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Use of Emulsion Explosives in Experimental Studies of Flows in the Bonding Zone in Explosive Welding

B. S. Zlobin[a], **V. V. Kiselev**[a],
A. A. Shterzer[a,b], **and A. V. Plastinin**[b]

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Abstract: Bonding of steels of different hardness through a ductile layer was obtained by explosive welding using an emulsion explosive. In the bonding zone, two types of waves were found: large waves and small waves which have not been observed in previous experiments. Empirical relations for calculating the wave size are proposed that take into account the influence of the strength and density of the colliding materials on them. Cracking in the bonding zone can be avoided by reducing the wave size.

Keywords: emulsion explosives, explosive welding, low-ductility materials, wave formation.

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INTRODUCTION

Low detonation velocity emulsion explosives (EMXs) have high detonability due to the presence of a highly dispersed matrix (emulsion of a mixture of ammonium and sodium nitrates with a density of 1.41 ± 0.01 g/cm^3 and a droplet size less than 1–2 μm). The physical sensitizer in EMXs are hollow microballoons of glass (MS-V microballoons of domestic production with a true density of 0.22 ± 0.02 g/cm^3) or polymer (Expancel microballoons with a density of 0.025 ± 0.003 g/cm^3). The detonation properties of EMXs are well studied [1–5]. Having a density of 0.6–0.9 g/cm^3, they steadily detonate at a velocity 2.5–4 km/s in thin layers 3–7 mm thick. These parameters are ideal for applying thin (less than 1 mm in thickness) coatings to metal surfaces by explosive welding. Such low-density EMXs are convenient for use in metalworking because their detonation velocity is almost independent of the thickness [5]. Compositions with higher density (0.9–1.2 g/cm^3) have an even lower critical thickness (up to 1 mm), but are unsuitable for explosive welding because they have a significant dependence of detonation velocity on thickness and, at high layer thickness, (5–10 mm), a high detonation velocity (up to 5 km/s). Examples of extending the capabilities of explosive welding by using EMXs to solve some practical problems are given, e.g., in [6–9].

The purpose of this work was to study the bonding zone of metals obtained by using EMXs. The ability of EMXs to steadily detonate in thin layers has made it possible to obtain new experimental data on wave formation in an oblique impact of metal plates during explosive welding.

EXPERIMENTS USING EMXs

A steadily detonating flat charge of mixtures of 79/21 AN/TNT with ammonium nitrate, which are widely used in explosive welding, has a minimum thickness (critical thickness) of ≈10 mm for a density of ≈0.9 g/cm^3. If it is necessary to joint, e.g., a copper strip 0.5 mm thick to a metal plate using this charge, the ratio of the mass of the explosive to the mass of the driver plate should be about two. For this value of

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[a] Design and Technology Department of the Lavrent'ev Institute of Hydrodynamics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, 630090 Russia; asterzer@mail.ru.

[b] Lavrent'ev Institute of Hydrodynamics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, 630090 Russia.

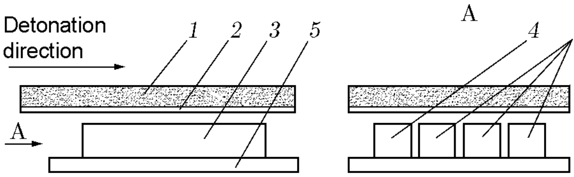

Fig. 1. Welding a copper plate to steel samples of different hardness: (*1*) explosive charge; (*2*) copper plate; (*3*) steel samples; (*4*) aluminum sample; (*5*) base.

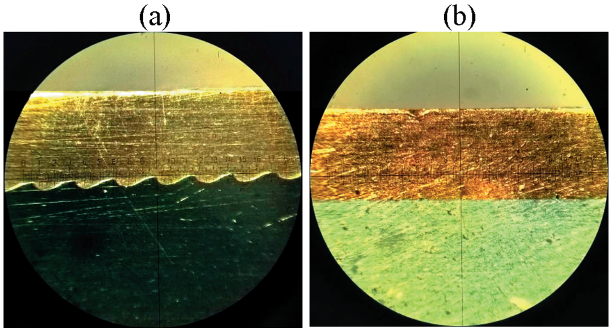

Fig. 2. Macrosections of the copper–steel with hardness HV = 460 (a) and copper–aluminum (b) bonding zones.

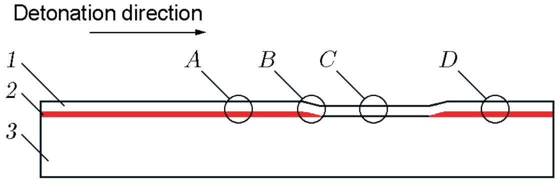

Fig. 3. Composite sample obtained by explosive welding: hardened steel plates (*1* and *3*) and copper interlayer (*2*); *A*, *B*, *C*, and *D* are the areas of investigation of the bonding zone.

the mass ratio, the collision angle of the welded plates calculated by the formulas from [10] is $\gamma \approx 24°$. At the same time, experience shows that to achieve bonding at the interface between, e.g., copper and steel at a velocity of the contact point of 2.6 km/s, it is sufficient to ensure a minimum collision angle $\gamma = 8°$. For this reason, plates with a thickness of less than 1 mm are driven, as a rule, using inert buffer layers. In this case, the size of the zone of high plastic deformations and the size of the waves are determined not by the thickness of the welded plate, but by the thickness and properties of the whole driver assembly. In this welding method, the amplitude of waves is often comparable to the thickness of the driver plate, so that in this situation, it is difficult to investigate the effect of the collision parameters on the wave size. However, the use of EMXs makes it possible to drive thin metal plates with a thickness of 1 mm or less (up to 0.3 mm) without additional buffers. In this case, the size of the zone of high plastic deformations and the magnitude of the waves formed in the bonding zone depend only on the thickness of the driver plate, other things being equal.

In welding of low-ductility metals and alloys, an excessive increase in the angle and hence the plate collision velocity enhances the deformation process in the bonding zone and leads to cracking, primarily, at wave crests [11]. In this situation, it is very important to control the size of waves because their reduction can prevent cracking. In addition to the kinematic collision parameters, it is evident that wave formation should also be influenced by the strength of the materials; however in the literature there are no experimental data on the effect. To study the influence of the strength of the colliding plates on the wave size, we performed experiments in which three steel samples of different Vickers hardness (HV = 145, 320, and 460) and an aluminum sample with hardness HV = 30 were simultaneously clad with a copper plate 1 mm thick with hardness HV = 60 according to the scheme shown in Fig. 1 [12].

The measured detonation velocity was 2.8 km/s, and the calculated collision angle $\gamma = 12°$. After the welding, microsections were made from the bimetallic samples and wave sizes were measured in three regions: 20 mm from the beginning (region 1), in the middle (region *2*), and 10 mm from the end of each sample (*3*). The results of the measurements are shown in Table 1.

It is characteristic that the bonding zone at the copper–steel interface has a distinct wave pattern, but at the copper–aluminum interface for the same collision parameters, waves are absent (Fig. 2). The size of the waves, primarily their amplitude, decrease with increasing hardness of steel samples.

It can be seen from Table 1 that increasing the hardness by a factor of about three decreased the wavelength λ by a factor of 1.64 and the wave amplitude a by a factor of 2.29. With a further increase in the hardness of the strongest of the welded materials, the shape of the bonding zone tends to acquire a nonwavy shape, as shown in [9] for the pair stainless steel (HV = 150)/a cemented carbide (HV = 1445).

The ability of EMX to detonate in thin layers also allowed an experimental investigation of explosive welding of strong low-ductility steels using thin copper layers. The experiments were conducted in two stages. In the first stage, a sample of 30 KhGSA steel 25 mm thick with a hardness HV = 423–435 was clad with a copper foil 0.3 mm thick with a hardness HV = 60.

Table 1. Length and amplitude of waves in the bonding zone

Hardness of steel sample HV	Region 1		Region 2		Region 3		Mean value	
	λ	$2a$	λ	$2a$	λ	$2a$	λ	$2a$
	mm							
460	0.302	0.071	0.283	0.071	0.267	0.071	0.280	0.070
320	0.380	0.114	0.401	0.114	0.362	0.114	0.380	0.110
145	0.457	0.157	0.485	0.157	0.442	0.157	0.460	0.160

Here $2a$ is the distance between the upper and lower wave peaks corresponding to the double amplitude of a sinusoidal wave a.

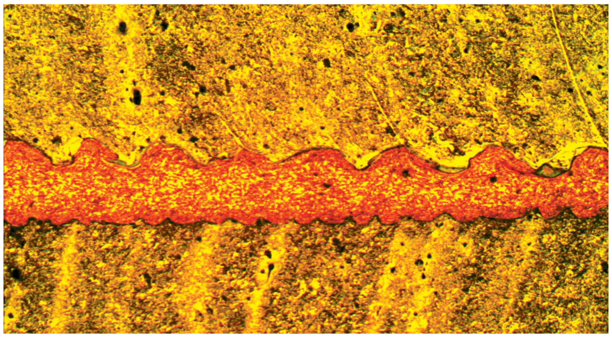

Fig. 4. Bonding zone obtained by driving steel onto steel–copper bimetal (region A in Fig. 3).

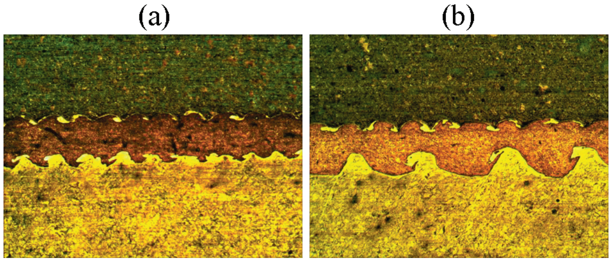

Fig. 5. Bonding zone obtained by driving a steel–copper bimetal onto a steel substrate: (a) region A in Fig. 3; (b) region D in Fig. 3.

Then, in a region 20-mm long, copper was removed, after which a 30HGSA steel plate 4 mm thick with a hardness HV = 311–320 was driven onto this bimetallic sample. The obtained composite sample schematically depicted in Fig. 3 was cut into microsections to study wave formation in different parts of the bonding zone.

Figure 4 shows the microsection of the bonding zone in region A (see Fig. 3). It can be seen that in the welding of a copper foil with a steel base, the wave size was determined by the thickness of the copper foil of 0.3 mm (the lower copper–steel interface in Fig. 4). In the subsequent process of driving the steel plate onto the obtained bimetal, the size of the waves was influenced by its thickness (steel plate) 4 mm (upper steel–copper interface in Fig. 4). The waves on the upper boundary of copper are 2.5–3 times larger in both the amplitude a and the length λ; it is seen how shear cracks originate at the wave crests.

In the welding of the same plates, but in a different sequence, the wave formation pattern is different, as evidenced by the following experiment. First, a steel plate 3 mm thick with a hardness HV = 460 was clad with a copper foil 0.3 mm thick. Then, the foil was removed from a region 20 mm long, and the resulting bimetal was clad on a steel plate 25 mm thick with hardness HV = 423–435. The velocity of the contact point was 3.0 km/s, the calculated collision angle $\gamma = 10°$. As a result, we obtained a three-layer steel–copper–steel sample similar to the one made in the previous experiment (see Fig. 3). Note that in the two experiments described, the size of the waves formed in the second stage of welding differed significantly. Figure 5a shows the bonding zone in region A obtained in the experiment where the bimetallic plate was the driver one. It can be seen that the waves are smaller here than in Fig. 4. In addition, in this case, there are no signs of the formation of shear cracks in steel. Since, previously, such a wave formation pattern (small waves) during welding of multilayer composites has not been observed, the experiments were repeated to avoid errors, and the results of several experiments coincided. Whereas small waves were observed in region A, in region D, whose microsection is shown in Fig. 5b, large waves were formed in the same experiment.

The wave formation pattern in regions B and C presented in Fig. 6 shows that in the place where the copper interlayer is interrupted and the steel–steel interface begins (region C), unlike the data of [13], large waves appear immediately. Unlike the small waves described above, their length λ and the amplitude a fall within the range of values (or even higher) calculated according to the classical formulas from [10]:

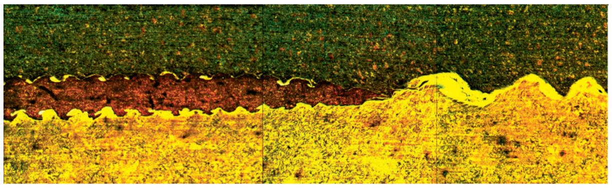

Fig. 6. Wave formation in the welding zone of steel plates through a copper layer (regions B and C in Fig. 3; the contact point moves from left to right).

$$\lambda/\delta = (16 - 26)\sin^2(\gamma/2), \tag{1}$$

$$0.14 \leqslant a/\lambda \leqslant 0.3, \tag{2}$$

where δ is the thickness of the driver plate.

Thus, the conducted experiments showed the existence of two types of waves (large and small) that can occur in the bonding zone during explosive welding. An additional experiment to study the welding of two steel plates was carried out using an aluminum interlayer. In the first stage, a steel plate 4 mm thick with a hardness HV = 120 was clad with aluminum 1 mm thick with a hardness HV = 30. Then, aluminum was removed by grinding from a region 25 mm long at a distance 70 mm from the end of the bimetal, and the resulting plate was driven onto a steel substrate 20 mm thick with a hardness HV = 120. The velocity of the contact point was 2.72 km/s, and the calculated collision angle $\gamma = 11.5°$. Examination of the bonding zone showed no wave formation at the aluminum–steel interface and the formation of waves with $\lambda = 0.64$ mm and $2a = 0.27$ mm at the steel–steel interface.

Table 2 shows the data on the wave parameters obtained in the above experiments: the thickness of the driver plate δ, the velocity of the contact point v_c, the collision angle γ, the density of the driver ρ_1 and fixed ρ_2 plates, the Vickers hardness of the driver plate (HV_1) and fixed plate (HV_2), the wavelength λ, and the wave amplitude a. The alloy with a hardness HV = 1445 (HRA = 89) is a MC 221 (TT10K8-B) cemented carbide based on tungsten, titanium, and tantalum carbides with a cobalt content of 8%. Asterisk at the wavelength indicates that the wave is small. The question mark indicates that the wavelength cannot be measured since the contact boundary in the microsections is flat, i.e., the amplitude is zero or, at least, less than random microroughness.

DISCUSSION OF THE RESULTS

The new experimental data on wave formation obtained using EMX requires a certain interpretation. The wave formation phenomenon in explosive welding has been the subject of many studies, and there are more than a dozen concepts explaining it. A detailed review of the of the literature on this topic is presented in [14]. However, until now, there is no satisfactory theory to calculate the wave size taking into account the mechanical and physical characteristics of colliding bodies. However, waves appear even in numerical calculations using molecular dynamics methods, although the thickness of the colliding plates is not more than 1000 Å [15]. In this paper, we do not propose any new theory of wave formation, but make an attempt to derive empirical relations for calculating wave sizes based on general hydrodynamic considerations and experimental data.

In describing flows in the plate collision zone, we will be guided by considerations similar to those described in [16], where the instability of stationary viscous fluid flow is explained using the Landau model [17]. It is assumed that at high pressures in the vicinity of the contact point and at high deformation rates, metal behave like a viscous incompressible fluid. The formation of waves indicates the nonstationarity of the flow in the bonding zone of two materials, which is characterized by two dimensionless parameters: the Reynolds number $\mathrm{R} = \rho ul/\eta$ and the Strouhal number $\mathrm{Sr} = u\tau/l$, where ρ and η are the density and viscosity of the medium, respectively, l is the characteristic linear dimension, u is the characteristic velocity, and τ is the characteristic time of the problem under consideration. According to [17], if perturbations in the form of waves in a fluid arise spontaneously, rather than under the influence of an external periodic force, then Sr is a certain function of R, i.e., $\mathrm{Sr} = f(\mathrm{R})$. Assuming that τ is the period of oscillations T, u is the velocity of the contact point v_c, and the characteristic linear dimension is the thickness δ_j of the cumulative jet produced by the impact of a driver plate on a thick substrate ($\delta_j = \delta\sin^2(\gamma/2)$ [18]), we obtain the expression $\mathrm{Sr} = v_c T/[\delta\sin^2(\gamma/2)]$. It can be shown that the perturbations arising in the stationary flow moving with velocity v_c satisfy the relation $v_c T = \lambda$, which implies that the perturbations are carried by the flow. Then, the wavelength is given by the formula

$$\lambda/\delta = f(\mathrm{R})\sin^2(\gamma/2). \tag{3}$$

Since the thickness of the cumulative jet is taken as the characteristic dimension, this the formula is similar to the known relation (1) with the difference that the numerical coefficient before the sine is replaced by a function of the Reynolds number. As an analog of the Reynolds number we will use the following expression [10, 19] adopted in explosive welding:

$$\mathrm{R} = \frac{(\rho_1 + \rho_2)v_c^2}{2(\mathrm{HV}_1 + \mathrm{HV}_2)}. \tag{4}$$

Table 2. Collision parameters and wave sizes

Welded materials	δ, mm	v_c, km/s	γ, deg	ρ_1, g/cm^3	ρ_2, g/cm^3	HV$_1$	HV$_2$	λ, mm	a, mm
Cu/Al	1	2.8	12	8.9	2.7	60	30	?	0
Cu/steel (145)	1	2.8	12	8.9	7.8	60	145	0.46	0.08
Cu/steel (320)	1	2.8	12	8.9	7.8	60	320	0.38	0.055
Cu/steel (460)	1	2.8	12	8.9	7.8	60	460	0.28	0.035
Steel (150)/cemented carbide (1445)	1	2.8	12	7.8	13.7	150	1445	?	0
Steel (460)/steel (429)	3	3.0	10	7.8	7.8	460	429	0.56	0.1
Steel (120)/steel (120)	4	2.72	11.5	7.8	7.8	120	120	0.644*	0.135
Cu/steel (429)	3.3	3.0	10	8.9	7.8	60	429	0.24*	0.05
Al/steel (120)	5	2.72	11.5	2.7	7.8	30	120	?	0

For welded materials, Vickers hardness is given in parentheses.

Generally speaking, it is wrong to call the ratio of the dynamic pressure to the strength of the material the Reynolds number; it is more correct to call it the Euler number, as is done in [20]. When the first researchers of explosive welding, such as Crossland, Cowan, and Holtzman [19, 21] called the parameter (4) the Reynolds number, their logic was based on the fact that in hydrodynamics, the static strength of the medium is zero and the Reynolds number (Re) coincides with the Euler number (Eu). This can easily be shown as follows. Let ρ be the density of the medium, η the viscosity, $\dot{\varepsilon}$ the strain rate, v the characteristic velocity, and l the characteristic dimension of the problem. Then, $\mathrm{Re} = \rho l v/\eta = \rho l v \dot{\varepsilon}/(\eta \dot{\varepsilon})$. Further, since $\dot{\varepsilon} = v/l$, we have $\mathrm{Re} = \rho v^2/\sigma = \mathrm{Eu}$, where $\sigma = \eta\dot{\varepsilon}$ are the shear stresses due to viscosity. Considering this, we can assume that for spontaneous perturbations in a fluid, the Strouhal number is a function of the Euler number. In this paper, we keep the historically established notation (the letter R) of the parameter calculated by formula (4) which is in fact the Euler number.

By processing the data in Table 2, we obtained linear dependences $f(\mathrm{R})$ for large and small waves (Fig. 7). The following formulas for calculating the wavelength are derived:

$$\lambda/\delta = (0.76\mathrm{R} + 18.5)\sin^2(\gamma/2) \qquad (5)$$

for large waves and

$$\lambda/\delta = (0.73\mathrm{R} - 1.70)\sin^2(\gamma/2) \qquad (6)$$

for small waves.

As for the wave amplitude, in addition to the Euler number, experiments indicate that it is strongly influenced by the ratio of the densities of the metals being welded. If the difference in density between the materials is large, regardless of their strength, welding occurs without waves, i.e., the amplitude tends to zero. This fact can be qualitatively explained as follows. Because wave formation is associated with the interpenetration of materials, it follows that decreasing the density of one of them reduces its dynamic pressure associated with the velocity perturbation in a direction perpendicular to the bonding boundary. Accordingly, the possibility of its introduction into the more dense material decreases.

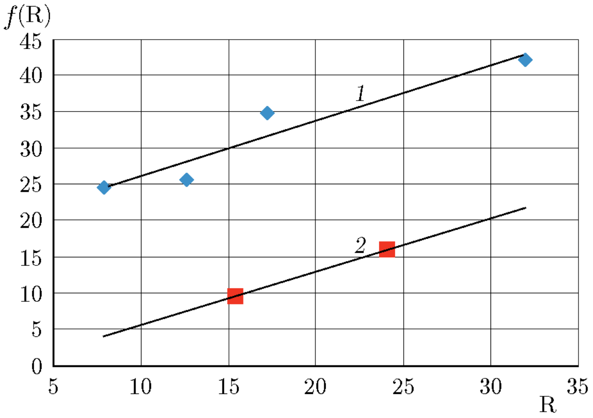

Fig. 7. Linear functions $f(\mathrm{R})$ for large (*1*) and small (*2*) waves: the points denoted as rhombuses and squares refer to the experimental data.

As a result of a search of various dependences of a/λ on the parameters ρ_1, ρ_2, R in order to better fit the experimental data, we chose the relation $a/\lambda = (\rho_{\min}/\rho_{\max})^n g(\mathrm{R})$. Minimum and maximum density values are chosen from the two densities ρ_1 and ρ_2. It is required to determine the function $g(\mathrm{R})$ and the number n. Processing of data on the wave amplitudes allowed us to choose $n = 2.6$ and the function $g(\mathrm{R})$ in the linear form $g(\mathrm{R}) = 0.0029\mathrm{R} + 0.1495$ (Fig. 8).

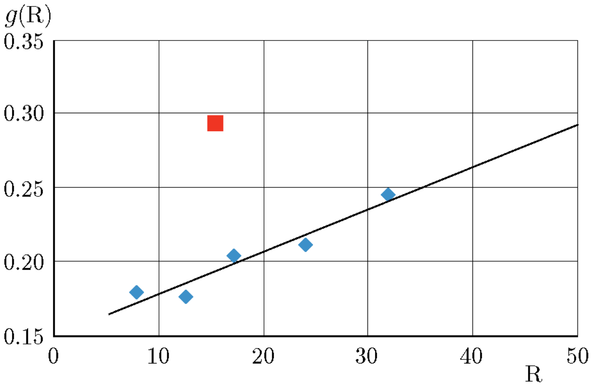

Fig. 8. Linear function g(R) constructed from the experimental data (points denoted by rhombuses and square).

Thus, the following formula for calculating the wave amplitude was obtained

$$a/\lambda = (\rho_{\min}/\rho_{\max})^{2.6}(0.0029\mathrm{R} + 0.1495). \qquad (7)$$

The reliability of the approximations for the chosen functions f(R) and g(R) is 92 and 93%, respectively. In Fig. 8, the square marks the point corresponding to the waves in the copper–steel bonding zone obtained in the experiment in which a steel plate clad with a 0.3 mm thick copper layer was driven onto steel (second row from the bottom in Table 2). The reason for which this point falls out of the general dependence for a/λ is still unclear, but it can be related to the probable tendency of transition from small waves into large ones.

It must be said that the possible existence of two types of waves was noted already in [10], but have not been observed in previous experiments.

CONCLUSIONS

1. Emulsion explosives with hollow microballoons can be used to obtain new experimental information on the flows arising from oblique collision of metal plates.

2. The existence of two types of waves—small and large—was found in welds with intermediate layers.

3. Empirical formulas for calculating the wave size were derived that take into account the effect of the strength and density of colliding materials.

4. Emulsion explosives with hollow microballoons can be used for bonding low-ductility materials by explosive welding through a thin layer of ductile metal. In this case, crack formation can be avoided by controlled reduction of the wave size in the weld zone. For this, a driver plate is first clad with a thin interlayer and is then welded to a fixed plate of low-ductility metal.

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