EFFECT OF THE INITIAL PARAMETERS ON THE PROCESS OF WAVE FORMATION IN EXPLOSIVE WELDING

A. A. Deribas, V. M. Kudinov, and F. I. Matveenkov

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A characteristic feature of joints obtained by explosive welding is the rather strict regularity and periodicity of the residual deformation in the impact region, which gives the contact surfaces a wavy shape (Fig. 1).

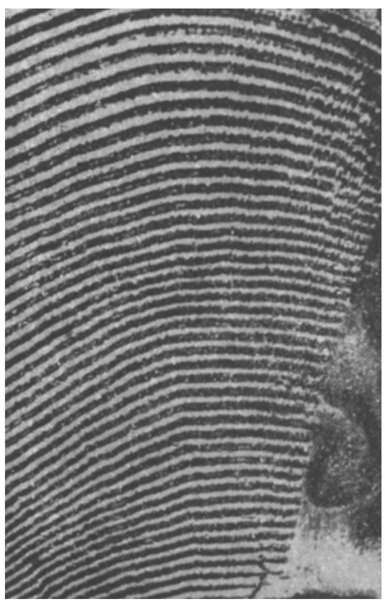

Fig. 1. View of the contact surface of an aluminum plate after impact.

The actual formation of waves as a result of the high-speed impact of metal plates was observed as long as 40 years ago by a group of scientists working on special shaped charges, under the leadership of Academician M. A. Lavrent'ev. Similar effects were also noted in the metal cladding of special structures at the points of impact of high-velocity bodies.

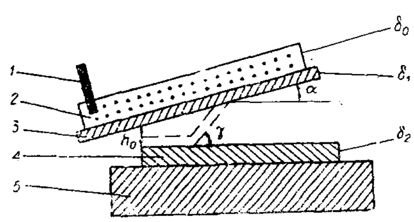

Fig. 2. Diagram of experimental setup: 1) detonator cap, 2) explosive charge, 3) projected plate, 4) fixed plate, 5) rigid base.

The first report on wave formation associated with the high-speed impact of two metal bodies was made in 1954 [1]. At the beginning of the sixties it was observed that the waves formed when metal plates collide promote the formation of a strong joint [2, 3]. The positive effect of wave formation in connection with explosive welding is evidently attributable to the following principal factors.

1. During wave formation most of the initial kinetic energy of the projected plate is converted not into compressive energy, but into energy of plastic wave flow, with subsequent conversion into heat. This prevents the development of tensile stresses during unloading, which might destroy the joint, and the metal in the joint zone is strongly heated, which in most cases favors the formation of a strong bond.

2. Wave formation is accompanied by the formation of a zone of interpenetration of the surface layers of the metals, in which both welded components are simultaneously present. The existence of this zone is attributable to purely mechanical processes associated with wave formation.

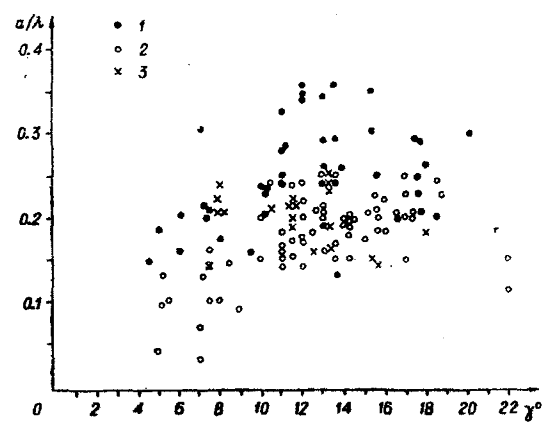

Fig. 3. Ratio of wave amplitude to wave length as a function of the impact angle: 1) Cu + Cu; 2) St. 3 + St. 3; 3) D16T + D16T.

3. Wave formation involves the active destruction and removal of the oxide films and the contaminants always present on the contact surfaces of welded plates. In this case part of the surface layer in the form of individual particles or larger formations is generally removed from the joint zone and a considerable part of the surface is completely cleaned.

4. Wave formation increases the total surface of the joints.

Thus, the process of wave formation is not only of independent scientific interest, but also of practical value in relation to the more general problem of explosive welding. This paper is concerned with a study of the effect of the initial impact parameters on wave formation and the establishment of the critical conditions under which wave formation takes place.

In the experiments we used the setup illustrated in Fig. 2. In most of the experiments we employed plates of standard area (50 × 200 mm). If the thickness of the projected plate exceeded 4 mm, the area of the plates was increased in order to eliminate the influence of the curvature of the projected plate due to unloading effects associated with expansion of the explosion products from the lateral faces of the charge.

The exact shape of the waves was established by photographing the microstructure of the welded joint. The corresponding thin section was always cut from the central part of the welded specimen. Under the microscope for each section we determined the amplitude a and length λ of 25–75 different waves, and then found the corresponding means. This method made it possible to determine the dimensions of the waves in each individual experiment correct to 10%.

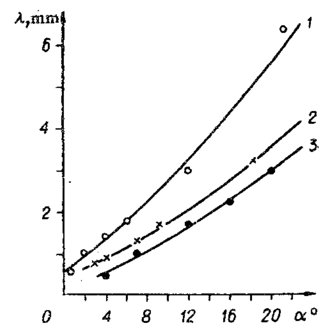

Fig. 4. Wave length as a function of initial angle: 1) D16T + D16T; 2) Cu + Cu; 3) St. 3 + St. 3.

In some experiments it was possible to separate the welded plates without serious damage; this enabled us to investigate the waves over the entire contact surface (see Fig. 1). Usually, the amplitude and length of the waves increase somewhat in the direction of propagation of the detonation front, but beneath the detonator no waves are formed at all. The wave front has the shape of an arc, whose individual elements may be somewhat displaced relative to one another.

The dimensions of the waves and their shape vary strongly as a function of the following initial impact parameters: initial angle between the plates α, the dimensionless quantity r equal to the ratio of the mass of explosive to the mass of a projected plate of the same area ($r = \rho_0\delta_0/\rho_1\delta_1$), the initial distance between the plates h_0, and the detonation velocity of the explosive (D). Here ρ_0 and ρ_1 are the densities of the explosive and the metal of the projected plate.

Under laboratory conditions it is possible to obtain waves measuring from tens of microns to 5–7 mm by varying the initial impact parameters, at this point the waves become commensurate with the thickness of the projected plate, and its outer surface acquires a wavy form. For these changes in the absolute dimensions of the waves the ratio of wave amplitude to wave length varies only very slightly, mainly in the region from 0.14 to 0.3. The corresponding experimental data were obtained as a result of analyzing 130 different experiments and are presented in Fig. 3.

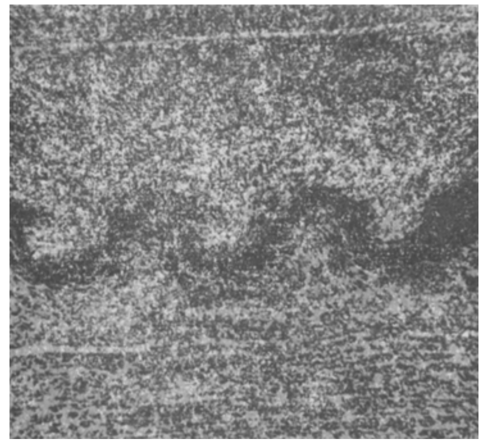

Fig. 5. Micrograph of St. 3 + St. 3 joint at $\alpha = 0$.

The small number of points lying below the indicated range of variation of q relate to critical impact regimes. In these regimes wave formation is unstable and may disappear altogether in response to a small change in the parameters. This makes it possible to select the wave length as the basic experimental parameter for the quantitative characterization of the wave dimensions.

Even in the first experiments it was established that the greatest influence on the wave formation process is exerted by variation of the initial angle between the plates α. In the first place, it was found tha when an explosive with a high detonation velocity is employed, there is a critical value of the initial angle α^* below which wave formation does not take place.

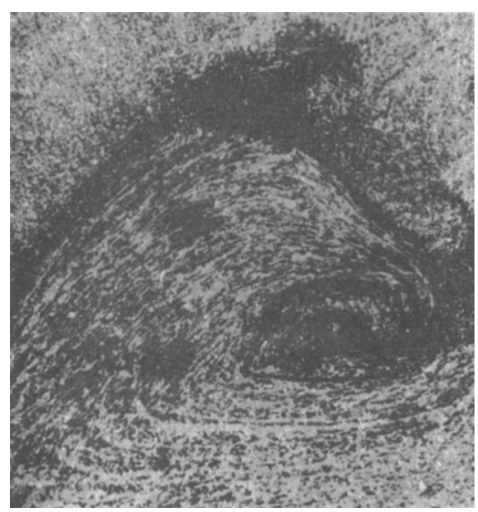

Fig. 6. Micrograph of St. 3 + St. 3 joint at $\alpha = 16°$, half-wave.

This was reported in [2, 3] and elsewhere. Secondly, an increase in the initial angle for the same charge

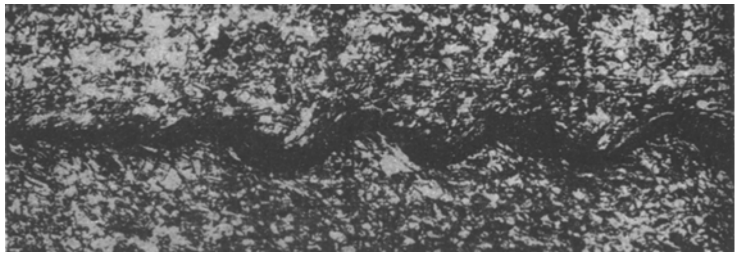

Fig. 7. Micrograph of Cu + Cu joint in the critical regime.

and initial distance between the plates (r = const, h_0 = = const) always leads to an increase in the wave dimensions [3,4].

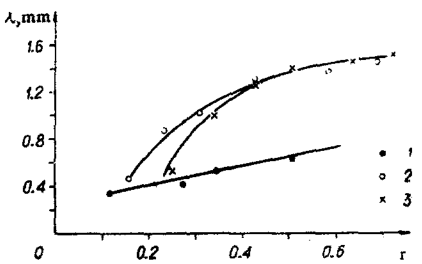

Fig. 8. Wave length as a function of the parameter r in various regimes: 1) Cu + Cu (α = = 3°); 2) Cu + Cu (α = 11°); 3) St. 3 + St. 3 (α = 9°).

The characteristics for certain like pairs of metals are presented in Fig. 4. In the case of very large angles ($\alpha \approx$ 15–30°) the waves begin to become strongly elongated and then disappear altogether. Under ordinary impact conditions this effect is sometimes observed at the very ends of the plates. Changes in the initial angle also affect the shape of the wave. Whereas at small angles the waves usually approach a sinusoidal form (Fig. 5), as the angle increases, the crests of the waves are deformed in the direction of propagation of detonation (Fig. 6).

In some cases deformation of the waves may even lead to separation and drifting of the wave crests. These changes in wave shape may be associated with an increase in the tangential component of the projected plate velocity and shearing between the impacting metals. At very large angles, before they disappear, the waves acquire a regular sinusoidal shape without any appreciable convolutions. Figure 7 shows how the waves disappear in the critical regime.

In order to investigate the effect of the size of the charge on wave formation, we performed a series of experiments in which we varied the parameter r at constant initial angles and initial distances between the plates. It was established that at any fixed initial angle there are definite critical values of the parameter r* for each metal pair below which the waves disappear. An increase in the parameter r, i.e., the thickness of the charge, always led to growth of the waves (Fig. 8).

In the following series of experiments we varied the thickness of the lower fixed plate (Fig. 9) while retaining the charge, the dimensions of the projected plate, and the relative position of the copper plates (r = const, α = const, h_0 = const). In order to exclude the effect of the rigid base the two plates together with the charge were suspended in the air.

As the initial distance h_0 between the plates is increased, the waves gradually grow to a certain limit. This indicates the need to take into account the acceleration of the projected plate when the distance between the plates is small.

The experimental data obtained do not enable us to establish directly the relation between the wave length and the velocity v_0 of the projected plate, the impact angle γ, and the velocity v_c of the contact point, since in each individual series of experiments not less than two of these parameters were varied at the same time. This follows from an examination of the equations presented in [6]:

$$v_0 = 1.2\,D\,\frac{\sqrt{1+1.18\,r}-1}{\sqrt{1+1.18\,r}+1} \tag{1}$$

$$\gamma = \alpha + 2\arcsin\frac{v_0}{2D} \tag{2}$$

$$v_c = D\,\frac{\sin(\gamma-\alpha)}{\sin\gamma}. \tag{3}$$

At the same time, calculation of the basic impact parameters in the critical regimes in which wave formation begins enabled us to establish the following features of the wave formation process.

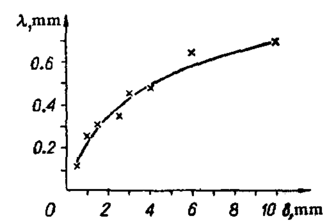

Fig. 9. Wave length as a function of the thickness of the lower plate for the pair Cu + Cu at δ_1 = 3 mm, α = 0°, γ = 10°.

1. For each fixed value of the initial angle there is a critical value of the projected plate velocity v^*_0 below which waves are not formed. These values increase significantly with increase in the initial angle between the plates. The table presents the basic im-

Impact Parameters in Critical Regimes

Type of explosive	Material of plate	δ_0, mm	δ_1, mm	α^*	v_0^*, m/sec	v_c^*, km/sec	p_c^*, 1000 atm
RDX	M3+M3	4.5	3	18°	300	0.85	30
	M3+M3	3.0	3	10°	200	0.95	40
	St. 3+St.3	4.5	3	5°	260	1.90	145
	St. 3+St.3	6.0	3	14°30′	360	2.00	160
Ammonite	D16T+D16T	10.0	10	5°	290	2.60	37
		15.0	10	8°	460	1.70	40
		25.0	10	16°	850	1.80	44

pact parameters calculated for various critical regimes. A comparison of these data shows that, irrespective of the value of the initial angle, for each metal pair there is a corresponding critical value of the velocity of the contact point v^*_c and when $v_c < v_c^*$ no waves are formed.

In order to establish the physical significance of the result obtained we will consider the motion of the plates in a moving coordinate system that moves along the fixed plate at the velocity of the contact point. In this system the collision of the two plates is similar to the meeting at an angle γ of two plane jets with flow velocities v_1 and v_2. In [6] it was shown that

$$v_1 = v_c \frac{\cos \frac{\gamma + \alpha}{2}}{\cos \frac{\gamma - \alpha}{2}}, \quad v_2 = v_c. \qquad (4)$$

In the impact regimes investigated these two velocities are roughly equal.

When the jets meet, their deceleration leads to the development of high hydrostatic pressures, whose values depend on the flow velocities v_1 and v_2. The maximum pressures possible at a given flow velocity were estimated from the formula for determining the pressures at the stagnation point:

$$p_c \approx \frac{1}{2} \rho_1 v_1^2 \approx \frac{1}{2} \rho_1 v_c^2.$$

The tabulated values of the pressures p_c^* in a number of critical regimes significantly exceed the critical yield stresses of the metals investigated [9]. Hence, one of the necessary conditions of wave formation is the presence in the impact region of pressures sufficient to produce plastic deformation of the metals. Under these conditions the strength forces are much lower than the inertial forces, and therefore it may be assumed that the mechanism of wave formation is a hydrodynamic problem. This assumption is confirmed by other authors [3, 5, 8].

2. In numerous experiments on the collision of plates projected by a charge of powdered RDX (D = = 6.2 km/sec), calculations of the contact point velocity have shown that wave formation takes place when that velocity is less than the speed of sound in the metals and the flow in the moving coordinate system is subsonic. If this criterion were valid, waves might be expected to be formed even when the plates were parallel ($\alpha = 0$), if an explosive with a detonation velocity less than the speed of sound were used. This follows directly from Eqs. (3) and (4). The first experiments in which ammonite No. 6 with a detonation velocity of 3.5–4 km/sec was used confirmed this conclusion. As a result the technically more convenient parallel-plate welding scheme was proposed.

These experimental data indicate that the high-speed impact regime changes sharply in the region of transition from sonic to supersonic flow. Such changes were theoretically predicted by Walsh, Shreffer, and Willig [7]. These authors established the existence of three different regimes: 1) subsonic flow $v_1 < c$, $v_2 < c$; 2) supersonic flow at angles exceeding the critical angles $\gamma > \gamma_{cr}$; 3) supersonic flow at angles $\gamma < \gamma_{cr}$. In the first two regimes, according to the data of [7, 8], a shaped-charge jet is formed, while the third corresponds to a jetless configuration with stable diagonal shocks starting from the impact point. The critical angles in various regimes were calculated in [5, 7, 8].

On the basis of an analysis of experiments on the impact of bullets against thin targets, Abrahamson [5] suggested that the criteria of wave formation coincide with the critical conditions for the formation of a shaped-charge jet. This conclusion is confirmed by the experimental data presented above. Wave formation in the second regime ($v_1 > c$; $\gamma > \gamma_{cr}$) was observed in special experiments on copper plates projected by a charge of 50/50 Composition B with a detonation velocity of 7.6 km/sec. Wave formation was recorded in the following regimes: $v_1 = 4.8$ km/sec, $\gamma = 8°$, $\gamma_{cr} = 4°$, and $v_1 = 5.1$ km/sec, $\gamma = 15°$, $\gamma_{cr} = = 6°$. We note that for other metals the second impact regime is not easily realized. Therefore, for purposes of welding metals and investigating the process of wave formation it is usual to employ subsonic regimes, in which the impact is sufficiently strong ($v_1 > > v_1^*$, $p_c > p_c^*$) and the velocity of the contact point is less than the speed of sound in the metals.

Our experimental material on the influence of the initial parameters on wave formation can be used to establish certain laws which we have employed constantly in making a more detailed study of the effect and in developing technical specifications for welding new pairs of metals and large sheets. These results will be described later in connection with a discussion of the mechanism of wave formation.

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