Calculation of the optimal corrugation of the plate surface for explosive welding

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Abstract. This article suggests profiling the surface of one of the welded plates in a special way during explosion welding. The principle and method of calculating the profile of the plate based on the materials and welding speeds of the plates are given. It is assumed that such profiling of the surface of the plate will allow to obtain more durable welded joints and even perform welding at a speed below the minimum collision speed for welding plates with smooth surfaces. As an example, a full calculation of plate profiling for specific collision parameters of welded plates is given.

1. Introduction
Explosive welding has a long history dating back to the 40s of the 20th century. A good historical review of domestic and foreign works, explosion welding models that have not lost their relevance, and references to the literature are given in [1]. More modern review can be found, for example, in the article [2]. In recent years, thanks to the development of computer technology and computer technology, it has been possible to obtain results that coincide with a wide range of experimental data. The last most impressive results were obtained in the works of numerical modeling using the SPH (smooth particle hydrodynamics) and ALE (arbitrary Lagrangian-Eulerian) methods [2–5], with the help of mainly commercial codes such as AUTODYN, CADFEM of ANSYS suite of software. Studies on the influence of the shape of roughness on explosive welding are not widely known and I could not find them in literature.

Explosive welding with explosive is carried out at an oblique collision of plates at some angle $\alpha_c$, and the velocity of the contact point, with a parallel arrangement of plates is equal to the speed of detonation $D_{\text{exp}}$, which in turn, usually below the speed of sound in welded materials. In [6] it was shown that for a given collision velocity of plates, there is an optimal collision angle $\alpha_{\text{opt}}$, at which the maximum compression and heating is achieved along the contact line of these plates. The speed of the contact point, in this case, is equal to the speed of the shock wave (SW) propagating along the contact $D_{\text{opt}}$. In the presented work, it is proposed to use a special corrugation of one of the plates like a saw with a triangular teeth to achieve that on the front slope of the tooth, the plates contact at an angle $\alpha_{\text{opt}}$ with the corresponding speed of the contact point $D_{\text{opt}}$, while the average speed of the contact point remains $D_{\text{exp}}$. 
Figure 1. Profile construction scheme for the case of movement of the local contact point from the base to the top of the tooth: O marks the beginning of the interaction of the falling plate 2 with the fixed plate 1.

2. Method for determining the surface corrugation profile

For simplicity, we first restrict ourselves to the case of welding plates from one material. The corrugation is supposed to be applied to the surface of the lower fixed plate in the form of parallel strips across the direction of motion of the detonation front. The triangular corrugation profile applied to the plate is a sequence of identical teeth, the cross section of which is an non-equilateral triangle.

2.1. Method 1

Assuming the beginning of the interaction of the plates at the base of the tooth, we determine the slope of the front surface of the tooth from the base of the triangular tooth to the top so that the local speed of the contact point is equal to $D_{\text{opt}}$. The second slope is defined as the shortest path to the base of the next tooth, i.e. in the direction of the velocity $U$ of the falling plate.

The profile construction scheme is shown in figure 1. The surface of the falling plate is drawn in red by a solid straight line. The red dashed line represents the new position of the surface of the falling plate displaced in a single time step with a speed $U$. Since a single time step is assumed, the velocity and displacement vectors are drawn identically, therefore, by the vector $U$, we mean both the velocity and displacement vectors, depending on the context. The same applies to other vectors. The red arc is drawn from the center displaced from point O with a velocity $U$ of radius $D_2 = D_{\text{opt}}$ for the falling plate. Similarly, the surface of the fixed plate and the arc from point O with radius $D_1 = D_{\text{opt}}$ are shown in blue. The above construction serves to determine the point X of the intersection of one of the arcs with the new position of the falling plate. From [6] it is known that for a given collision velocity there are uniquely determined angles between the direction of impact and the surfaces of the colliding bodies at
Figure 2. Profile construction scheme for the case of $D_{\text{opt}} > D_{\text{exp}}$ when the local contact point moves from the top to the base of the tooth.

which maximum pressure is realized in both bodies in the vicinity of the contact point. At the same time, in explosive welding case the speed and angle between the surface of the falling plate and the direction of speed are determined by the acceleration of the falling plate by products of explosion. If the angles coincide accidentally, then a solution is found. In this case, both arcs intersect the new position of the boundary at one point. In the general case, one should choose a solution in which a strong solution with maximum pressure is realized only in one of the plates, for which the intersection point is further from point O along the line of the new position of the surface of the falling plate. The propagation velocity of perturbations along this plate will be called the leading perturbation velocity. The direction $OX$ defines the position of the front edge of the profile tooth. The height $h$ of the tooth is determined from the fact that it should be commensurate with the thickness of the weld.

2.2. Method 2

On the other hand, it is possible to form a profile from the condition that the interaction begins from the top of the tooth, then the local speed of the point of contact is directed from the top to the base in the opposite direction from the average speed of the point of contact. The position of the back side of the tooth side should be taken so that the unloading from the back side with respect to the local point of contact is not too strong, therefore, the choice in the direction of the speed $U$ may possibly set the tooth too sharp. In this case, the beginning of the next tooth should be moved away by the distance $D_2 = D_{\text{opt}} \tau$, where $\tau$ is the travel time of the local contact point from the top to the base of the tooth. The corresponding circuit is shown in figure 2.

If $D_{\text{exp}} > D_{\text{opt}}$ for the plates being welded, it is possible to implement the special mode of plate corrugation, when two contact points are formed on each vertex of the triangular profile of the corrugated surface, each of which moves at a speed of $D_{\text{opt}}$ in both directions along each of the slopes of the triangular profile until it converges with the contact point moving along the adjacent surface of the neighboring triangle. The scheme of this mode is shown in figure 3. $X_L$ is the intersection of the perturbation arc with the new location of the surface of the falling plate.
Figure 3. The scheme of building a profile for the case $D_{opt} < D_{exp}$.

on the left side, and it determines the inclination of the left side of the tooth. Similarly, $X_R$ is the intersection of the perturbation arc with the new location of the surface of the falling plate on the right side and determines the inclination of the right side of the tooth.

3. An example of calculating the optimal corrugation of a plate surface for a specific task of explosive welding
Numerical simulation was carried out in the BIG2 code based on the Godunov method with the allocation of the detonation front on adaptive moving grids [7]. The motion of the medium is described by the equations of hydrodynamics taking into account the elasticity and plasticity according to the Mises criterion. The spherical part of the stress tensor is described by wide-range equations of state for copper [8] and Mie–Grüneisen type equations for ammonia nitrate and detonation products [9].

The simulation included three stages. At the first stage, a statement was chosen for explosive welding of two copper plates using bulk explosive based on ammonia nitrate. Numerical simulation is carried out excluding plate corrugation to obtain a quasi-stationary solution in coordinates relative to the detonation front. At the second stage, the data obtained in the first calculation are used where also on the basis of numerical modeling, $\alpha_{opt}$ and $D_{opt}$ are determined. At the last stage, the corrugation profiles are determined by the above methods.

3.1. Stage 1. Numerical simulation of explosive welding of plates with a smooth surface
Consider the result of numerical simulation of the interaction of smooth copper plates in a typical formulation of explosive welding.

When one of the plates accelerated by sliding detonation hits, the second plate parallel to the first, at a certain distance from it figure 4, where numerical grids are painted in accordance with the gradations of density. The calculation was carried out in the coordinates of the detonation front with the following boundary conditions and initial data. Unreacted explosive flows into the stationary detonation front with a mass velocity equal to the detonation velocity of the explosive. Also, two parallel copper plates 3 and 4 mm thick, 6 mm apart, are continuously flowing from the right at the same speed. The boundary conditions of the rigid wall are indicated above.
Immobility is established on the left boundary with the flow condition. Figure 4 shows that the angle of incidence of the plate at acceleration by explosives is constantly changing, in addition, the interaction of the plates is carried out in subsonic mode, and the parameters of the plates before the collision, near the contact point, change rapidly as they approach the contact point, what is clearly seen in figure 5, where the picture on a numerical grid painted taking into account density gradations is shown with approximately 50x magnification of figure 4. We assume that the transverse size of the weld is about 1 mm and, accordingly, the height of the profile tooth
Table 1. Parameters are taken from calculation 1 to calculate $D_{\text{opt}}$ and $\alpha_{\text{opt}}$ in calculation 2.

| No | $D_{\text{exp}}$ (km/s) | $\rho$ (g/cm$^3$) | $P$ (GPa) | $U_x$ (km/s) | $U_y$ (km/s) | $\alpha$ (degree) |
|----|---------------------|-----------------|--------|----------|----------|---------------|
| 1  | 2.78                | 8.7             | 0.54   | -2.52    | 0.35     | -9.31         |
| 2  | 2.78                | 8.6             | 0.67   | -2.23    | -0.81    | 21.74         |

Figure 6. (a) Scheme for calculating the optimal parameters of plate collision $D_{\text{opt}}$ and $\alpha_{\text{opt}}$. (b) The pressure field.

is 0.5 mm. Based on this, we take the averaged parameters for the first and second plates from the region of 200 $\mu$m along the plates to the point of contact. As a result, we get the following data given in table 1, where $\rho$ is density, $P$ is pressure, $U_x$ is mass velocity component along the $x$-axis, $U_y$ is mass velocity component along the $y$-axis, $\alpha$ is the angle of inclination to the $x$-axis.

3.2. Stage 2. Calculation of $D_{\text{opt}}, \alpha_{\text{opt}}$

For the second calculation, we take the thermodynamic parameters of the colliding plates from table 1 and the relative collision velocity $|U| = 1.2$ km/s. The optimal parameters of interaction between two copper samples are calculated by the [6] method. The calculation scheme is shown in figure 6(a). The calculation is carried out with the allocation of the shock wave front. The
flow field behind the SW front is covered by a numerical grid, which, in addition to the SW front, is bounded by two planes of symmetry. The pressure field as a result of the calculation is shown in figure 6(b). As a result of this calculation we get $D_{opt} = 5.87$ km/s, $\alpha_{opt} = 11.56^\circ$ while the angle between colliding plates from the calculation of stage 1 is $\alpha = 31.05^\circ$.

3.3. Stage 3. Determination of the corrugation profiles
The angle between the surface of the incident plate and the direction of velocity is in this case $90 - \alpha_{opt}/2 = 84.22^\circ$. In calculation 1, this angle is $90 - \alpha + \arctan(U_y/U_x) = 82.06^\circ$.

Calculated angles for front surface of the tooth are $\beta_1 = 19.45^\circ$ by method 1 and $\beta_2 = 42.14^\circ$ by method 2. The graphical solution for both variants is shown in figure 7(a), where all lines and vectors are drawn to scale obtained from the solution. It can be seen that upper point is almost the same as the intersection of two circles, which means that there are strong solutions with maximum pressure in both plates. On closer examination, it can be distinguished that the perturbation on the first plate is the leading one. For lower point, it is seen that leading perturbation is in the upper plate. If set the profile height to 0.5 mm, then we get the desired profiles from the teeth according to schemes 1 and 2. In figure 7(b), green color marked contours of the respective teeth, line of the incident surface of the plate at time of touching the base of the gently sloping tooth and when it touches the top of sharp tooth, and also shows the velocity vector of the falling plate.

4. Conclusions
A method for calculating the corrugation of the surface of one of the welded plates in explosive welding is proposed. Using such corrugation of the plate surface, it is expected to achieve the highest pressures and temperatures in the weld region for the specified plate collision parameters, which in turn can reduce the lower limit of the welding window.
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