metal quality meets the requirements of the international standards and specifications, in particular, AD Merkblatt W8, Iuli 1987, specification 1264 (Germany), NC-501 (France). Continuity of layer joining is 100 % by zero class. Shear strength of the joint determined in different plate zones is not lower than 150 MPa, pull strength is higher than 250 MPa (Table). Joint zone structure is wave-like without any brittle inclusions.

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PECULIARITIES OF INSTABILITY OF THE PROCESS OF EXPLOSION CLADDING OF LARGE-SIZE BILLETS

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The most probable causes of instability of properties of the joining zone in explosion clad large-size billets are revealed on the basis of analysis. Results of experimental studies of variations in temperature of the mating surfaces with increase in length of the plates, as well as peculiarities of violation of the geometry of positional relationship of long plates ahead of the detonation front are presented.

Keywords: *explosion cladding, large-size billets, detonation velocity, temperature of mating surfaces, flyer plate, vertical displacement, detonation front, collision velocity and angle*

Explosion welding of metals is a controllable process resulting in formation of a joint in the solid state. In this process, the distributed parameters (parameters of the kinematic and energy sub-groups) can be varied by varying in a certain way the technological (design) parameters, through affecting the deformation and temperature-time welding cycles that determine properties of the welded joints [1]. Theoretically (in accordance with one- and two-dimensional models of acceleration [2–4]), providing constant size of the gap, h, between the plates welded over the entire welding area, as well as constant height of the captive charge, H, should lead to constant values of collision velocity V_{col}, contact point velocity V_{c} and collision angle γ and, therefore, guarantee stability of the process and properties of the joining zone of an explosion welded composite. However, this is not the case in practice of explosion cladding of large-size billets [5–14].

The purpose of this study is to analyse causes and experimentally investigate peculiarities of instability of the process of explosion cladding of large-size billets.

Analysis of literature data allows distinguishing at least three most probable causes that lead to fluctuations of the wave profile and increase in the amount of the fused metal along the length of the resulting bimetal [5–12].

In principle, increase in wave parameters in the end part of the billets welded could be related to enhancement of parameters of a high-velocity collision of the plates, taking place because of increase in detonation velocity D of an explosive along the length of the charge. However, this hypothesis put forward as early as in 1974 in study [8] found no experimental verification.

In particular, study [15], where detonation velocity D of explosives 4 m long was measured by the Dotrisch method [2] every 200 mm, shows that absolute deviations from the mean value of D are not in excess of ±3 %, which, according to [2], corresponds to the accuracy of the measurement method used and, therefore, evidences a high stability of detonation properties of long explosive charges.

A number of researchers [5–7, 13, 16, 17 etc.] put forward a more convincing assumption that variations in properties of the joint along the length of the large-size billets welded is a result of preheating of the colliding surfaces under the impact by a high-temperature flow of particles of the shock-compressed gas of a cumulative origin, moving ahead of the contact point.

If, according to [5], we assume for simplification that the compression of air in the gap between the plates is caused by a flat piston moving along the detonation front at contact velocity V_{c}, the state of the shock-compressed air ahead of the contact point

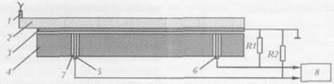

Figure 1. Scheme of experiments on investigation of variations in temperature of surfaces of the explosion welded metal plates in the initial and end sections of a pack: *1* — electric detonator; *2* — explosive charge; *3* — flyer copper plate; *4* — target plate; *5, 6* — constantan rods; *7* — insulator; *8* — digital memory oscillograph

can be written down in the form of the following equation system [18]:

$$\begin{cases} p_w = \dfrac{2\rho_0 V_w^2}{k+1}, \\ u_w = \dfrac{2V_w}{k+1}, \\ T_w = \dfrac{T_0 p_w (k-1)}{p_0 (k+1)}, \end{cases} \tag{1}$$

where V_w is the velocity of the shock wave front; p_w and T_w are the pressure and temperature of air behind the shock wave front, respectively; k is the polytropic exponent; ρ_0, T_0 and p_0 are the initial density, temperature and pressure of air; and $u_w = V_c$ is the mass velocity behind the shock wave front.

The calculations from (1) show that temperature of the shock-compressed air at V_c = 1800–4000 m/s amounts to 2300–6300 °C [16] under a pressure of 5–20 MPa, which agrees with the experimental data [17].

As the contact point moves along the billet welded, because the former lags behind the shock wave front, the time of the effect of a heated air on the mating surfaces grows obeying the following dependence [16]:

$$t = L\frac{V_w - V_c}{V_w V_c}, \tag{2}$$

where L is the distance from the sensor to the point of the beginning of welding.

According to study [16], at distance L = 1–2 m this time may exceed 100 μs, increasing with decrease in V_c.

Study [17] suggests using the following dependence to calculate heat flow q from the shock-compressed air inside the surface of the plates welded:

$$q = \mathrm{St}\cdot\rho u c_p (T^* - T_{\mathrm{col}}), \tag{3}$$

where $T^* = T\left(1 + \dfrac{k+1}{2}\mathrm{M}^2\right)$ is the deceleration temperature [17]; St and M are the Stanton and Mach numbers, respectively; T, c_p and ρ are the temperature, heat capacity and density of gas, respectively; u is the mass velocity; and χ is the adiabatic exponent.

As follows from estimation (in rough approximation for the model of an instantaneous flat heat source) of the process of heating the near-contact volumes of the plates welded during time t (2), made by the authors of [16], thickness of the metal heated to several hundreds of degrees at L = 1 mm is 10–20 μm, which, in their opinion, does influence the general thermal situation in the near-weld zone and, hence, formation of the joint.

According to the calculations made in study [7], power of the heat flow from gas to metal at V_c = = 4.0–4.5 km/s is approximately 10^3–10^4 MJ/(m^2·s), which, for a time of its effect equal to $t \sim 100$ μs from formula (2), gives an increment of energy input to the joining zone (in the form of heat) equal to about 0.1–1.0 MJ/m^2. Such energy inputs become commensurable with the values of energy consumed for plastic deformation of metal in the near-weld zone. However, they are localised in a narrower zone and can lead to fusion of metal of the near-contact metal layers up to 100 μm thick.

Many methods are available now for measurement of temperature in the bulk of metal under pulse loading [3]. The most promising of them is the method of dynamic thermocouples that form during the explosion welding process at collision of two dissimilar elements (e.g. copper and constantan). Key drawback of the method is the presence of baroEMF, which introduces a significant error to the experiment. At the same time, assuming that the value of baroEMF of a specific thermocouple for identical experimental assemblies is constant, investigation of changes in thermal situation in the joining zone with distance from the beginning of the pack welded can be reduced to qualitative comparison of temperatures in different sections on the basis of a value of the pulse signal (in the form of a voltage jump) fixed by an oscillograph (at the moment

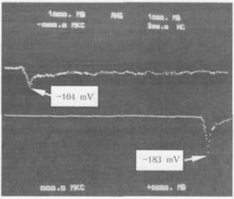

Figure 2. Oscillogram of the temperature mode fixed in one of the experiments: upper curve — sensor located in the initial section of the plates welded (100 mm from the beginning of welding); lower curve — sensor located in the end section of the plates welded (550 mm from the beginning of welding)

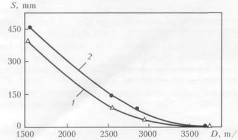

Figure 3. Dependence of distance S between the investigated section of the 2 mm flyer plate and detonation front upon the explosive charge detonation velocity under explosion welding conditions (*1*) and at the absence of the target element (*2*); distance from the beginning of welding to the investigated section is $x_i = 750$ mm, minimal value of vertical displacement of the investigated section is $\Delta = 4$ mm

of touching the thermocouple elements), characterising an almost instantaneous growth of temperature.

Variations in temperature of the mating surfaces with distance from the explosive charge initiation point were qualitatively assessed by conducting a series of experiments based on the method of local dynamic thermocouples [3, 19, 20]. The point of the experiments was as follows (Figure 1). Long copper plate *3* accelerated by explosive charge *2* was caused to collide in series with constantan rods *5* and *6* located in fixed (target) steel plate *4* at different distances from the beginning of welding. Insulator *7* was placed between the constantan rod and steel plate to eliminate their electric contact. The thermoEMF signal was registered by using digital oscillographs C9-8 and GDS-820C. Velocity of the contact point during the experiments was maintained within a range of 2100 to 2200 m/s.

As a result, a substantial difference in amplitudes of the electric signals was detected, this reflecting formation of the maximal instantaneous thermoEMF + baroEMF in the copper–constantan joint at a distance of 100 and 550 mm from the beginning of welding. A typical oscillogram fixed in one of the experiments is shown in Figure 2.

Therefore, the effect of preheating the mating surfaces of the plates to be explosion welded, which shows up in cladding of large-size billets, will certainly foster fluctuations of the wave profile and increase in the amount of the fused metal over the joining surface in bimetal.

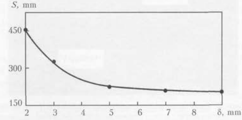

Figure 4. Dependence of distance S between the investigated section of the plate upon its thickness δ at the absence of the target plate ($x_i = 750$ mm, $\Delta = 4$ mm, $D = 1500$–1550 m/s)

In our opinion, the most significant factors leading to instability of structure and properties of the joining zone in explosion welding of long plates are vertical displacements of sections of the flyer plate ahead of the contact point under the explosive charge that has not yet detonated. This causes changes in the initial size of the setting gap, h, during explosion welding, thus resulting in deviation of the values of collision angle γ and collision velocity V_{col} from the calculated ones. This violation of the geometry of positional relationship of long elements, which was experimentally proved in studies [7, 9, 21, 22], may occur both due to the pressure of the shock-compressed gas (air) present between the plates welded [5], and due to the effect of inertia forces of a shock-wave origin [12, 23]. In our opinion, investigation of peculiarities of violation of the geometry of positional relationship of long elements being explosion welded is of a high scientific and practical interest, as this phenomenon, firstly, allows explaining non-uniform elongation deformation of the long plates, in addition to fluctuations of waves and increase in the amount of the fused metal along the length of the plates [14], and, secondly, outlining the new, scientifically justified ways of stabilising their properties, which is an important task, as the technological approaches known by now are of low technical feasibility and low efficiency.

Several series of experiments, the parameters of which are given in the Table, were carried out to investigate the character of vertical displacements of sections of the flyer metal plate by using the specially developed procedure described in detail in [22]. Distance S between the detonation front in an explosive charge and section of the flyer plate located ahead of the front and moved vertically to a distance of not less than Δ (gap between the needle sensor and surface of the flyer plate) was determined in the experiments using different input conditions and parameters of explosive loading.

Experiments 1–6 were conducted by the parallel scheme of explosion welding, and in experiments 7–15 the target plate was not used to exclude the effect of the shock-compressed gas present between the elements welded. In experiments 1—10, 14 and 15 the detonation velocity was varied over a wide range (1500–3800 m/s) and thickness of the flyer plate was kept constant, whereas in experiments 11–13 (as well as 7 and 14), on the contrary, thickness of the flyer element was varied from 2 to 9 mm and parameters of the explosive charge (H, ρ_{ex}) providing the detonation velocity of about 1500 m/s were kept constant. In addition, in experiments 1, 4–7, 10 and 14, the size of the setting gap, Δ, was varied from 2 to 5 mm along a vertical between the surface of the flyer plate and contact displacement sensors, and two lines of the sensors were installed at distances of 600 and 750 mm from the beginning of the flyer plate.

Conditions of explosive loading of plates in experimental study of the character of violation of the geometry of positional relationship of long elements ahead of the contact point

Experiment No.	Material of plates welded	Sizes of plates, mm	Detonation velocity D, m/s	Setting parameters			Distance S between section and detonation front at the time moment of needle sensor short-circuiting, mm
				Welding gap h, mm	Coordinate of installation of needle sensors x_i, mm	Gap Δ between needle sensor and plate surface, mm	
1	$\frac{\text{Steel St.3}}{\text{Steel St.3}}$	$\frac{2\times200\times800}{9\times200\times760}$	1510	3	600/750	2 4 5	236/386 236/386 236/386
2			2560		750	4	91
3			2860		750	4	33
4			3750		600/750	2 4 5	7/0 0/0 0/0
5		$\frac{2\times200\times800}{9\times200\times760}$	1540		600/750	2 4 5	151/301 151/301 117/297
6			3740		600/750	2 4 5	0/0 0/0 0/0
7	$\frac{\text{Steel St.3}}{-}$	$\frac{2\times200\times800}{-}$	1550	–	600/750	2 4 5	304/454 304/454 304/454
8			2550		750	4	152
9			2760		750	4	107
10			3700		600/750	2 4 5	0/0 0/0 0/0
11		$\frac{3\times200\times800}{-}$	1530		750	4	336
12		$\frac{5\times200\times800}{-}$	1560		750	4	220
13		$\frac{7\times200\times800}{-}$	1520		750	4	209
14		$\frac{9\times200\times800}{-}$	1510		600/750	2 4 5	341/201 329//201 51/201
15			3800		600/750	2 4 5	3/2 2/0 0/0

Note. Numerator gives values for the flyer plate, and denominator — values for the target plate.

As follows from analysis of the results obtained in experiments 1–4, size S decreased non-linearly (Figure 3, curve *1*), approximately from 420 mm at a mean value of V_c = 1510 m/s (experiment 1) and detonation velocity D ~ 3750 m/s (experiment 4) with increase in the detonation velocity. In this case, no vertical displacements of sections of the flyer plate ahead of the contact point were observed (the time fixed by the displacement sensors strictly corresponded to the moment at which the detonation front passed through their location plane). Similar changes in the S value were noted in the case of the 2 mm flyer plate (experiments 7–10) and absence of the target (fixed) element (Figure 3, curve *2*), as well as in investigation of the geometry of positional relationship of sufficiently thick and massive plates in experiments 5, 6, 14 and 15.

Increase in thickness of the flyer element in experiments 7, 11–14 at a relatively low value of detonation velocity D, equal to 1510–1550 m/s, leads to decrease in a value of S (Figure 4), approximately from 450 mm in the case of using the 2 mm flyer plate (experiment 7) to about 200 mm at plate thickness δ = 9 mm (experiment 14).

The results of experiments 5 and 14, where the contact sensors with different values of Δ were in-

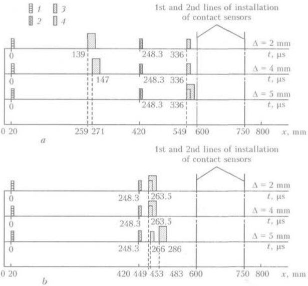

Figure 5. Diagrams plotted on the basis of the results of experiments 14 (*a*) and 5 (*b*) for positions *x* of the detonation front at the moments when investigated sections of the plate make vertical displacements *D*: *1* — pulse signal triggering scanning of oscillographs; *2* — pulse signal fixing that the detonation front has passed a distance of 420 mm; *3, 4* — pulse signal fixing displacement Δ of sensors of the 1st and 2nd lines, respectively

stalled in two lines, also allow an unambiguous conclusion that violation of the geometry of positional relationship of long elements ahead of the detonation front, at the absence of the target plate and under explosion welding conditions, may occur in different ways. This conclusion follows from analysis of the diagrams (Figure 5) plotted on the basis of the results of experiments 5 and 14, the only and fundamental difference in which was the presence of the target plate (see the Table).

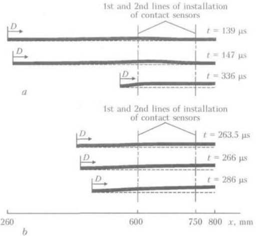

Figure 6. Hypothetical representation of changes in shape of the long flyer metal plate 9 mm thick ahead of the detonation front at time moments *t*, corresponding to short-circuiting of the contact sensors, according to the results of experiments 14 (*a*) and 5 (*b*): dashed line — initial position of internal surface of the long flyer plate; the explosive charge and target plate present in experiment 5 are not shown

It can be easily seen from the diagram plotted on the basis of the results of experiment 14 (Figure 5, *a*) that contact sensors of the 1st and 2nd lines, having a gap of 2 and 4 mm, short-circuited in series. Displacements of both investigated sections to 5 mm occur synchronously. Therefore, it can be assumed (Figure 6, *a*) that initially the displacement of the first section is of a local character, and then the situation changes because of acceleration of the right end of the plate, leading to simultaneous short-circuiting of all the sensors of the 2nd line and displacement of the first section at least to 5 mm. The presence of the target plate in experiment 5 leads to a substantial change in the situation (Figure 5, *b*). At the beginning, the displacement of both sections to 4 mm occurs synchronously and is characterised by an intensive acceleration, this being evidenced by simultaneous short-circuiting of the sensors having a gap of 2 and 4 mm. It took extra 22.5 μs for the first section of the plate to cause short-circuiting of the sensor with gap Δ = = 5 mm (i.e. for further upward displacement to 1 mm), and no more than 2.5 μs for the second section. Therefore, the initial stage of vertical displacements (to 4 mm) is characterised by a dramatic acceleration of both first and second investigated sections, after which a substantial difference can be seen in changes of the velocities of the latter (the second section moves at a much higher velocity, compared with the first section, this being evidenced by a difference in time of short-circuiting of the contact sensors with a value of the setting gap equal to 5 mm). Therefore, it can be assumed (Figure 6, *b*) that under explosion welding conditions the parallel welding scheme is transformed into the angular one with some variable angle α. In this case, violation of the geometry of positional relationship of the elements welded is of a non-local character, this explaining some «congestion» of pulses within a narrow time range (see Figure 5, *b*).

CONCLUSIONS

1. It was established that violations of the geometry of positional relationship of the elements being explosion welded ahead of the detonation front and effect of preheating of the colliding surfaces are the main causes of changes in properties of the joint along the length of the billets welded, which show up in increase in sizes of the waves and amount of the fused metal.

2. It was experimentally determined that in the case of vertical displacements outpacing the detonation front (in a number of cases, comparable with welding gap size h), outpacing value S decreases with increase in the detonation velocity of the captive explosive charge (up to complete termination of the vertical displacements of the flyer element sections) and thickness of the flyer element.

3. It was reliably proved that the flyer metal plate accelerated by a sliding detonation wave (at the absence of the target plate) is characterised by the disturbances occurring in it, which are the result of action of the inertia forces of a shock-wave origin, while under conditions of explosion welding of long elements arranged by the parallel scheme the latter can be transformed into the angular one due to the dominating effect of the shock-compressed air moving in the gap between the plates.

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