Plastic deformation and wave formation on the interface of metals welded by ultrasound-assisted explosive welding

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Abstract. This paper presents the influence of the effect of ultrasound on the wave formation and plastic deformation in the metals welded by ultrasound-assisted explosive welding. It has been established that the influence of high-frequency acoustic waves on the metal leads to a reduction of the dynamic yield stress, which in turn leads to changes in the properties of the surface layers of metal and in the conditions of bonding between the collided plates upon explosive welding. It has been shown that the changes in the length and amplitude of waves that arise in the weld joint upon the explosive welding with the simultaneous action of ultrasonic vibrations is connected with a decrease in the magnitude of the deforming pulse and time of action of the compressive stresses that exceed the dynamic yield stress behind the point of contact.

1. Introduction
The high-speed collision of bodies upon the explosive welding is accompanied by a number of unique effects and phenomena, including wave formation, intense strongly-localized plastic deformation of the metal in the heat-affected zone, cumulation, and seizure of metals [1, 2]. At the same time, in a number of cases upon the explosive welding local regions of fused metal are formed in the weld joint, which decrease the strength and service properties of the welded composite. These regions are especially dangerous in the composites in which the base layers may interact and form intermetallic compounds, such as Cu + Al, Al + Fe, etc. It was shown that the formation of alloys is a consequence of shear plastic deformation, which leads to a nonuniform the uneven heat release in the welding joint [3–5].

Earlier [6], we carried out original studies of the metal bonding upon the explosive welding under the action of ultrasonic vibrations. It has been established that the action of ultrasonic vibrations on the zone of the formation of the weld joint in the process of explosive welding exerts a substantial influence on the structure and properties of the obtained joints, which manifests in a significant decrease in the parameters of the arising waves and in an increase in the microhardness of the metal of the heat-affected zone near the weld.

Changes in the microstructure were found (on the example of copper), which manifest in a decrease in the size of the blocks of the mosaic and an increase in the textural (second kind) stresses compared with the standard sample with an equilibrium structure. It has been shown that a change in the size and structure of the deformed zone upon the explosive welding with the application of ultrasonic vibrations is the result of the simultaneous action of these processes at the stage of the formation of the joint and it is almost independent of the original fine structure of the material.
However, the problem of the influence of the amplitude and frequency of ultrasonic vibrations on the structure and properties of weld-joint zone remains open. The study of this problem is the purpose of this work.

2. Materials and methods
In experiments, we used as the objects of investigation aluminum AA1135 4 mm thick and as-annealed copper C11000 3.5 mm thick.

Explosive welding was carried out simultaneously with ultrasound vibrations supplied to a based plate in an explosion chamber according to the propagation of ultrasonic vibrations to the welding direction (Figure 1) [7]. A piezoceramic transducer was attached to a fixed plate with a metal rod welded to it. The distance between the based plate and the piezoceramic transducer in all experiments was kept constant (no more than 100 mm), and an ultrasonic generator was located outside the explosive chamber where it was turned on 30-60 seconds before detonating an explosive charge. For the sake of comparison, the same metal pairs were explosively welded under the same conditions without ultrasound processing (reference samples) (Figure 1, (4)).

Parameters of explosive welding regimes (Vc is the velocity of the collision point and Vi is the velocity of the impact) were calculated using an EW Calc application software package [8]. The detonation velocity of an explosive substance was controlled by electrocontact method. Time registration was conducted with ChZ-63 electronic frequency meters.

As the source of ultrasonic waves, we used a UZGI-2 setup with a piezoceramic converter and with a waveguide in the form of conical and stepped concentrators, which are characterized by a minimum coefficient of transformation and by a wide range of the amplitudes of vibrations.

An OLYMPUS BX61 optical microscope was used for metallographic studies.

To study the features of plastic deformation of near-weld volumes of metal under the conditions of high-speed glancing collision, we used the procedure [7] based on the use of the model of layered samples with a thickness of the layers of 50 μm. Explosive welding with the simultaneous action of an ultrasound on the fixed plate was implemented using regimes that ensured the formation of a sinusoidal profile of the welding-joint line. For a comparison of the obtained results, the explosive

Figure. 1. Schematic illustration of ultrasound-assisted explosive welding: (1) electric blasting detonator, (2) explosive charge, (3) flyer plate, (4) still (reference) base plate, (5) vibrating base plate, (6) supporting feet, (7) waveguide, (8) piezoceramic transducer and (9) ultrasonic generator.
welding of the same pairs of metals was also performed using identical regimes, but without the action of ultrasound (control samples).

3. Results and discussion
The research showed that the ultrasound-assisted explosive welding has a significant effect on the structure and properties of the heat-affected zone of the formed joints. The greatest changes are observed in the case of the oppositely directed ultrasonic vibrations relative to the welding direction, which will be further analyzed (hereinafter referred to as test samples). Under the action of oppositely directed longitudinal ultrasonic vibrations, parameters of the wavy interface of the welded aluminum joint (Figures 3 b, 3 c) decreased almost three times to yield an average wave height $2a \approx 0.18$ mm and wavelength $\lambda \approx 0.36$ mm, whereas for the reference samples $2a \approx 0.56$ mm and $\lambda \approx 0.88$ mm (Figures 3 b, 3 c). A similar effect was observed in the case of the explosive welding of the copper samples (Figures 2 b, 2 c).

The study of the plastic deformation of the metal in the heat-affected zone upon the explosive welding of uniform aluminum and copper plates under the action of ultrasound revealed the following features.

![Figure 2](image-url)

**Figure 2.** Diagrams of the maximum shears $g_{\text{max}}$ (a) and the deformation of the transverse layered model of a copper joint in (b) control sample without the application of ultrasound and (c) in a sample with the action of ultrasound.

Upon the explosive welding with the simultaneous application of ultrasound, the maximum residual shearing deformation $g_{\text{max}}$ measured in the close proximity to the conditional line of joining of the layers is about 155%. At the same time, in the control sample obtained under identical conditions
of explosive welding but without the application of ultrasound, the shearing strain is smaller, i.e., $g_{\text{max}} \sim 130\%$. With moving from the line of joining, $g_{\text{max}}$ decreases sharply with a slightly different gradient (Figure 2 a). A similar distribution of the residual shearing deformation $g_{\text{max}}$ is also observed in the case of the welding of model aluminum plates (Figure 3). Thus, following the explosive welding with the action of ultrasound the maximum residual shearing deformation $g_{\text{max}}$ measured in the close proximity to the conditional welding joint line (WJL) in the aluminum samples is about 175%, whereas in the control sample without the action of the ultrasound, the values of $g_{\text{max}}$ are $\sim 155\%$.

The analysis of the distribution diagrams of $g_{\text{max}}$ and of the microstructure of copper and aluminum samples show that, together with an increase in the maximum values of $g_{\text{max}}$ and a decrease in the parameters of the interface between the layers, a larger volume of metal is involved into the plastic deformation upon the explosive welding under the action of ultrasound (Figures 2, 3). It is also worthwhile to note that the values of the residual shearing strain $g_{\text{max}}$ measured at the identical distances from the conditional WJL are different for the samples with the application and without the application of the ultrasound. Taking into account the results obtained in [6, 7], the following assumption can be made. Upon the action of ultrasonic vibrations on the metal, an acoustoplastic effect takes place in it, which consists of a reduction in the yield stress of the material at a constant rate of deformation.

As a result, smaller power expenditures are required for the dislocations and vacancies to overcome barriers; thus, they can easier move and interact with each other. In turn, this leads to changes in the

![Figure 3. Diagrams of maximum shears $g_{\text{max}}$ (a) and deformation of transverse layered model of an aluminum joint in (b) control sample without the application of ultrasound and (c) in sample with the application of ultrasound.](image)
plastic properties of the surface layers of metal and to changes in the conditions for the formation of the bond between the colliding plates.

Let us try to explain the change of the parameters of the wave in the weld joint zone taking into account the results of the works [5, 9–11], in which it has been shown that the area limited by the diagram of \( g_{\text{max}} \) is nothing but the work of deformation determined by the following dependence [5, 8]:

\[
A = S_k \int_0^\delta \varepsilon(y) dy
\]  

(1)

where \( \varepsilon(y) \) is the current magnitude of the degree of deformation; \( \delta \) is the thickness of the plate investigated; and \( S_k \) is the resistance of the material to deformation (or the maximum strength of the material, which depends on the ultimate tensile strength and relative reduction in area), which is numerically equal to the dynamic yield stress (640 MPa for copper; and 108 MPa for aluminum).

Note that the experiments were carried out under the identical conditions, where the energy spent for the plastic deformation \( (W_2) \) of the metal of the heat-affected zone upon the explosive welding was constant.

However, in all series of experiments with the application of high-frequency acoustic vibrations, we observed an increase in the area (25–35% on average depending on the grade of the material in the \( g_{\text{max}} \)-\( y \) coordinates) limited by the \( g_{\text{max}} \) diagram. An increase in this area indicates an increase in \( W_2 \), which is impossible, since the energy introduced by the high-frequency acoustic wave into the system under consideration is less by several orders of magnitude than that that comes from the explosion welding.

It is logical to assume that an increase in the area of the diagram of \( g_{\text{max}} \) upon the explosive welding with the application of ultrasound is connected with the change in the dynamic yield stress due to the development of the acoustoplastic effect. Based on the obtained diagrams of \( g_{\text{max}} \), it is not difficult to estimate the values of the dynamic yield stress under the action of ultrasound for copper we obtained 458 MPa and 71.9 MPa for aluminum, respectively.

It has been shown in [5, 9–11] that the sizes of waves that rise in the weld joint zone are caused by the magnitude of the deforming pressure impulse \( I_d \) calculated through the following dependences:

\[
I_d = \int_{\tau_p}^{\tau_\text{p}} P_{\text{max}} e^{-\tau/\theta} d\tau = P_{\text{max}} \theta (1 - e^{-\tau_p/\theta}),
\]  

(2)

in which the rate of the pressure release \( \theta \) after the transformations (under the assumption that in the process of interaction of the collided plates the contact pressure after the time \( \tau_p \) will decrease from \( P_{\text{max}} \) to \( \sigma^d_t \)) takes on the form

\[
\theta = \frac{\tau_p}{\ln \frac{P_{\text{max}}}{\sigma^d_t}},
\]  

(3)

The peak pressure \( P_{\text{max}} \) of the pulse is determined by the dependence [12]

\[
P_{\text{max}} = \frac{\rho_1 c_{o1} \rho_2 c_{o2} - V_c}{\rho_1 c_{o1} + \rho_2 c_{o2}},
\]  

(4)

(where \( \rho_1, \rho_2 \), and \( c_{o1}, c_{o2} \) are, correspondingly, the densities and the speeds of sound in the flyer plate and in the fixed plate, respectively) and changes exponentially; according to [13], the time of the interaction of the metals

\[
\tau_c = \frac{2 \delta_{\text{min}}}{c_o},
\]  

(5)

where \( \delta_{\text{min}} \) is the minimum thickness of the plate and \( c_o \) is the speed of sound.
The calculations according to the dependences (2‒5) show that the decrease in the time constant \( \theta \) reduces the value of the deforming pulse \( I_d \) (for copper with 4 kN\( \cdot \)s/m\(^2\) to 3.35 kN\( \cdot \)s/m\(^2\) and for aluminum from 0.9 kN\( \cdot \)s/m\(^2\) and 0.8 kN\( \cdot \)s/m\(^2\)) and the time \( \tau \) of the action of the compressive stresses that exceed after the point of contact at which the plastic flow of metal can occur. This is apparently one of the main factors that are responsible for a change in the length and amplitude of the wave in the weld joint zone upon explosive welding under the action of high-frequency acoustic vibrations.

4. Conclusions

The action of vibrations exerts a substantial influence on the structure and properties of the weld joint zone of copper and aluminum plates bonded using explosive welding, the parameters of the waves decrease by 2.0–2.5 times, there are hardly any regions of fused metal, and the strength of the tearing-off of the layers increases by 15–20% compared with samples obtained by explosive welding without the application of ultrasound.

It has been established that the influence of high-frequency acoustic waves on the metal leads to a reduction of the dynamic yield stress, which in turn leads to changes in the properties of the surface layers of metal and in the conditions of bonding between the collided plates upon explosive welding.

It has been shown that the changes in the length and amplitude of the wave in the weld joint zone upon the explosive welding under the action of high-frequency acoustic waves is connected with a decrease in the magnitude of the deforming pulse and the time of action of the compressive stresses that exceed the dynamic yield stress beyond the contact point at which the plastic flow of the metal is possible.

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