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NEW EXPLOSIVE WELDING TECHNIQUES

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НОВЫЕ ТЕХНОЛОГИИ СВАРКИ ВЗРЫВОМ

Purpose − analysis of the variety of factors of the physical phenomena accompanying the process of the power explosive effect for development of new processes of metal treatment: explosive film coating of hardening and updating of a superficial layer of an item. Industrial approbation of cladding techniques by explosion of item surfaces of complex configuration and determination of parameters of the process of the explosive welding of high-strength pig-iron (graphite of the spherical form) with Godfield steel.

Approach − the analysis of the physical phenomena accompanying the process of explosive loading of materials is carried out. The opportunity of use of the explosive metal treatment for production of items and materials with unique properties which cannot be produced by other methods is found. As a result of experimental researches new alloys and techniques of the explosive metal treatment for the sphere of manufacturing are received.

Findings − the technology of modifying effect of the explosive loading and production of monolithic edges of three − layer spherical bottoms is tested. The parameters and borders of the explosive welding of Godfield steel with high-strength pig-iron are determined.

Research and practical implications − the techniques of the explosive cladding of basic surfaces of aluminium and pig-iron axle-box cases are developed, this has increased their wear resistance 10−12 times.

Value − the investigation shows original technique of making monolithic edges of shells comprising several not bound with each other layers and also explosive welding of items with a complex configuration and an original method of formation of counter cumulative jets for stable applying coatings of amorphous materials on the hardenable items.

<u>Keywords:</u> *coating technique, shock waves, cladding, fast crystallization, metastable, impact.*

The introduction

At the various schemes of the impulse impact there can be achieved the required forming, hardening, connection, splitting and continuity disturbance [1-5].

The character and intensity of the impulse impact on an item even in one process can essentially differ and open opportunities for changing geometrical, mechanical, physical, etc. properties. The disturbance extending with certain final speeds as waves of stress (loading, unloading and also reflected ones), forms in the item the disturbance areas which in time expand. Each area of disturbance has its stressed state characterized by the tensor of stress and tensor of deformation and is determined by the disturbance nature.

In the vicinity of the direct action of the pulse power factor the area of loading disturbance arises which in time spreads with the final speed. At time t_p, when the growth of deformation stops, the process of unloading begins.

Disturbance appropriate to the process of unloading spreads in the material with the final speed as a wave of unloading. The secondary area of disturbance of the wave of unloading located inside the area of loading disturbance is formed. At the exit of the wave of stress on the surface or at the interaction of the waves of stress in the body there appears a phenomenon of reflection. The reflected wave of loading, spreading in the opposite direction, forms the secondary area of disturbance of the reflected wave. At transition of the front of the wave of stress from one area of disturbance to another the movings of particles of the environment are continuous under the condition of preservation of the environment continuity.

In addition, the process is further accompanied by the influence of expanding products of detonation directly or in the transmitting environment on the workable material, causing additional deformation.

The originality of the researches firstly consists in nonstandard engineering solutions of applying nanocoatings at the explosive powder or monolithic plate throwing onto the surface of the hardenable item. Secondly, it consists in the briginal cladding technique with materials which are know to be unwelded with explosion. Besides, the investigation shows original technique of making monolithic edges of shells comprising several not bound with each other layers and also explosive welding of items with a complex configuration and an original method of formation of counter cumulative jets for stable applying coatings of amorphous materials on the hardenable items.

The purpose of the work

The analysis of the variety of factors of the physical phenomena accompanying the processes of the explosive power impact for hardening and updating of a superficial layer of an item, explosive cladding of the contact surfaces of an item of complex configuration, production of compositions with Godfield steel.

Material and results of researches

A shock-wave character of the explosive loading causes a number of the physical phenomena not inherent to the static loading, such as occurrence of high temperatures at the front of a powerful shock wave with formation of high-temperature phases, polymorphic transformations, crushing of grains and formation of twin defects, formation of cumulative jets, "multiple" chipping under the influence of shock waves of high amplitude, sintering, destruction, deformation and welding [6-8]. These physical phenomena can find application in the following technologies: 1) fast crystallization; 2) production of amorphous materials; 3) modifying effect of shock waves; 4) production of thin and film coatings; 5) cladding, hardening and welding. The processes, parameters of which correspond to the boundary characteristics for each of the processes, have large opportunities for creation of new techniques of the explosive treatment.

We shall consider the technological applicability of the chipping phenomenon. The interaction of the falling and reflected shock waves in a loaded material results in the occurrence of increasing stretching stresses, which can lead to destruction named chipping. This phenomenon is most of all influenced by the form of the wave of stress and the limiting value of the destroying stress $\sigma_в$ in the loaded material. The location of a chipping crack in a solid material or a place of separation in a laminated material depends on the form of the wave of stress. At propagation of the wave in a material the steepness of the curve $\sigma(t)$ behind the front of the wave decreases with the increase of the thickness of the loaded poly− or monomaterial δ, that results in an increase of the chipping thickness Δ. At propagation of the wave of stress of large intensity $\sigma > 2\sigma_в$ multiple chipping occurs, i.e. some following one after another parallel chippings occur.

During the explosive working which is not connected with splitting and destruction, chipping occurrence is an undesirable phenomenon. Usually for prevention of chipping a reflecting surface of the material is directly supported against the other body absorbing energy [9]. The prevention of chipping is also made by the use of fascinating plates and mastics [9]. Thus chips absorbing a significant quantity of energy, can be used for performance of a number of auxiliary operations.

The useful application of chipping is, first of all, separation of layered products for their recycling after performance of their designation. For this purpose on the outside surface a layer of the explosive substance is applied, the parameters of which are chosen so that the destruction takes place on the interface.
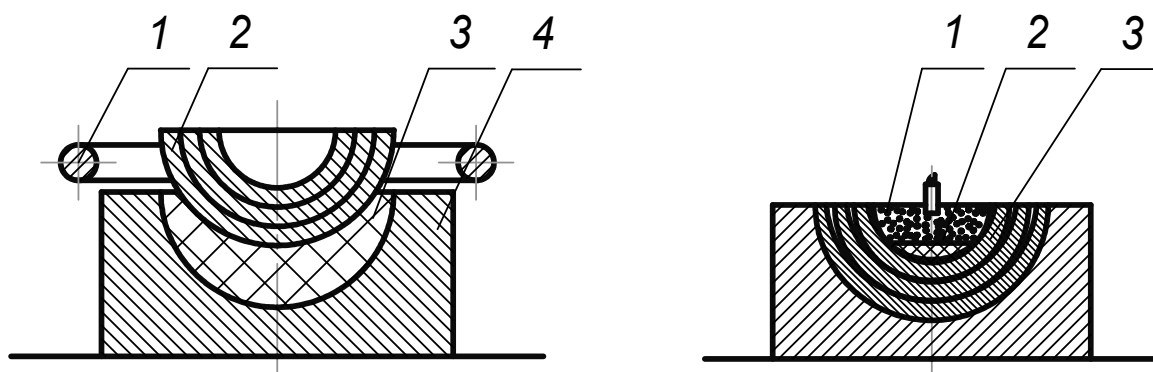

Fig. 1. Scheme of production of items with the monolithic edges:
1 – explosive substance; 2 – layered piece; 3 – spacer; 4 – matrix

At connection of multi−layered items among themselves by the methods of fusion welding large technological difficulties arise at separation of the stack as a result of thermal heating by an electrical arch. It is desirable to ensure solidity of edges and dense, without bonding, bearing of item layers. To solve this problem is possible as follows (fig. 1). Preliminary made items 1 are collected in a stack and deformed unless a required configuration of bottom 2 is produced. Then separation of the edges of bottom 2 is made. For this purpose the bottom is placed in matrix 3 so that the edges of bottom 2 bulge out above the plane of the top end face of matrix 3, for what a spacer 4 is put in a cavity of the matrix. After that along the outside perimeter of the edge of bottom 2 a ring charge of an explosive substance 5 is put and its initiation is made.

As a result of the effect of the explosion there is separation of layers of multi-layer bottom 2 at its edge. After that the multi-layer bottom is placed in matrix 3 and the explosive welding of the bottom edges is made with calibration and compaction of layers.

Thus, the chipping effect finds its use as a functional and intensifying factor and is connected with treatment and production of layered items and use of lamination both of constructive and technological methods. This method has found application at manufacturing layered vessels of high pressure (fig. 2).

The process of the explosive welding can find application not only for cladding plates and cylindrical shells, but also for cladding and hardening surfaces of items of complex configuration.

The process of cladding basic surfaces of axle-box cases, made from high-strength pig-iron plates, by Godfield steel plates was tested under the offer of German railway car constructors.

One of the basic research problems of the process of the explosive cladding is the opportunity of forecasting formation of a welded joint at certain modes of collision for materials with known physical-mechanical properties. Despite of abundance of the scientific and technical sources on determination of the area of welding of various material combinations, there are no data on welding pig-iron and Godfield steel. However the arising demand for such combinations has resulted in the necessity of creation of the explosive welding of pig-iron and Godfield steel with copper.
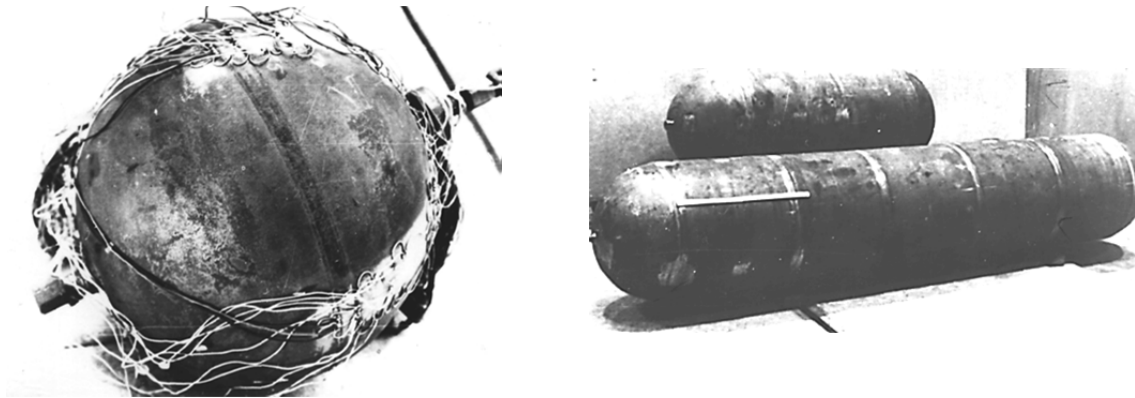

Fig. 2. Vessels of high pressure

Some uncertainty at the experimental determination of the modes of collision, ensuring welding by explosion, is connected with the absence of the precise criterion ascertaining the result of welding of items. Basically, items are considered to be welded only in that case, when the strength of the seam is as strong as the initial materials. Such a criterion of weldability seems to be acceptable at the explosive cladding. Usually a welded seam at such treatment is strengthened and exceeds the strenght of less strong metal from the combination. If this condition at the explosive welding is not fulfilled then, as a rule, it results in stratification during the subsequent treatment and operational loadings. But in a number of cases a low strength of bonding layers is required. In such cases it is considered, that the welding did not occur when the strength of the seam tends to zero. Probably, from our point of view, it is necessary to limit the strength of the welded seam to a minimum in each specific case, proceeding from the conditions of operation of the clad product. For example, the association of boiler installations workers in Japan as a criterion use shear-strength of binary combinations welded by explosion. For the majority of clad metals the criterion is accepted equal to 140 MPa, for steel cladded by copper or copper alloys it is 100 MPa, for steel cladded by aluminium it is 50 MPa. For steel with a corrosion-resistant coating used for vessels of high pressure the allowable shear strength makes 200 MPa.

The strength of joints received by the explosive welding of various combinations of metals insignificantly changes over a wide range of change of the modes of collision. Transition from the modes with a satisfactory strength to the modes not ensuring formation of a welded seam (the strength of the seam is equal to zero), occurs in the narrow limits of changing of the modes of collision.

When the model of an ideal liquid [9] is used, two parameters characterizing an oblique collision out of a class of parameters are chosen as the most essential: either the angle of collision γ and the speed of the contact point v_κ, or the angle γ (dynamic angle of rotation) and the relative speed of the contact point (a ratio of the contact point speed to the sound speed).

The area of the explosive welding is limited on the plane γ, v_κ by four curves. Physical sense of these curves is the following: the right border corresponds to transition to supersonic modes of collision, the top border corresponds to excessive heating of the connection zone. The bottom and left borders depend on the termination of wave formation. The welding of high-plastic metals (aluminium, copper and some their alloys) is possible without formation of waves. The true left border of welding is set for them.

The area of the explosive welding can be presented in a three-dimensional space (angle of collision, relative speed of the point of contact, average weight or thickness of colliding plates). The three-dimensional area of the explosive welding practically is used rather seldom. The introduction of the third parameter is connected with critical conditions of the existence of a viscous current.

The physical mechanisms limiting the values of viscosity at superhigh speeds of deformation, depend on a specific nature of the deformable body. In the given concrete case, it is mostly probable, that for fragile pig-iron restriction are due to a minimum of the shear deformation $\Delta \bar{\gamma}$. A criterion of the bottom border is used in this case $\gamma \cong \Delta \bar{\gamma}$.

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The minimum of the thickness of a plastic soft layer is determined such that not involving a fragile material for copper and pig-iron into the process of deformation

$$\sigma_{DT}^{M} + B\dot{\varepsilon}_{i}^{n} < \sigma_{DT}^{T}, \qquad (1)$$

where σ_{DT}^{M}, σ_{DT}^{T} – dynamic limits of fluidity of copper and steel; $\dot{\varepsilon}_{i}$ – intensity of speeds of deformation; B, n – hardening constants.

Approximately the minimal size of the thickness of the plastic layer can be determined from the ratio for compression of the plastic layer on a rigid surface. The maximal pressure is taken either in the acoustic approximation $p = \gamma \, \rho v^2$, or in hydrodynamical $p = 0,5\rho v^2$. The thickness of the layer ignoring the inertial components will make:

$$\Delta = \frac{1,15\sigma_s(0,5\ell \pm x)}{p - 1,15\sigma_s}. \qquad (2)$$

where σ_s – limit of fluidity of a sublayer; ℓ – length of the item.

We take this value for minimal, which corresponds to ~1.8 mm.

As in practice it is inconvenient to use the spatial area of welding, it makes sense to determine the minimal and optimum thickness of the plastic layer. The optimum thickness for small values of the dynamic angle of rotation is determined from the energy criterion and makes

$$h \cong 2\overline{E} / \gamma^2 \rho v^2, \qquad (3)$$

where $\overline{E}$ – optimum value of the kinetic energy.

This kinetic energy corresponds to the optimum size of a welding gap ensuring speed-up of the piece to the maximal speed of collision. At the same time it depends on the weight of a mobile item, and hence, on its thickness.

With the purpose of unification of the experiments in determination of the quality of welding depending on the thickness of a layer, it makes sense instead of the thickness of a layer to consider a ratio of weights of the clad plate and a layer within the area of welding on parameters γ and v_κ and their invariance. The samples welded by explosion were tested for destruction at shear (operational requirements regulate shearing forces). As a result, the dependence f $(h/h_{np}, \tau_{cp})$ for the steel+copper+pigiron couple (fig. 2) is received.

Having determined the optimum – allowable size of a layer, we build the area of welding in the coordinates $(v_\kappa; \gamma)$ at the fixed value of h.

The connection of copper with steel by traditional methods of welding is a rather complex task. Iron and copper have strongly differing temperatures of crystallization, bad wetting with respect to each other and a limited reciprocal solubility in a solid state. Nevertheless, the explosive welding provides a strong connection for this couple in a rather wide range of the parameters of collision. The dependence between the parameters of collision and copper strength is not determined, since practically on all the modes of welding destruction occurs in copper. Tests for formability do not result in stratification.

The process was carried out as follows. The explosive welding was carried out under a parallel scheme. In this case $v_\kappa = D$. The variation of the speed of detonation was carried out by addition of phlegmatizers in the explosive substance. The dynamic angle of rotation γ was varied by the change of the parameter of welding, that resulted in a change of height of a charge of the explosive substance, and consequently, the speed of detonation. In the experiments plates from technically pure copper with the thickness of 4÷6 mm and cast blanks from Godfield steel and high-strength pig-iron were used. After the construction of the copper – Godfield steel area of welding the technique of the explosive cladding of lugs of the axle-box cases by plates from Godfield steel welded to copper plates was tested. The mode of the welding excluded formation of eddy zones and minimal presence of melt.

The speed of detonation of the explosive substance was preliminary measured according to the Dotrish method and the method of registration of time of unfolding strips of foil put in the layer of the explosive substance. The received data on the area of welding of the researched combinations were compared with the data received from the experiments on throwing a copper plate by a wedge charge of the explosive substance. The height of the charge of the explosive substance was chosen so that on the initial sector there was a sound welding of plates, and on the final sector the welding did not occur. The thickness of the copper plate was changed in the limits from 2 to 18 mm. Such experiments have allowed to determine the area of welding and the dependence $\gamma = \gamma$ (r). As the plates thickness grows the divergence of the experimental data takes place in the interval from 5 % to 20 %. At thickness of the plate higher than 12 mm the welding by explosion does not occur, that is probably connected with dependence of the parameters of the external loading necessary for bending of a thrown plate on its thickness.

The results of the experiments are given in tables 1–3 and fig. 3, 4. The necessity for performance of the experiments was connected with the absence of data on welding copper with pig-iron and Godfield steel and a significant disorder of experimental and theoretical data on the assessment of the area borders of welding homogeneous and heterogeneous materials.

Table 1

Limiting modes of welding

№	Godfield steel			High-strength pig-iron		
	$v_к=D$	r	β, radian	$v_к=D$, m·sec⁻¹	r	γ, radian
1	1,790	0.42	0.12	1,820	0.39	0.12

Table 2

Modes of welding copper with Godfield steel and pig-iron

$v_к$, m·sec⁻¹	γ, degrees	Result (Godfield steel)	Result (pig-iron)
4,450	14	-	-
4,330	12	-	+
4,240	16	-	+
3,860	17	-	+
3,920	10	+	+
3,990	14	-	-
2,830	10	+	+
2,200	10	+	+
1,780	20	-	-
3,100	12	+	+

Table 3

Characteristics of ammoniac saltpeter explosive substances

Description of Explosive Substance	Composition %		Speed of detonation D $H_{вв}=d_{кр}$, m·sec⁻¹	Critical diameter $d_{кр}$, mm
	Ammoniac saltpeter	*Trinitrotoluene*		
Ammonite 6ZhV	71	29	$\dfrac{4200}{4120*}$	$\dfrac{10-12}{6*}$
Welding Ammonite AS1	85	15	$\dfrac{3200-3600}{3510*}$	18–20
Welding Ammonite AS2	90	10	$(3,000-3,100)*$	
Welding Ammonite AS3	94	6	$\dfrac{2100-2600}{2440*}$	24–28
Welding Ammonite AS4	99	2	1,700–1,900*	38–40

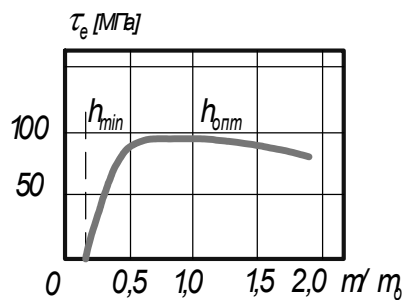* – data received experimentally. Others are taken from references [12, 13].

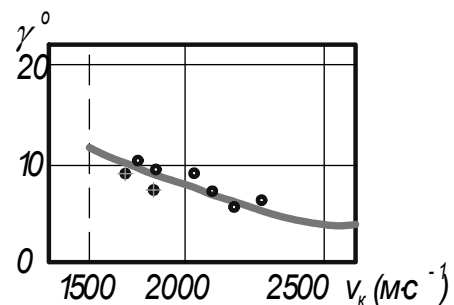**Fig. 3. Dependence of the shear strength of connection on the thickness of a layer**

Fig. 4. the Left and bottom borders of the area of welding of a clad metal of Godfield Steel+copper with high-strength pig-iron

For charges with the thickness of 30-100 mm the use of dependence (4) gives a divergence with the experimental data within the limits of 18 %.

$$D=1300+37,0 \cdot H-10,62C- 8,04 \cdot H^2+0,6008 \cdot C^2+6,145 \cdot H \cdot C-0,004628 \cdot H \cdot C^2, \qquad (4)$$

where C – percentage of ammoniac saltpeter; H – thickness of a charge, mm.

Fig. 5. The axle-box case made from high-strength pig-iron

Thus, the optimum sizes of thickness of a layer and the border of the area of welding of pig-iron with plates from Godfield steel, cladded by copper are received (fig 5).
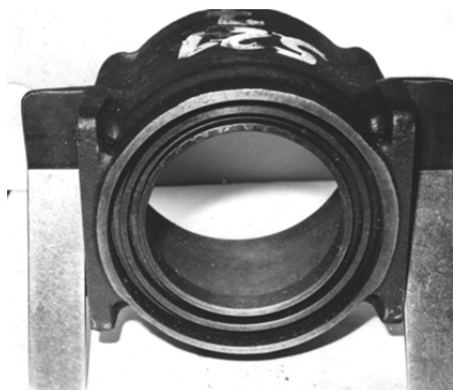
Conclusions

1. The study and estimation of the variety of factors of the physical phenomena accompanying the process of power effect of the explosion allowed to develop essentially new processes of application of thin metal coatings, superfast crystallization, dynamic hardening and diffusive saturation of the superficial layer.

2. The technique of the explosive cladding of basic surfaces of aluminium and pig-iron axle-box cases is developed. The parameters are determined and the area of the explosive welding of pig-iron with Godfield steel is constructed.

Аннотация. Установлена возможность использования взрывной металлообработки для получения деталей с уникальными свойствами, которые не могут быть достигнуты другими методами обработки. В результате экспериментальных исследований разработаны новые технологии взрывной металлообработки для различных сферы производства. Апробирована технология получения монолитных кромок трехслойных сферических днищ. Определены параметры и границы сварки взрывом стали Гадфильда с высокопрочным чугуном. Разработаны технологии взрывного плакирования опорных поверхностей алюминиевых и чугунных корпусов букс, что повысило их износостойкость в 10-12 раз.
<u>*Ключевые слова:*</u> *плакирование, ударные волны, сварка взрывом, быстрая кристаллизация, метастабильная фаза, удар*

Анотація. Встановлена можливість використання вибухової металообробки для одержання деталей з унікальними властивостями, які не можуть бути досягнуті іншими методами обробки. У результаті експериментальних досліджень розроблені нові технології вибухової металообробки для різних сфер виробництва. Апробована технологія одержання монолітних крайок тришарових сферичних днищ. Визначені параметри й границі зварювання вибухом сталі Гадфільда з високоміцним чавуном. Розроблені технології вибухового плакування опорних поверхонь алюмінієвих і чавунних корпусів букс, що підвищило їх зносостійкість у 10-12 разів.
<u>*Ключові слова:*</u> *плакування, ударні хвилі, зварювання вибухом, швидка кристалізація, метастабільна фаза, удар*

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