Features of behavior of the contact boundary of metals during explosion welding: Numerical simulation

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Abstract. The results of numerical simulation of wave formation under an oblique impact of metal plates during explosion welding are presented. The numerical simulation was carried out on the basis of the elastoplastic approximation. It is shown that the elastoplastic behavior of metals may be a possible source of instabilities. Further evolution of the process of wave formation and the formation of a periodic wave structure of the interface are already determined by the hydrodynamic behavior of materials. The temperature at the contact boundary of plates obtained in the calculation exceeds the melting point. The calculated wavelengths coincide with the experimental data.

1. Introduction
The explosion welding still attracts the attention of many researchers [1–8]. This is due to several reasons. First, the compound of any metal couples can be obtained during the explosion welding, what is unattainable by any other type of welding. Second, there is no universally accepted physical theory describing the phenomena accompanying this process. In particular, there is no satisfactory theory of wave formation. The lack of correct understanding of the nature of waves on the contact boundary of metal plates naturally inhibits the development of the explosion welding technology, because the weld parameters (amplitude and wavelength) are actually unpredictable. Significantly greater progress has been made in the area of experimental investigation. It was found that the phenomenon is observed only under the certain impact parameters. The main ones are the speed of the contact point and the impact angle.

In this paper we model (using equations of state for real materials and models of elastoplastic behavior) the process of wave formation under an oblique impact of metal plates during explosion welding.

2. Explosion welding. Features of wave formation. Well-known concepts of wave formation phenomena
Interesting in terms of High Pressure Physics the wave formation phenomena on the contact boundary of metal plates acquired a great practical importance in the early 1960’s when the explosion welding and its related phenomena started to be systematically investigated. It is known a large number of works, both experimental and theoretical, in which several concepts of
the mechanism of wave formation are presented: Abrahamson mechanism [9]; Bahrani, Black, Crossland mechanism [10]; mechanism of Kudinov and Koroteev [11]; Hunt concept [12]; wave formation and Karman vortex street [13]; Robinson concept [14]; concept of Godunov, Deribas and Kozin [15]; wave formation within the framework of the theory of elasticity [16]; capillary wave generation theory [17].

2.1. The wave formation within the framework of the theory of elasticity
Godunov and Sergeev-Albov [16] considered the problem of the collision of the plates in the elastic formulation based on plastic deformation in a small neighborhood of the point of contact through the introduction of a point source of the Maxwell stress relaxation. As a result of this task, they came to the conclusion that if in the vicinity of the contact point there is no mass outflow, i.e. cumulative jet is missing, the stressed path will be formed on the connection line of the plates. If there is a mass outflow of a certain intensity, the stressed path is not formed. Considering the stressed path as an elastic rod under longitudinal load, the authors identify the wave formation during the explosion welding with the loss of stability of this rod.

2.2. The mechanism of Kudinov and Koroteev
By analyzing the experimental data, the authors of [11] concluded that the coincidence of the criteria jet- and wave generation still does not define the role of the jet during the wave formation, but only indicates the possibility of deformation or buckling of the free surfaces of two plates in front of the point of contact. Assuming that the buckling have a shape of humps, the formation of waves can occur as a result of alternate occurrence of deformation humps in front of the contact point.

In addition, the authors of [11] carried out a quantitative evaluation of the wave parameters based on a qualitative description discussed above. The resulting expression for the wavelength is in satisfactory agreement with the experimental data presented in [1].

3. Numerical simulation. Setup of the problem and the models used
3.1. Numerical method
The numerical method [18] is based on a Godunov type scheme that has a second order of accuracy in space. The curvilinear rectangular moving grids are used. The computational
domain is divided into several sub-areas so that their boundaries were either material boundaries or shock fronts, and moved accordingly. The square covered by the grid grows with the expansion of the boundaries. To maintain a given spatial resolution the number of grid cells automatically increases.

The code is implemented in two versions. In the first one the system of Euler equations and in the second one the equation for an elastic body with ideal plasticity by the method proposed in [19, 20] are integrated.

3.2. The initial setup

It is calculated the collision of two copper plates in the initial setup, where a stable wave formation has been observed in the experiments. The thickness $\delta_1$ of the top plate is 2.5 mm, the bottom plate thickness $\delta_2$ is 5 mm, the collision angle $\gamma$ is $20^\circ$. The upper plate at a speed

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**Figure 2.** The initial stage of the wave formation, 0.3 $\mu$s. Stress deviator tensor components (GPa): $S_{11}$ (a); $S_{22}$ (b); $S_{12}$ (c).
Figure 3. The initial stage of the wave formation, 1 µs. Stress deviator tensor components (GPa): $S_{11}$ (a); $S_{22}$ (b); $S_{12}$ (c).

of 1 km/s, directed normal to the surface, impacts on the lower, fixed plate. The speed of the contact point is approximately 2.92 km/s. Bulk speed of sound in copper is about 4 km/s. That is, it is as usual for explosion welding, subsonic regime, for which there is no analytical solution with attached shock waves as in the supersonic case. The problem is solved in the coordinates where the point of contact is fixed, and the contact boundary between the plates is oriented along the axis $X$. In these coordinates, the velocity components along the $X$-axis are $-2.67$ km/s for the upper plate and $-2.91$ km/s for the lower plate. So the difference between them is $0.24$ km/s. In $Y$ direction the velocity components are $-0.65$ km/s for the top plate and $+0.32$ km/s for the bottom one.

The scheme of the initial setup with the boundary conditions is shown in figure 1. All boundary conditions are “free” excluding top fluxing boundary and bottom fluxing boundary where the matter flows inside under normal conditions with fixed correspondent velocities. In these calculations, the contact boundaries of the plates are not allocated. The substance of one
plate can flow into the other, whereby the interaction mode is carried out with strong adhesion. The same should be said about the interaction of the cumulative jet with plates.

The wide-range equation of state for copper was used [21]. The copper is under normal conditions at the initial moment. The elastoplastic behavior of copper was simulated under the ideal plasticity theory. We used the following parameters [22]: the shear modulus of 48.7 GPa, the yield strength of Mises of 0.4 GPa.

4. The simulation results
The simulation was performed in full elastoplastic formulation until the formation of a stable wave pattern.

The process of wave formation observed in these calculations can be divided into two parts: the initial stage of the loss of flow stability and the advanced wave formation stage.

4.1. The initial stage of the loss of flow stability
Up to the time of 0.5 $\mu$s, the interface between the plates is smooth, the jet formation is not observed. Nevertheless, the stress deviator tensor components are already experiencing disturbance (figure 2). In figures 2a and 2b the wave structure characteristic for the instability of shear flows is shown. It should be noted that the stress deviator tensor component $S_{12}$ is also experiencing oscillations at the contact point in the top plate (figure 2c).

Between 0.5 $\mu$s and 1 $\mu$s the nature of oscillations at the interface is dramatically changing. Strong oscillations of stress deviator tensor occur along the contact boundary (figure 3).

Thus, we can say that at the initial stage the elastoplastic behavior may be the source of the loss of stability, which is consistent with the conclusions of [16], where the wave formation in welding explosion was linked to the loss of stability of an elastic rod, which occurs between the colliding plates.

4.2. The advanced wave formation stage
Further, from 1 $\mu$s and up to about 2 $\mu$s, an increase of the amplitude and wavelength is observed in the calculation. The elastoplastic behavior of the material plays an important role, but not decisive. The hydrodynamic behavior is coming at the forefront and the wave formation takes place according to the mechanism proposed by the authors of [11].

The hump formed on the free surface of one of the plates increases due to the incoming of the plate material to the back jet until it does not collide with the free surface of the other plate. Its collision with another plate deforms the free surface of the latter and leads back to the forming of the back jet on this plate, and respectively to the forming of the hump in reverse. The process is repeated cyclically.

Figure 4 shows the pressure distribution at different times. It can be seen that the point corresponding to the maximum of pressure fluctuates in the vicinity of the contact point. It is displaced alternately, in the upper or in the lower plate. Accordingly, the localization of the maximum pressure corresponds to the top of the hump in the Kudinov–Koroteev mechanism.

This process can be better illustrated by the figure 5, which shows the component of the stress deviator tensor $S_{22}$ at the different time points. In this figure the characteristic wave structure is clearly observed. The humps correspond to the maximum value of $S_{22}$ along the contact line. Waves on the boundary line can be determined by the minimum value of $S_{22}$.

From a comparison of the maximum pressures and stresses in figures 4 and 5 one can say that the wave formation process is hydrodynamic and the elastic forces do not play a decisive role in it.

After 2 $\mu$s the typical explosion welding wavy structure of the contact gap have already been formed.
Figure 4. The advanced wave formation stage. Pressure (GPa) at different time points: 1.5 µs (a); 2.0 µs (b); 2.25 µs (c); 2.5 µs (d).
Figure 5. The advanced wave formation stage. The stress deviator tensor component $S_{22}$ (GPa) at different time points: 1.5 $\mu$s (a); 2 $\mu$s (b); 2.5 $\mu$s (c).

Figure 6. The calculated wavelength. The stress deviator tensor component $S_{11}$ (in GPa) is presented. The dotted line is the boundary between plates.
Figure 7. Temperature (K) at different times: 0.5 µs (a); 1.5 µs (b); 2.0 µs (c); 2.5 µs (d).
In this calculation we observed the formation of cumulative jets. And at first glance it looks like that they are triggers of hump formation. But cumulative jets in the calculations consisted of strongly heated metal with low density and did not play a significant role on the hydrodynamics of the calculation, which coincides with the conclusions authors of [11] about the role of the cumulative jet in wave formation.

The calculated wavelengths correspond to the experimental (see figure 6, the wavelength calculated according to the empirical formula $\lambda = 32\delta_1 \sin^2(\gamma/2) \approx 0.2412$ cm [23]).

4.3. The temperature in the contact area

The mathematical simulation was carried out on the basis of the equation of state with temperature. It is shown that the braking process in the contact area is accompanied by local heating of the substance to temperatures above the melting area (figure 7).

5. Discussion

Despite the fact that the modeling is somewhat idealistic, however, it has shown that the elastoplastic behavior of metal during explosion welding contributes significantly to the dynamics of the process. At the initial stage the elastic behavior may be the source of the initial perturbation, leading to the further growth of instabilities.

The further evolution of instabilities in this calculation is to have a predominance of inertial forces or, in other words, hydrodynamically. And taking into account that in the calculation the copper, quite soft material, is simulated, the elastic forces do not play a determining role. Nevertheless, it is worth noting that for small angles of impact and sufficiently rigid materials may exist regimes where the elastic forces will be comparable to the hydrodynamic and significantly affect the nature of the wave formation.

In addition, the simulation did not take into account the effect of high explosive (HE), despite the fact that the process is called explosion welding. Test calculations using explosives indicates that the material of the accelerated plate is compressed much longer than in this calculation. Furthermore, interaction HE with plate serves as an additional source of elastic waves, resulting in loss of stability. That requires a separate study.

6. Conclusion

Numerical simulation of the explosion welding process on the basis of the elastoplastic approximation has shown that the elastoplastic behavior of metals can be a possible source of instabilities growth to wave formation at the interface of welded plates. Further evolution of the process of wave formation and the formation of a periodic structure of the waves at the interface is already determined by the hydrodynamic behavior of materials and mechanisms Kudinov–Koroteev. The welded plates are heated at the contact boundary above the melting temperature. The additional evidence of the adequacy of the simulations is the fact that the wavelengths obtained in the calculation correspond to the experimental.

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