UDC 621.791.13

Modeling of the Welding Process of Flat Sheet Parts by an Explosion

Mikhail A. MARININ, Sergei V. KHOKHLOV, Valentin A. ISHEYSKIY
Saint-Petersburg Mining University, Saint-Petersburg, Russia

The list of materials subject to explosive welding is very extensive and amounts to several hundred combinations of various alloys and metals, and the variety of explosive welding schemes has more than a thousand options. In almost all technical solutions, the process involves the sequential creation of physical contact of the materials to be welded and their connection due to plastic deformation of the contacting surfaces. The strength of such a connection depends on the mode of the welding process. With the correct selection of the parameters of the mode, it is possible to obtain a high-quality connection of the required strength. However, the experimental selection of such options is a very laborious and costly process.

Computer simulation and application of mathematical models for solving dynamic problems of explosion mechanics simplifies the search for optimal parameters and allows to predict the expected result in the shortest possible time. The article discusses the issues of modeling of explosive welding of metals, calculations related to the parameters of the process of formation of the weld using the Ansys Autodyn software package. A model is presented for analyzing the deformation process of explosion welding of a plate and its connection with a matrix. The main parameters of explosion welding (velocity, pressure, time) are determined. The adequacy of the obtained values was evaluated in the systems aluminum – copper and copper – steel. It also provides a comparative analysis of simulation results and field experiments.

Based on numerical calculations, a conclusion was substantiated on the suitability of the model obtained for a preliminary analysis of the main welding parameters at the preparatory stage.

Key words: math modeling; dynamic processes; deformation processes; explosive metal welding; welding process mode

How to cite this article: Marinin M.A., Khokhlov S.V., Isheyskiy V.A. Modeling of the Welding Process of Flat Sheet Parts by an Explosion. Journal of Mining Institute. 2019. Vol. 237, p. 275-280. DOI: 10.31897/PMI.2019.3.20

Introduction. Aluminum and copper are two metals that are often used in the automotive, defense, and aerospace industries due to their high conductivity and ease of fabrication. Most often, bimetallic compounds are lighter but provide the required strength. Experimental selection of the welding process parameters to obtain a high-quality description of such compounds with a certain set of parameters is a very expensive and laborious process.

Computer simulation and application of mathematical models for solving dynamic problems of explosion mechanics greatly simplifies the search for answers to theoretical and practical tasks of blasting operations. When choosing the parameters of explosive welding, the usage of mathematical modeling leads to a reduction in economic costs and time resources at the exploratory stage. A preliminary forecast of the physical result allows you to choose a reasonable process flow to achieve the desired result. By varying the installation angle of the part, the size of the initial gap, the detonation velocity of the explosive, it is possible to simulate several scenarios and obtain the parameters for the velocity at collision, the velocity of collision point movement, etc.

The basis of the mathematical model and the calculated dependencies for determining the parameters of shock-wave impact are the equations and calculations presented in [6, 8]. The kinematic and thermomechanical parameters of the process are taken from [1, 8], which consider the physical aspects of explosive welding.

The models and dependencies presented in [1, 8] have several limitations. In work [8], the considered charge and the plate without a finite length are the assumptions, which do not take into account the complexity of the wave processes at the edges of the model and, as a result, gives an incomplete picture of the formation of a weld at the extreme edges of the plate. In [1], dependences describing the complex behavior of an explosive with several assumptions are presented, as a result of which there is a heterogeneity of the detonation velocity in the explosive charge. Also, not all models consider areas of flow instability, which, in turn, are responsible for the formation of a wave pattern of the weld surface [6].

Modeling of explosive welding of composite materials. There is much software that allows increasing the accuracy of solving dynamic non-stationary problems. The integrated mathematical apparatus allows the use of complex design models in which both boundary and convergence conditions are specified for the main parameters of the process. Such software includes the Ansys, universal finite-element (FEM) analysis system with Autodyn and LS-Dyna packages. These packages are designed for explicit dynamic analysis, modeling of the highly linear dynamics of solids, liquids, gases, and their interaction [4, 11].

In solving the problem modeling explosive welding of composite materials, the main goal was to check the adequacy of the obtained values of the flying velocities and parameters of the collision of the plates. The applicability of the proposed model was estimated by comparing the calculated values with the results of the calculation of existing theoretical dependencies and their correlation with the results of model experiments.

Several problems on the propagation of a plane detonation wave in a two-dimensional formulation were solved in [6]. For composite explosives, the Wilkins – Geyrouh model was used [11]. The Jones – Wilkins – Lee equation was chosen as the state equation [12]. The calculation was made using the LS-Dyna package. Comparison of pressure values at the shock wave front showed their satisfactory convergence [3].

Formulation of the problem. Ammonite charge 6 ZhV with ammonium nitrate with a thickness of 15 mm with a 1:1 ratio of components is performed by flying a plate with a thickness of 2 mm. The process begins with point detonation; the detonator is located on the left edge in the center of the left edge of the charge. When describing the behavior of an explosive, the Wilkins – Geyrouh model was chosen [11]. The John – Wilkins – Lee model was adopted as the state equation [11, 12]. To describe the behavior of a metal plate under dynamic loading, the Johnson-Cook model [9] and the Mie – Gruneisen equation of state [14] were adopted. The solution of the problem was carried out using the multi-component Lagrange-Euler method in a plane formulation. When calculating, a finite element mesh was used, consisting of 31,212 nodes and 15,600 elements. The maximum element size did not exceed 0.1 mm. The calculation was made using the Autodyn package.

Figure 1 shows the position of the plate during the propagation of the detonation front and the distribution of the velocity of the explosion products, the main parameters of the plate collisions are the following: v_0 is the plate collision velocity, v_c is the contact point velocity, β is the angle of collision.

Discussion of results. As a result of the calculation, graphs of pressure distribution over time (Fig.2, *a*) and velocities of points of the plate by distance from the point detonation (Fig.2, *b*) were obtained. The first point is located at a distance of 15 mm from the left edge at the lower boundary of the plate; the second and third points are at distances of 30 and 40 mm.

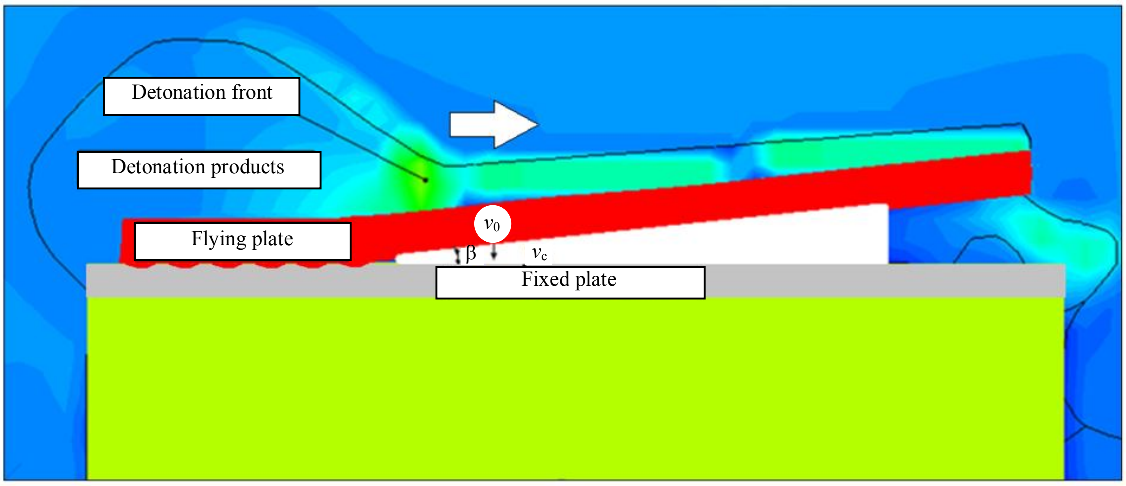

Fig.1. The position of the flying plate during the propagation of the detonation front.

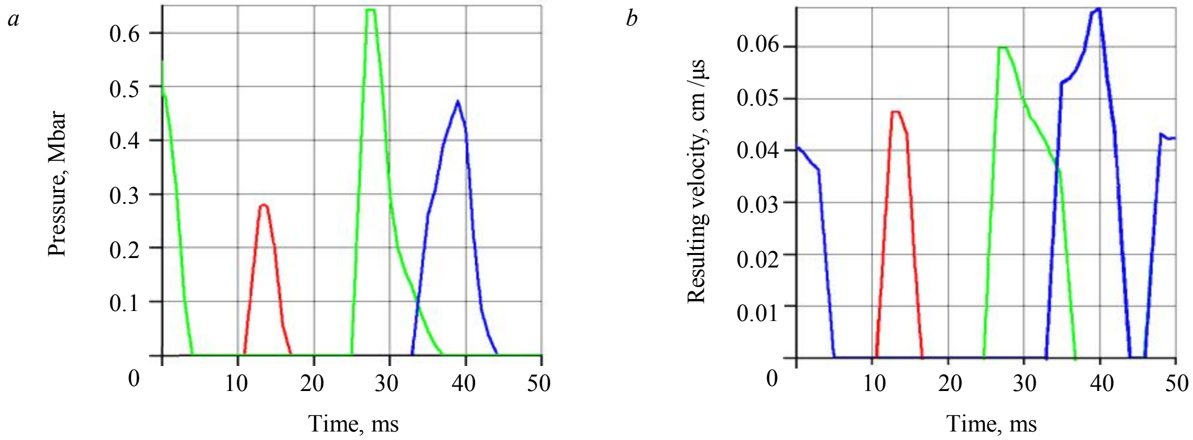

Fig.2. Distribution graphs obtained by calculating the model for pressure versus time (*a*); velocities of the points of the flying plate by distance from the starting point of the detonation (*b*).

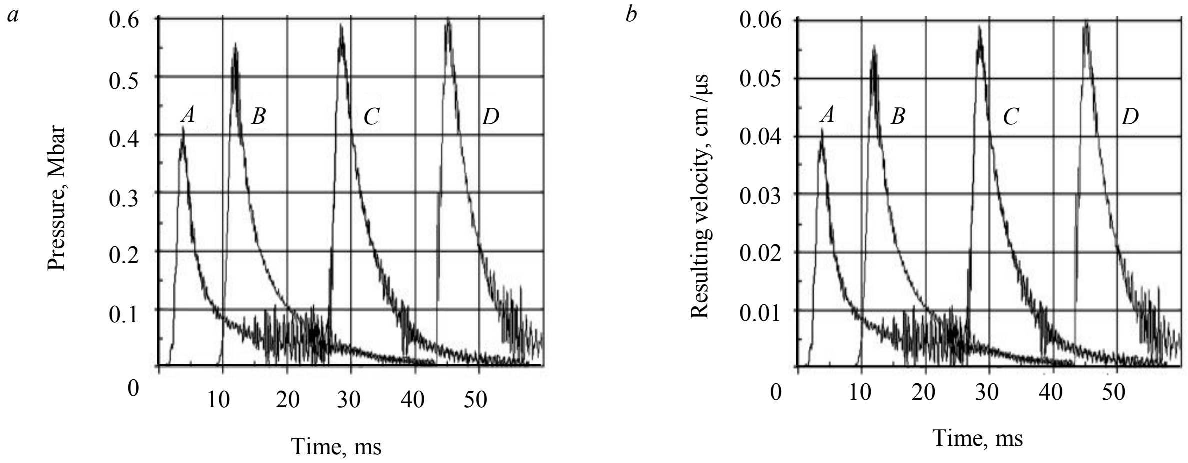

Fig.3. Distribution graphs based on the results of [3] for pressure versus time (*a*); velocities of the points of the flying plate by distance from the starting point of detonation (*b*); A, B, C, D – distance from the edge equal to 5; 20; 50; 80 mm.

Based on experimental data on the pressure distribution over time (Fig.3, *a*) and velocities (Fig.3, *b*) [3], a comparative analysis of the obtained results was carried out. It can be concluded that there is a short section at which the value of the flying plate impact angle approaches the asymptotic value. The length of the section is 45-50 mm. An oscillatory process is observed in the colliding plates behind the shock wave front. Table 1 shows the values of the velocity of the flying and the impact angle, obtained as a result of modeling, the data of [3], together with the results of the calculation according to the theoretical method [8], in which the angle of impact was determined from the expression

$$\beta = \frac{0.992r}{r + 2.71 + \dfrac{0.194}{y}}, \tag{1}$$

where $r = \dfrac{\rho_0 h_0}{\rho_1 h_1}$ – dimensionless coefficient; ρ_0 – charge density; ρ_1 – plate material density; y – the gap between flying plate and foundation; h_0 – charge width; h_1 – flying plate width.

In theoretical calculations of impact velocities for most metals, the Wittmann dependence yields significantly underestimated velocity results when welding aluminum alloys and are not applied in practice. A dependence was proposed in [10], which in most cases gives an overestimated result. In particular cases, the overestimation of the velocity values reaches 30-40 % compared with the actual experimental values.

Table 1

The values of the impact angle and the flying plate velocity

Material	Impact angle, degree.			Flying velocity, m/s		
	Calculated values	Data from [5]	Modeling	Calculated values	Data from [5]	Modeling
Aluminum	16°30'	15°30'-17°20'	16°00'-17°30'	575	540-600	520-640
Copper	8°15'	7°45'-8°40'	7°30'-8°30'°	280	270-300	250-310
Steel	9°20'	8°40'-10°35'	9°10'-10°20'	310	305-370	305-340

A more accurate result is given by the dependence proposed in [14]. However, it has a critical assumption. At large strength differences of the welded metals, the strength value is influenced by the strength of the more solid metal. The optimal value of the velocity in this case increases. Therefore, for comparison, the calculated dependence was chosen, allowing to consider the detonation rate of the explosive used. Impact velocity calculated from [8]:

$$v_0 = 2D\sin\left(\frac{\beta}{2}\right), \tag{2}$$

where D – charge detonation velocity; β – flying plate collision angle.

The calculated values of the flying velocity and the angles of the collision of the plate, the simulation results, and the data obtained in [3] are summarized in Table 1.

The discrepancy between the values of the collision angles of the flying plate for different materials, calculated from dependencies (1) and (2), the data of [3] and the simulation results do not exceed 10%. The calculation was performed for small values of the relaxation factor, which ensured high convergence with the theoretical and experimental data. Based on the results of the calculation and their correlation with the experimental results [5, 10], it can be concluded that the model is adequate and applicable to the calculation of the indicators of the impact angle.

The discrepancy between the values of the calculation of flying velocities compared with theoretical calculations was 25 %. By thickening the computational network and decreasing the iteration step, it is possible to reduce the error of the obtained results. When comparing with the results of [3], the discrepancy reaches 10 %, which is a satisfactory result.

The developed model allows making a qualitative assessment of future weld. Figure 4 shows a section of a copper-steel composite on an aluminum substrate, obtained by explosive welding [9, 13]. There are a clear wave-like line and the influx of welded metals, both during the experiment and in the model. To assess the adequacy of the model, the predicted pattern of the weld can be estimated by the parameters of the amplitude and the wavelength of the leak generated during the collision (Fig.5). Evaluation of the predicted welding result was made at the values of the flying velocities and impact angles presented in Table 1.

Analysis of the obtained results (Table 2, Fig.5) indicates a satisfactory picture and the adequacy of the qualitative process of the weld formation. The divergence of the wavelengths for the copper-steel system varies from 5 to 15 % compared with the results of [8] and from 5 to 10 % compared with the results of [3]. For the aluminum-copper system, the discrepancy varies from 10 to 20 % [8] and from 5 to 10 % [3, 7]. The divergence of the amplitude of the wave does not exceed 10 %. The obtained indicators indicate that the simulation results can be applied to predict the area of structural formation at the contact boundary of the welded metals and a preliminary assessment of the qualitative picture of the predicted weld.

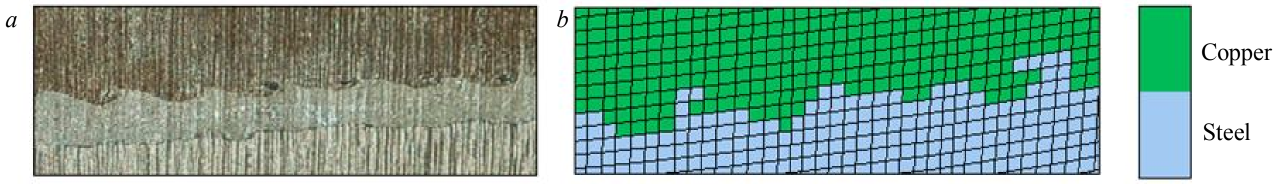

Fig.4. The microstructure of the copper – steel compound: *a* – a full-scale experiment [13]; *b* – the calculated model

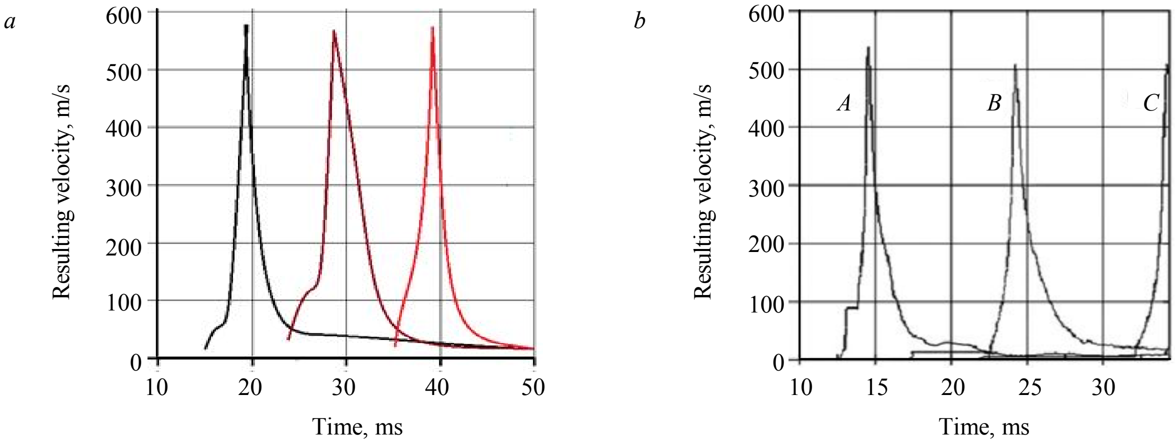

Fig.5. Graphs of the velocity dependences at characteristic points on time: *a* – modeling calculations; *b* – calculation according to the paper [3]; *A*, *B*, *C* – the distance from the edge 5, 20, 50 mm.

Table 2

Parameters of the formed weld structure

Parameters	Copper-steel			Aluminum-copper		
	Calculations	Data from [5]	Modeling	Calculations	Data from [5]	Modeling
Wavelength, microns	240	250-280	230-260	200	230-250	240-270
Double amplitude, mkm	70-80	80-90	70-85	80	70-80	70-85

Conclusions. To study and search for the parameters of the explosive welding, a series of computational experiments were conducted, the basis of which was the analysis, interpretation, and comparison of the results of computer simulation with actual results.

Based on the study of the kinetics of plate elements collision with the workpiece during explosive welding in aluminum-copper and copper-steel systems, a conceptual model for designing optimal technological processes for explosive welding using the Autodyn software package was developed. Test problems were created on its basis, and solving them gave satisfactory experimental data. The presented model makes it possible to more accurately estimate the parameters of the collision at the initial stage of acceleration, to calculate the collision speeds and the optimal parameters of the explosion welding mode to ensure the high-quality realization of the welded joint.

REFERENCES

1. Wave formation in oblique collisions: a collection of articles. Ed. bu I.V.Yakovleva. Novosibirsk: Izd-vo Instituta diskretnoi matematiki i informatiki, 2000, p. 221 (in Russian).

2. Denisov I.V., Rozen A.E., Kryukov D.B. et al. Mathematical modeling of deformation and explosive processes occurring during explosion welding. *Izvestiya Volgogradskogo gosudarstvennogo tekhnicheskogo universiteta*. 2006. N 9(24). Seriya «Svarka vzryvom i svoista svarnykh soedinenii». Iss. 2, p. 79-87 (in Russian).

3. Rozen A.E, Los' I.S., Muizemnek A.Yu., Khorin A.V., Zhuravlev E.A. Simulation of the deformation process in the tasks of reinforcement and explosion welding using the LS-DYNA program. *Tekhnicheskie nauki. Mashinostroenie i mashinovedenie*. 2010. N 1 (13), p. 123-132 (in Russian).

4. Muizemnek A.Yu. Mathematical modeling of processes, impact and explosion in the LS-DYNA program / A.Yu.Muizemnek, A.A.Bogach. Penza: Informatsionno-izdatel'skii tsentr PenzGU, 2005, p. 106 (in Russian).

5. Tyumentsev A.N., Ditenberg I.A., Pinzhin Yu.P. et al. Features of the microstructure and mechanisms of formation of submicrocrystalline copper, obtained by methods of intense plastic deformation. *Fizika metallov i metallovedenie*. 2003. N 4 (96), p. 33-43 (in Russian).

6. Pshenichnyuk A.I., Kaibyshev O.A., Astanin V.V. A superplasticity model based on the ideas of cooperative grain boundary sliding. *Matematicheskoe modelirovanie sistem i protsessov*. 1998. N 6, p. 99-109 (in Russian).

7. Gundorin V.V., Ermolovich E.I., Kuznetsov I.A., Smirnov A.S., Yashin V.B. Explosive welding on thin gaps: features and prospects of using bulk explosives. *Vestnik tekhnologicheskogo universiteta*. 2016. Vol. 19. N 19, p. 48-52 (in Russian).

8. Explosion Physics: In 2 volumes. Ed. bu L.P.Orlenko. Moscow: FIZMATLIT, 2002. Vol. 2, p. 656 (in Russian).

9. Kuzkin V.A., Mihaluk D.S. Application of numerical simulation for identification of Johnson-Cook material model parameters for aluminum under high-speed loading. *Computational Continuum Mechanics*. 2010. Vol. 3, p. 32-43.

10. Kaya Y. Investigation of copper-aluminum composite materials produced by explosive welding. *Metals*. 2018. Vol. 8. N 780.

11. LS-DYNA: Theoretical Manual / Editer J.Hallquist. Livermore, LSTC, 1998, p. 628.

12. Nan Y., Jiang J., Wang S., Men J. One parameter-obtained method for JWL equation of state considered detonation parameters. Explosion and Shock Waves. 2015. Vol. 35(2), p. 157-163.

13. Shock-Assisted Materials Synthesis and Processing: Science, Innovations and Industrial Implementation. Edited A.A.Deribas, Yu.B.Scheck. Moscow: Torus Press Ltd., 2008, p. 152.

14. Shyue K.M. A Fluid-Mixture Type Algorithm for Compressible Multicomponent Flow with Mie-Gruneisen Equation of State. *Journal of Computational Physics*. 2001. Vol. 171, p. 678-707.

***Authors*: Mikhail A. Marinin,** *Candidate of Engineering Sciences*, *Associate Professor*, *marinin_ma@pers.spmi.ru* (*Saint-Petersburg Mining University*, *Saint-Petersburg*, *Russia*), **Sergei V. Khokhlov,** *Candidate of Engineering Sciences*, *Associate Professor*, *khokhlov_sv@pers.spmi.ru (Saint-Petersburg Mining University*, *Saint-Petersburg*, *Russia*), **Valentin A. Isheyskiy,** *Candidate of Engineering Sciences*, *Associate Professor*, *isheyskiy_va@pers.spmi.ru* (*Saint-Petersburg Mining University*, *Saint-Petersburg*, *Russia*).

The article was received on 15 June, *2018*.

The paper was accepted for publication on 20 December, *2019*.