPa (Table 1).

In addition to the time parameters t_s and t_p, the strength of the explosive-welded joint is greatly affected by the kinetic energy W_{sep} of the flyer plate. The flyer plate may separate from the main plate as a result of the unloading waves formed in the flyer plate and moving into the zone of the welded joint.

This kinetic energy of separation can be determined from the following equation:

$$W_{sep} = \frac{\rho_1 \delta_1 \left(u_1^{II}\right)^2}{2}, \qquad [12]$$

where u^{II}_1 is the mass velocity of the flyer plate behind the front of the unloading waves (Fig. 4 **a**).



5 *The critical thickness of the flyer plate in explosive welding aluminium to St3 steel: 1) the time of arrival of unloading waves, t_p; 2) the solidification time of molten metal, t_s.*

The calculations carried out using equation [12] make it possible to explain differences in the weldability of thick and thin plates on the basis of energy considerations. For example, when throwing a 5 mm aluminium sheet on steel, the kinetic energy of separation is $W_{sep} = 0.195$ MJ/m^2, and the strength of the joint is $\sigma_j = 95$ MPa; increase in the thickness of the aluminium flyer plate to 20 mm increases the value of W_{sep} to 0.780 MJ/m^2 and this results in fracture of the already produced welded joint (Table 1).

It is also important to mention that for the complete fracture of the welded joints the tensile stresses σ_p must act for a certain period of time t_d (Fig. 3 **a**) during which microfailures of local areas buildup. In this case, as the tensile stresses increase, the value of the t_d, required for the complete failure of the welded materials decreases.

On the basis of the analysis of the experimental data it has been established that in explosive welding it is important to take into account certain critical conditions resulting in the failure of the produced welded joint or in a decrease of its strength. The failure criterion may be represented in the form of a function depending on a number of parameters:

$$K_p = f\left\{\delta_1, W_{sep}, W_2, A_f, \sigma_p, \sigma_{d.p.}, \Delta p_{res}, t_p, t_s, t_d\right\}. \quad [13]$$

In order to define more accurately the function of the failure criterion, especially in explosive welding dissimilar metals, it is important to determine the relationship between the resultant tensile stresses σ_p and the duration of action of these stresses t_d and the dynamic ultimate strength $\sigma_{d.p.}$.

Conclusions

1. The method of explosive welding determines the nature of the stress state in the metals in explosive welding. For example, when using a flyer sheet with a lower acoustic rigidity and a stationary sheet with a higher acoustic rigidity, the weld boundary is characterised by the formation of tensile stresses having a negative effect on the strength of the weld.
2. The optimum stress state is formed in the method of explosive welding in which the flyer component is represented by steel and also in the conditions of explosive welding characterised by high residual pressures greatly decreasing the amplitude of the tensile wave.
3. In explosive welding, it is important to take into account the failure criterion. Using this criterion, in relation to the stress state produced in the metals, it is possible to determine the effect of a number of parameters on the strength of the welded joint.

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