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Formation of welded joints in explosive welding large metallic laminated composites

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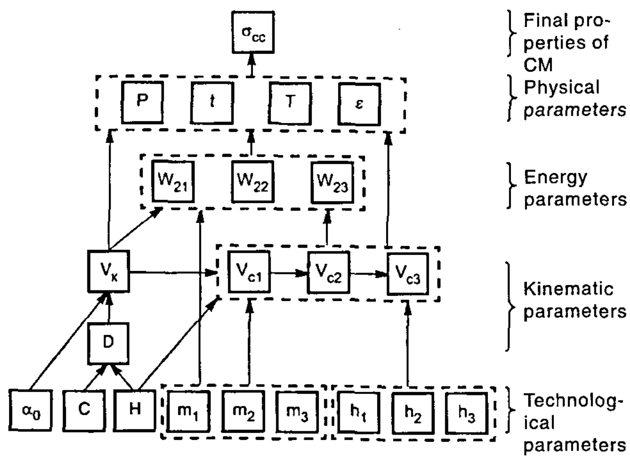
Explosive welding is a highly efficient and economical process of production of metallic laminated composite materials (LCM) with different structures and for different applications. The formation of the welded joint takes place as a result of the effect of deformation on welded materials and is characterised by the high speed of collision of the materials with the shorter duration of the process resulting in a two-stage topochemical reaction leading to the formation of the final properties of the welded joints. These properties are determined by the degree, nature and duration of deformation.[1–7] Consequently, explosive welding may be regarded as a conventional controlled technological process. Analysis of the phenomenological model of explosive welding, for example of four-layer composites (Fig. 1), illustrating in the simplified form the interaction between different groups of the parameters and the final properties of the laminated composite materials, indicates that the variation of the technological (design) parameters makes it possible to change the distributed (kinematic, energy, physical) parameters. The quantitative relationships have been found between the different groups and subgroups of the parameters, and reliable mathematical models have been developed describing both the process of high-speed collision of the welded elements and the deformation processes taking place in the weld zone of the joint in the conditions of high-pressures whose application makes it possible to determine and optimise the explosive welding conditions.



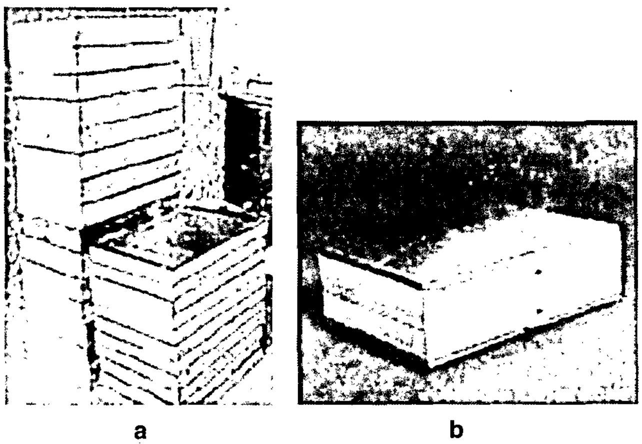
1 *Phenomenological model of explosive welding a four-layer composite (α_0 – setting angle, C – the composition of the mixture of the explosive substance (ES); H – the height of the ES charge; m_1–m_3 – unit mass of the welded plates; h_1–h_3 – the setting gap; D – the speed of detonation of the ES; v_k – contact speed; v_{c1}–v_{c3} – the speed of collision of the layers of the composite; W_{21}–W_{23} – the energy used for plastic deformation of the metal; p – the pressure in the collision zone; t – the duration of the effect of p; T – the temperature in the welded joint; ε – the degree of plastic deformation of the welded zone metal; σ_{cc} – the strength in separation of the layers of the produced composite material, the indexes indicate the number of the interlayer boundary of the composite).*

The maintenance, on a constant level within the limits of the entire welding area, of all the design and the distributed parameters of the process should lead at first sight automatically to the stabilisation of the properties of the explosive welded joint. However, explosive cladding of large components is associated with the realisation of the so-called 'scale factor' which often has a negative effect on the quality of the composite materials.

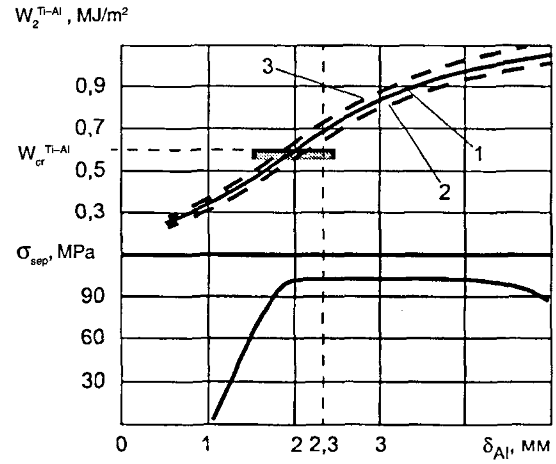
Analysis of a large number of experimental data obtained by different investigators[1,2,4] and of the results by the authors of this article makes it possible to characterise all possible factors affecting the process of formation of the welded joint in explosive welding large-size laminated composite materials leading in the final analysis to the instability of the properties of the composite materials within the limits of the area of the welded joint and, in some cases, to the formation of defects of different type, directly associated with the overall dimensions of the welded components.

Initially, analysis will be carried out of the main possible defects in the zone of the welded joint detected in large explosive-welded components. The defects of the weld zone, together with lack of fusion at the edges of the welded joint, typical of metallic laminated composite materials of all possible dimensions, with the length greatly dependent on the properties and thickness of the welded materials, include local lack of fusion defects, nonmetallic inclusions and also areas with molten metal.

The first two types of defects are of the random nature and depend, even if the welding conditions have been correctly selected, on the efficiency of preparation of the initial materials, the culture of production, etc. This may be illustrated on the following example. In explosive welding a titanium VT1-0+AD1 aluminium +AMg6 3-



2 *Composite titanium–aluminium components, produced by (a) explosive welding and (b) the antenna casing produced from them after testing at a pressure of 2.5 MPa.*



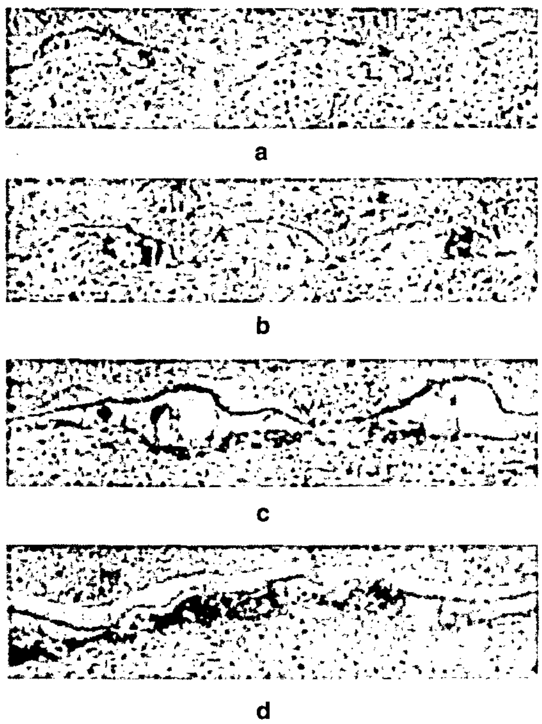
3 *Dependence of the value of W_2^{Ti-Al} at the boundary of the titanium–aluminium composite and of σ_{sep} on the thickness δ_{Al} of the intermediate layer of the AD1 alloy: 1) Calculated energy; Possible values of the energy realised in the zone of the welded joint at random deviations of the welding gap to the (2) smaller and (3) wider side.*

layer composite with the thickness of the layers being 5.0, 2.0 and (30–60) mm, respectively, (Fig. 2) (this laminated composite material is used for the production of antenna systems for aerospace technology for objects such as Energiya-Buran, Progress, Soyuz, Salyut, Mir, Alpha International Space Station, etc) local lack of fusion defects of arbitrary shape and dimensions were found in certain cases in the joint zone of welding titanium to aluminium.

Detailed analysis of the energy conditions of the formation of the welded joint in these composite materials[8] shows that for the selected combination of the thicknesses of the layers of the composites, the energy W_2^{Ti-Al}, used for the plastic deformation of metal in the welding process at the examined interface, is on the critical level (W_{2cr}^{Ti-Al} = 0.6 MJ/m²), corresponding to the 'threshold' of equal strength (Fig. 3). In the case of random deviations of the setting parameters from the nominal (calculated) values, for example, a decrease in the size of the welding gap as a result of local deflection of the welded sheets (this is observed in explosive welding large components), the energy W_2^{Ti-Al} at the VT1-0–AD1 interface decreases below W_{2cr}^{Ti-Al} (Fig. 3, curve 2) which resulted in the formation of lack of fusion defects. An increase in the thickness of the central aluminium sheet by only 0.3 mm increased the value of W_2^{Ti-Al} to 0.65–0.76 MJ/m² (Fig. 3) and, consequently, it was possible to produce a guaranteed full-size strength joint in the layers of the entire area of the welded components.These results were taken into account in the development of a technological process of explosive welding of three- and five-layer titanium–aluminium blanks for the the bodies of antenna devices, and the corresponding alterations were introduced into the Technical Instructions for the composite materials.

Areas with molten metal in up to 20% of the total area of the welded joints are fully permissible in the welded joints of identical material or dissimilar materials and alloys with similar properties, for example, stainless steel + low carbon steel, copper + steel, brass + steel, aluminium + aluminium alloy, etc, because the solid solutions, present in the melts, do not decrease the strength of the produced welded joints. The situation is different in composite materials whose components may produce brittle intermetallic compounds, for example, titanium + steel, copper + aluminium, zirconium + steel, etc. Here, the inclusions of molten metal, containing a large quantity of intermetallic phases, are potential areas of brittle fracture of composite materials operating, for example, under alternating loading, and also areas with high electrical resistance,[9] which greatly decreases the user properties of composite materials for electrical engineering applications. In contrast to the first two types of defects, the last type of defects in the weld zone may be of the random nature; in explosive welding, a local increase of the size of the initial gap or a local increase of the density of the charge of the explosive substance results in a corresponding 'forcing' of the parameters of a high-speed collision of the layer of the composite materials and the energy conditions of its formation, or it may be of a systematic nature reflected in a monotonic increase of the amount of cast inclusions in the welded joint with an increase in the distance from the initiation point. For example, in Ref. 3 in explosive welding long titanium–steel components, the results showed a gradual increase of the parameters of the wave profile ('swinging' effect) and the volume of the molten areas increased from practically 0 (30 mm from the edge of the component) to 100 % in the final stage of the component (Fig. 4). This was a reason for a significant instability of the strength properties of the bimetal: the separation strength of the layers decreased from 300 MPa at the beginning of the component to 10 MPa at the end. A similar variation of the parameters of the wave profile and of the amount of molten metal on the length of large steel components was recorded many times by other investigators[10–12] and also in the experiments carried out by the authors of the present article.

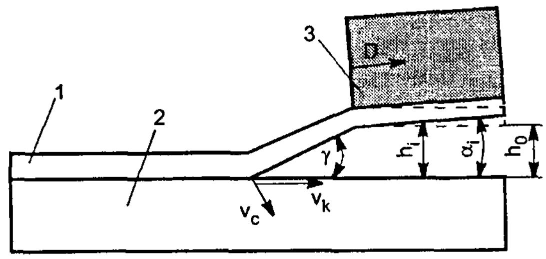
Possible reasons for the occurrence of the previously mentioned 'swinging' effect of the wave profile in the



4 *Microstructure (× 30) of the welded joint of the titanium + steel bimetal at a distance of (a) 30, (b) 1000, (c) 2500 and (d) 3800 mm from the zone of priming of the ES charge.*[4]

weld zone with a decrease of the length of welded plates will be examined.

1 The forcing of the parameters of high-speed collision of the plates as a result of an increase in the speed of detonation of the explosive substance along the length of the charge[10] which, however, does not have reliable theoretical substantiation and experimental confirmation.
2 Heating of the welded surfaces in front of the contact line as a result of the effect of the high-temperature flow of the particles of the compressed gas of cumulative origin.[13] On the basis of the experimental data obtained in Ref. 13 it was shown that the heat flow from the gas into the metal is 10^9–10^{10} J/(m^2 s). Under the effect of this flow, with an increase in the distance from the initiation area there may be a moment in which the energy, transferred into the metal from the gas, becomes comparable with the energy used for plastic deformation. The total thermal effect may result in more intensive melting of the interface of the welded metals, but it should not increase the parameters of the wave profile.
3 The vertical displacement of the cross sections, situated ahead of the contact point, resulting in a disruption of the geometry of collision of the welded elements (Fig. 5).



5 *Variation of the mutual position of the plates in the process of explosive cladding (h_0 – the initial setting gap, h_i, a_i – the gap and the initial angle in some cross-section of a package of plates, the broken line indicates the initial position of the flyer plate): The (1) flyer and (2) stationary plates; 3) The ES charge.*

The variation in the mutual deposition of the plates during welding (progressing with the movement of the detonation front) increases the angle of collision γ as a result of transition from the parallel welding procedure to the angular variant with the variable setting angle α_{0_i}, a small increase in the speed of collision v_c (this increase decreases with a decrease in the relative gap *h*/*H*), and in a decrease in the speed of the contact point v_k.

Calculations were carried out by computer modelling[14] of the variation of the parameters in the weld zone in explosive welding to aluminium sheets with a thickness of 5 mm and with a length of 1000 mm each. The following assumptions were made: the initial angle α_i between the flyer sheet and the stationary sheet changes in a linear

Table 1

Series No.	Material of welded sheets	Sheet thickness*, mm	Setting parameter: Height of ES charge, mm	Setting parameter: Detonation speed, m/s	Setting parameter: Welding gap, mm	Calculation parameters: v_k, m/s	Calculation parameters: v_c, m/s	Calculation parameters: γ, deg	Calculation parameters: W_2, MJ/m^2
1	Aluminium	5.0	25		1.0				
				2600		2600	460	9.2	0.5
2	Aluminium	5.0	15		5.0				

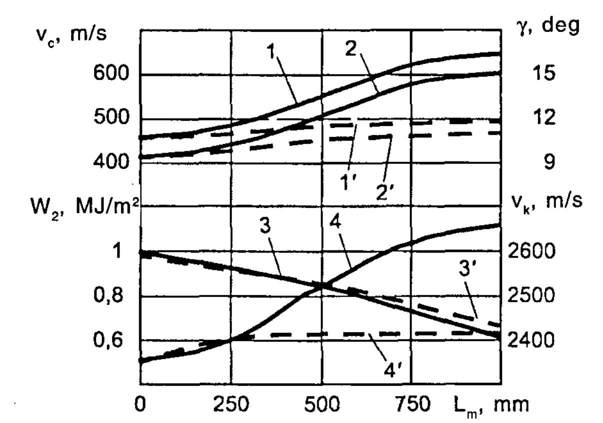
*The numerator gives the data for the flyer sheet, the denominator for the stationary sheet.

manner from 0 to 1°; instantaneous variations of the setting parameters results in an instantaneous change of the kinematic parameters.[2] Cases, differing in the values of h/H, will be investigated. The initial data for computer modelling the dynamics of the variation of the explosive welding parameters and the length of the sheets are presented in Table 1.

The results obtained in computer modelling show that the parameters of the process change along the length of the sheets in the following manner, depending on h/H. For example, at $h/H = 0.04$ (see Table 1, series 1) over a length of 1000 mm, the speed and angle of collision increased from 460 m/s and 9.5° to 650 m/s and 15°, respectively (Fig. 6, curves 1 and 2) which, in the case of a small change in the speed of the collision point, which decreased to 2400 m/s (Fig. 6, curve 3), resulted in a large increase in the energy input in the zone of the welded joint: from 0.5 (in the initial part of the specimens) to 1.15 MJ/m^2 (in the final part). According to Ref. 3, this rapid increase in the collision parameters (v_c and γ) results in a large increase in the size of the waves in the zone of the welded joint, and an increase in the energy input results in the formation of areas with molten metal and in an increase in the volume of these areas.

The variation of the collision parameters in explosive welding in the conditions of a full acceleration of the flyer plate are different, i.e. at $h/H = 0.3$ (in Table 1, series 2). The intensity of variation of these parameters (with the exception of v_k) is not so large (Fig. 6, curves 1', 2', 4'). Consequently, it may be expected that the instability of the structure and properties of the area of the welded joint will be smaller than in the first case.

If the assumption on the disruption of the collision geometry in the process of explosive welding of long components is accurate (see Ref. 3, where the variation of the welding gap is associated with the effect of the air interlayer between the welded components compressed to high pressure, and Ref. 15 in which the vertical displacement of the cross-section of the flyer element is justified on the basis of the shockwave approach), then, firstly, this makes it possible to explain, in addition to the effect of 'swinging' of the waves and the increase in the amount of the alloys along the length of large components, also their nonuniform elongation deformation,[1, 16] and, secondly, indicates the methods of stabilisation of the properties of these welded joints.



6 *Dynamics of the variation of the parameters v_c (1,1'), γ (2,2'), v_k (3,3') and W_2 (4,4') along the length of the welded components (the broken line indicated data from Table 1, series 2).*

The currently available methods, i.e. welding with a negative angle, the development of artificial 'waves' in the flyer element prior to welding, and also rigid fixing of the welded components together, are characterised by low efficiency.[3] The preferential evacuation of the gap between the welded components or filling the gap with a gas with the speed of sound higher than, for example, in the case of air, are more efficient.[17,18] However, these methods are characterised by a high labour content and are expensive.

The most suitable method of stabilisation of the collision velocity and angle and, consequently, the properties of the welded joint in explosive welding of large and long components is the formation of a profiled charge of explosive substance with a small increase in the thickness of the charge along the length of the welded components. This is confirmed by the results of a large number of experiments in which the value of the so-called 'bevel' of the charge was selected arbitrarily. The accurate determination of the profile of the charge of the explosive substance, ensuring maximum stabilisation of the properties of the welded zone of large composite components, requires additional investigations.

Conclusions

1 The main reason for the disruption of the collision geometry of explosive-welded large or long elements is the vertical displacement of the cross-sections of the flyer plate situated in front of the contact point underneath the not yet detonated charge of the explosive substance.
2 The formation of the profile charge of the explosive substance with a small decrease in its thickness along the length of the welded components stabilises the properties of the produced welded joint.

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