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## Article

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## RESEARCH OF THE STRESS-STRAIN STATE OF A WORKPIECE UNDER THE DOUBLE BENDING BY THE PULSE LOADING

The object of research is the technology of metal processing by high-speed and high-energy methods, plastic deformation of layered metal compositions. Theoretical studies are based on the main provisions of the theory of joining metals in the solid phase, the theory of plasticity, explosion welding technology, plastic deformation of layered metal compositions, and their heat treatment.

The main problem of creating layered metal compositions using explosion energy, including wear and corrosion resistant, electrical, materials with high ballistic resistance, etc., is that they have not yet taken their rightful place in the range of modern structural and functional materials. This can be explained by the limited application of this process, as well as the lagging behind the theory and experimental base in the field of joining various metals in the solid phase and providing the necessary performance properties according to the needs of modern industry.

The process of deformation of the cladding blank during the explosion welding is considered. The process of the workpiece collision is considered in three stages: the movement of the element of the cladding workpiece before the collision, its inertial movement and deformation. The equations of motion and equilibrium of the elements of the workpiece are described. A joint solution of the equations of plasticity and equilibrium of the blank element in the double inflection zone is presented.

The work is devoted to solving the problem of increasing the level of production and economic indicators of the manufacture of layered metal compositions through the development of methods for calculating and optimizing the technological parameters. Explosion welding, as the most versatile, promising, and economical method, which still has many possibilities for the application of mathematical modeling and process optimization, has been investigated for the production and subsequent processing of the main groups of industrial metal compositions. This makes it possible to solve the problem of replacing traditional materials with layered metal compositions.

The results obtained are important from the point of view of the application of cost-effective materials with high mechanical, operational, and technological properties.

**Keywords:** double deformation, workpiece reverse bending, explosion welding, explosion cladding, bimetallic composition, welded cladding.

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## 1. Introduction

Modern production equipment, technological and instrumental equipment, vehicles, military equipment etc. are working in conditions characterized by extreme operating parameters (high thermal and mechanical loads, aggressive environment, etc.). Therefore, the elements of the equipment are constantly experience necessities in materials with a complex of incompatible mechanical properties: wear and abrasive resistance, high strength and low density, corrosion resistance and high electrical and thermal conductivity. The required set of properties can be achieved by of combining several materials into a single structural unit.

Such materials are producing by combining of dissimilar metals into monolithic compositions, in particular, in layered ones. Therefore, the demand for metal compositions continues to grow, and the requirements for their properties and quality are increasing. One of the effective methods for layered compositions producing is explosion welding [1]. Improvement of this process is associated with the development of methods for calculating of its technological parameters [2, 3]. It is necessary to predict not only the mechanical properties of the compositions joint, but also to predict the operational characteristics of the cladding layer. For this, it is necessary to solve the problem of elastoplastic deformation of layers during

the explosion welding. This will allow to calculate the process of jet formation for elastoplastic units and the compressive stresses of colliding workpieces time of existence. These data allow to determine the quality indicators of the welded joint. In addition, this solution makes it possible to determine the deformations at which the properties of the cladding layer (such as wear and corrosion resistance, fatigue strength, etc.) are corresponding to the limit uniform deformations [3, 4].

Therefore, it is relevant to obtain the engineering dependencies for the calculation of the workpiece deformed state, which ensures the highest quality indicators in terms of operating characteristics.

Thus, as the object of research was chosen the technology of metal processing by high-speed and high-energy methods, plastic deformation of layered metal compositions. And the aim of research is theoretical studies of the main provisions of the theory of joining metals in the solid phase, the theory of plasticity, explosion welding technology, plastic deformation of layered metal compositions, and their heat treatment.

## 2. Methods of research

The study used the finite difference method, which consists of the following: the solution of the problem of the collision of the flyer plate (clad) and the fixed target plate (substrate or base plate) is considered in three stages. The first is the movement of the element of the flyer plate before the collision with the target plate. At this stage, let's accept the assumption that it is possible to neglect the deformation energy of the flyer plate in comparison to the kinetic energy of its movement. The second stage is the inertial motion of the flyer plate and its collision with the surface of the fixed base plate. The dependencies of the second stage are caused by the duration of the explosion is tens of microseconds, and the workpiece deformation duration is a milliseconds. The third stage is the deformation of the flyer workpiece after the collision with the fixed base plate [5].

The explosive welding schematics in case of obtaining two-layered and multilayered compositions are shown in Fig. 1.

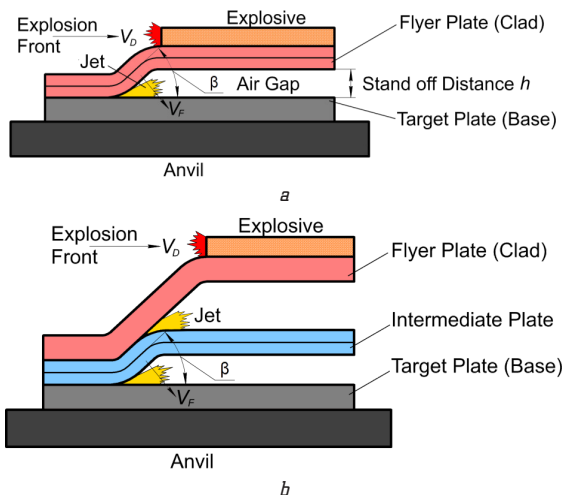


Fig. 1. Explosive welding schematics:  
a – explosive welding of two-layered composition; b – explosive welding with an internal layer

The flyer plate element equation of motion under the action of varying pressure has the form [6]:

$$\rho \delta \frac{d^2 h}{dt^2} + \rho_1 c_1 \frac{dh}{dt} = P_m \exp(-t/\theta), \quad (1)$$

where  $\delta$  – the flyer plate element thickness;  $\rho$  – the flyer plate density;  $\rho_1, c_1$  – the density and the soundspeed in the environment behind the plate;  $h$  – the gap between the welded plates;  $P_m$  – the pressure of the detonation products on the plate at the moment of the shockwave release onto the free surface;  $\theta$  – the time constant for the decline of detonation products;  $t$  – the time of the process.

The solution of (1) has the form:

$$h = r + \frac{\theta}{m} \cdot P_m \cdot [1 - \exp(-t/\theta)] \cdot t, \quad (2)$$

where  $r$  – the flyer plate element radius of curvature;  $m$  is the mass of the element of the plate square unit.

When the plate moves by inertia forces, let's divide the flyer plate surface into flat areas in contact with the target plate surface and cylindrical areas, which are forming the bending radius of the flyer plate [7, 8] (Fig. 2).

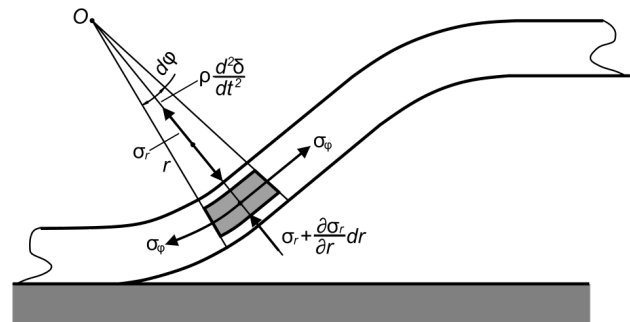


Fig. 2. Equilibrium of the flyer plate element  $\sigma_r + \frac{\partial \sigma_r}{\partial r} dr$  on the bending radius

When solving the equilibrium equation of an element at the bending radius of the flyer plate, together with the plasticity condition, let's obtain:

$$\rho \cdot \frac{d^2 \delta}{dt^2} = -\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_\phi}{r} + \frac{\sigma_r}{\delta} \cdot \frac{d\delta}{dr}, \quad (3)$$

where  $\sigma_r$  and  $\sigma_\phi$  – respectively radial and latitudinal stresses in the flat element of flyer plate;  $\delta$  – the element thickness.

The solution of this equation has the form:

$$\sigma_r = -P_m + \beta \cdot \sigma_S \cdot f + \rho \cdot (r \cdot \ddot{r} + \dot{r}^2) \cdot f + \rho \cdot \left( \frac{r^2 \cdot \dot{r}^2}{2b^2} - \frac{\dot{r}^2}{2} \right), \quad (4)$$

where  $\beta$  – Lode-Nadai coefficient;  $\sigma_S$  – yield strength;  $b$  – radius of the flyer plate outer surface ( $b = r + \delta$ );  $f = \ln(r/b)$ .

The pressure  $P_m$  is found from the following solutions. The flyer plate elements equation of motion under the action of detonation products pressure can be written in the form [6, 8]:

$$Dm \frac{d^2 x_1(t)}{dt^2} + \rho c \frac{dx_1(t)}{dt} = P(t), \quad (5)$$

where  $dx_1/dt$  – velocity of the flyer plate in the direction of displacement;  $P(t)$  – pressure, which describes the detonation products action on the flyer plate. The detonation front pressure changes according to the law:

$$P(t) = P_m \exp(-t/\theta). \quad (6)$$

The solution of (5) when neglecting the second term has the form:

$$\dot{x}_1(t) = \frac{P_m \theta}{m} (1 - \exp(-t/\theta)) + v_0, \quad (7)$$

where  $v_0$  – the initial velocity of the flyer plate element at the moment of the shockwave release to the free boundary.

To determine  $P_m$  and  $\dot{x}_1$  the Chapman-Jouguet condition [9] for the pressure at the detonation front is used:

$$P_m = \rho_0 D^2 / (k+1), \quad (8)$$

where  $\rho_0$  – the initial density of the explosive;  $D$  – detonation velocity of the explosive;  $k$  – indicator of the explosive adiabatic.

The pressure on the plate to the pressure of the detonation products ratio is determining by the equation:

$$P_x / P_m = [0.5(3k-1)k^{-1}]^{2k/(k-1)}. \quad (9)$$

At the moment of the shockwave release to the free surface, the pressure of the detonation products on the plate is determined by the expression:

$$P_x = [0.5(3k-1)k^{-1}]^{2k/(k-1)} P_m [H \cdot D^{-1}(H/D + t_0)], \quad (10)$$

where  $t_0 = \delta_M / c_M$  – the time of a shockwave passing on a flyer plate;  $c_M$  – the shockwave velocity in the plate;  $\delta_M$  – flyer plate thickness;

$$c_M = a + \lambda u_x, \quad (11)$$

where  $u_x$  – the mass velocity of the flyer plate;  $a$  – the soundspeed;  $\lambda$  – the shock compression coefficient of the plate material.

The shockwave velocity at the moment of release on the flyer plate free surface is determined by the ratio:

$$c_M = P_0 \cdot (\rho_0 \cdot u_x)^{-1}. \quad (12)$$

The system of equations for calculating  $P_x$ ,  $u_x$  and  $c_M$  at the moment of the shockwave release on the plate free surface has the form:

$$\begin{cases} P_x = [0.5(3k-1) \cdot k^{-1}]^{2k/(k-1)} P_m [H \cdot D^{-1}(H/D + t_0)]^k, \\ c_M = a + \lambda u_x, \\ t_0 = \delta_M / (a + \lambda u_x), \\ P_x = \rho_0 \cdot u_x \cdot c_M. \end{cases} \quad (13)$$

At the explosive charge blast, the maximum pressure at the front of the shockwave is determined by the empirical formula [2, 5]:

$$P_m = \frac{1.08}{(r_0)^{1.08}} \cdot 10^4, \quad (0.0773 \cdot 10^{-4} \leq r \leq 1.082 \cdot 10^{-4}), \quad (14)$$

where  $r_0 = h / \sqrt{q}$  – reduced explosion distance;  $h$  – explosion standoff distance (air gap size), m;  $q$  – explosion energy per length unit, J/m.

The change in pressure, depending on the location of the shockwave front point, is approximated by the dependence:

$$P_m = (31.14 + 89.86\lambda + 380.69\lambda^2) \cdot 10^5, \quad (15)$$

where  $\lambda$  is the length of the arc along the shockwave front from a given front point assigned to the length of the arc from the axis of charge to the front point equidistant from both ends.

According to the foregoing, the field of the shockwave peak pressures can be described with sufficient accuracy by expression:

$$P_m = 0.1241 \cdot 10^7 \left( \frac{q}{q_0} \right)^{0.572} \cdot r_0^{-1.144} + \left[ 0.1166 \cdot 10^8 \cdot \left( \frac{q}{q_0} \right)^{0.4} \cdot r_0^{-0.805} - 0.1241 \cdot 10^7 \left( \frac{q}{q_0} \right)^{0.572} \cdot r_0^{-1.144} \right] \cdot \lambda. \quad (16)$$

The solution of the equilibrium equation of a flyer plate flat element (Fig. 3), taking into account the mass character of inertia forces with the adoption of the plate cross section velocity linear relationship along its thickness, has the form:

$$\sigma_r(\delta) = \sigma_{\max}^{DYN} \cdot \frac{\delta}{\delta_0} = \sigma_{\max}^{DYN} \frac{d\delta}{\delta}, \quad (17)$$

$$\frac{d\sigma_r}{d\delta} - \frac{\sigma_r}{\delta} = -\frac{\sigma_{\max}^{DYN}}{\delta}. \quad (18)$$

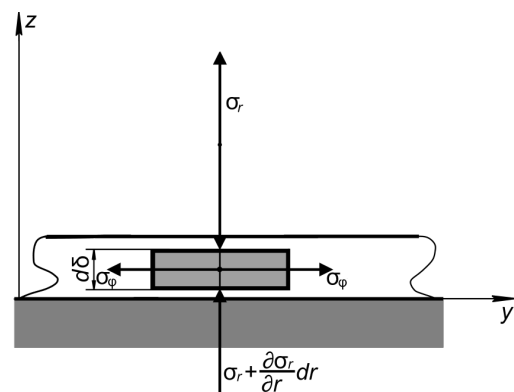


Fig. 3. Equilibrium of the flyer plate element at the collision moment

The solution of this equilibrium equation has the form:

$$\sigma_r = \sigma_{\max}^{DYN} \cdot \frac{\delta}{\delta_0} \left[ \left( \frac{1}{\delta} - \frac{1}{\delta_0} \right) \cdot \delta_0 + \frac{\sigma_r(0)}{\sigma_{\max}^{DYN}} \right], \quad (19)$$

where  $\sigma_r(0)$  – the stress acting in a flyer plate at the moment of collision with the target plate and equal to:

$$\sigma_r(0) = P_m + 2 \cdot \beta \cdot \sigma_s \cdot \ln \frac{h + \delta}{h}; \quad (20)$$

$\sigma_{\max}^{DYN}$  – maximum stress at collision:

$$\sigma_{\max}^{DYN} = 0.75 \cdot \rho \cdot V^2. \quad (21)$$

Taking into account that the flyer plate section displacement velocity by its thickness at the distance  $\delta_0$  from the outer surface varies linearly [10], i. e.  $\frac{d\delta_0}{dt} = V_0 \frac{\delta_0}{\delta}$ , let's obtain:

$$\frac{d^2V}{dt^2} = \frac{d}{dt} \left( V_0 \cdot \frac{\delta_0}{\delta} \right) = \frac{V_0^2 \cdot \delta_0}{\delta_0^2}. \quad (22)$$

With this in mind, let's obtain:

$$\sigma_r = \rho \cdot \frac{V_0^2}{\delta_0^2} \cdot (\delta^2 - \delta_0^2) + \sigma_r(0), \quad (23)$$

$$\frac{d\sigma_r}{d\delta} - \frac{\sigma_r}{\delta} = -\rho \cdot \frac{V_0^2}{\delta_0^2} \cdot \delta. \quad (24)$$

The solution of this equation has the form:

$$\begin{aligned} \sigma_r &= e^{\left(-\int_{\delta_0}^{\delta} \frac{1}{\delta} d\delta\right)} \cdot \left[ \int_{\delta_0}^{\delta} -\rho \frac{V_0^2}{\delta_0^2} \cdot \delta \cdot e^{\int_{\delta_0}^{\delta} \frac{1}{\delta} d\delta} d\delta + C \right] = \\ &= \rho \frac{V_0^2}{\delta_0^2} \cdot (\delta^2 - \delta_0^2) + \sigma_r(0), \end{aligned} \quad (25)$$

where  $C$  corresponds to the boundary condition; at  $b=r+\delta$  it has value  $C=\sigma_r(0)$ .

When the flyer (clad) plate element strikes the rigid surface of the target (base) plate, its kinetic energy of transforms into the potential energy of deformation [11].

The value of the specific potential energy  $W$  under the action of inertial forces in the clad element with a length  $dr$  at the distance  $z$  can be expressed by the follows:

$$dW = \sigma_{\max}^{DYN} \cdot \frac{z}{\delta} d\epsilon_i, \quad (26)$$

where  $d\epsilon_i$  – the increment of strain intensity.

For the flat deformed state, the increment of the strain intensity will be equal to [12, 13]:

$$d\epsilon_i = \frac{\sqrt{2}}{3} \sqrt{(\epsilon_z - \epsilon_y)^2} = \frac{2}{3} \frac{dz}{\delta}, \quad (27)$$

where  $\epsilon_z = dz/\delta$  and  $\epsilon_y = -\epsilon_z = -dz/\delta$ .

Then the clad element specific strain energy value will be equal to:

$$W = \frac{2}{3} \cdot \sigma_{\max}^{DYN}. \quad (28)$$

And the specific kinetic energy margin of the clad element value will be equal to:

$$T = 0.5 \cdot \rho \cdot V. \quad (29)$$

When neglecting the energy loss on local collapse at collision, deformations of the target plate and friction of the flyer plate on the target plate, let's take  $W=T$ .

According to the above, the flyer plate displacement velocity at the moment of collision with the target plate surface will be found from the solution of equation (1) and system of equations (13):

$$V = \frac{P_m \cdot \theta}{m} \cdot (1 - \exp^{-t/\theta}) + u_x. \quad (30)$$

The value of the time constant of the pressure decline in the shockwave is calculated from the empirical dependence [6, 12]:

$$\theta = 0.115 \cdot Q^{0.5} \cdot \left( \frac{h}{Q^{0.5}} \right)^{0.43} \cdot 10^{-3}, \quad (31)$$

where  $Q$  – the charge mass per plate length meter, kgs.

### 3. Research results and discussion

To study the strain state across the thickness of bi-metallic compositions under the pulse compression, in particular, under the explosion welding, the grid method, the «inserts» method and the metallographic method are currently used. The metallographic method is based on the study of the hardening of individual grains of the deformed metal microstructure.

The above methods for the strain state determining have some drawbacks. The grid method requires a high class of accuracy and surfaces finishing, which providing a zero gap between the surfaces to preserve the dividing grid during the explosive welding. The «inserts» method allows to determine the metal layers shear displacements direction and magnitude, but does not give the picture of the plastic deformations values realized in the contact layers. Therefore, the listed methods are suitable for the study of shear deformations only in the areas located at a certain distance from the joint line, in which the strains are homogeneous.

At present, there are no methods for studying the stress-strain state in the surface layers of colliding plates. Probably the most promising is the application of the method of the stress-strain state determining by hardness distribution, which is based on the assumption of appearance of a monosemantic functional relationship between the deformed metal hardness and the stress state intensity. This method can be successfully used to find the boundaries of the deformation zone if it occupies only a localized area of the deformed body volume, as well as to determine the lines of different strain intensities ( $\epsilon_i$ ) and stress intensities ( $\sigma_i$ ) over the entire material volume.

Moreover, the hardening degree is different in each sublayer. Thus, in the field of plastic deformations, the dependence  $\sigma_i(\epsilon_i)$  in each sublayer has its own parameters. This caused by the heterogeneity of structural, mechanical and geometric nature as a result of the bimetal production technological cycle.

When modeling the process of layered blanks pulsed deformation, the deformed metal layer is divided into three characteristic zones:

I – the zone of the colliding plates surface layers intense deformation. Plastic deformation in this area provides activation and interaction between the initial elements of the composition.

II – the zone of the colliding plates surface layers deformation. In case of the wave-like profile of the connection

line, its characteristic feature is the plastic deformation non-homogeneity in the layers, which are parallel to the weld zone.

III – the zone of deformation over the entire depth of welded plates, a characteristic feature of which is the deformation homogeneity of the metal in the layers, which are parallel to the weld zone.

Experimental verification of the numerical and analytical calculations results was carried out on the hardness distribution in deformed plates according to the methods of G. Del' and V. Ogorodnikov [10, 14]. For the target plate (normal quality structural carbon steel Cr3пс (in GOST codification); US analogues – carbon steels A284Gr.D and A57036, EU analogues – carbon steels Fe37-3FN, Fe37-3FU and S235) a calibration chart was taken under the dynamic compression conditions. For the flyer plate (corrosion- and heat-resistant steel 08X18H10T (in GOST codification); US analogue – stainless steel AISI 321, EU analogues – stainless steels 1.4541, X10CrNiTi18-10 and X6CrNiTi18-10) a calibration chart was taken under the dynamic stretching, compression and bending. The hardness measurement was carried out through 0.5 mm in the cross section, starting from the joint zone. As strain gauge transducers, standard sensors of 49.4–49.49 ohms were applied. Measurement of the sensor resistance of the when exposed to loading was carried out by the potentiometric method. The DC source was connected to the strain gauge through an additional ballast resistance. The signal appearing on the sensor as a result of deformation was amplified by a strain amplifier with a transmission frequency from 0 to 700 Hz and recorded by an oscilloscope.

Solving together the equations (1), (21), (30) and (31) at  $Q=4$  kg/m, let's obtain the collision velocity value of 148.12 m/s and the maximum stress values by numerical method. Such stresses exceed the yield strength of the clad material and cause an intense flow of metal. The obtained values of  $HV$ ,  $\sigma_i$  and  $\varepsilon_i$  by both methods are presented in in the Table 1.

Stresses and strains intensities

Table 1

Distance from the joint zone, mm	Material (GOST codification)	Stress intensity (numerical analysis), MPa	Hardness HV	Stress intensity ( $\sigma_i=f(HV)$ method), MPa
0	Cr3	1060	460	1020±120
0.25	Cr3	1040	440	1010±142
0.5	Cr3	996	350	980±111
0.75	Cr3	784	260	800±92
1.0	Cr3	560	180	590±64
1.5	Cr3	560	160	540±62
2.0	Cr3	560	160	540±62
0	08X18H10T	1090	460	1120±126
0.25	08X18H10T	1090	455	1120±126
0.5	08X18H10T	1090	375	1090±118
0.75	08X18H10T	1090	374	1090±118

The adequacy of the mathematical description of the strains change in time with experimental data was confirmed by the F-test (Fisher criterion). The errors margin calculated from the adequacy variance was  $\pm 14.2\%$  with a confidence level of 0.95 and a significance level of 0.05.

Comparison of the values of stress intensity, determined numerically and found from the graph, testifies to the reliability of the results obtained and the perfection of the techniques.

It is known that in the production of wear-resistant compositions, carbon structural steel is usually used as the main layer, and high-carbon tool steels containing 0.60...1.30 % carbon are used as the cladding layer.

The following compositions were obtained by explosion cladding:

- 1) annealed manganese steel+1.5 mm copper. In some cases, the separation of the copper layer is possible;
- 2) annealed manganese steel+6 mm aluminum. All the plates were successfully joined;
- 3) annealed manganese steel+6 mm aluminum+carbon steel plate. All plates are welded well, however, in certain cases, tearing of the outer layer of carbon steel is possible;
- 4) four-layer «sandwich» of titanium+aluminum+titanium+titanium. All plates are welded reliably.

In the case of the formation of compositions entirely consisting of non-ferrous metals, including titanium, the proposed technology demonstrates the high reliability of the formed compounds.

But as it can be seen from the above, further development of explosion welding technology requires improvement of the theoretical basis and experimental research. This is especially true in the case of creating compositions using manganese steel and copper, as well as multilayer compositions using structural steel, in which the number of layers exceeds two ones.

#### 4. Conclusions

Based on the solution of equilibrium equations during the collision of the flyer plate (clad) with the target plate (base) at the explosion welding processes, the dependences of the dynamic compression stresses from the explosive loading pressure arising are obtained. This making it possible to specify the mechanism of the clad shape change under the pulse load before and during the collision with the base plate.

The experience of using metal compositions obtained by explosion welding shows that the wear resistance of manganese steels (or mangalloy) during abrasive wear in a composition obtained by explosion cladding with aluminum is 1.24 times higher than the wear resistance of these steels in the initial state.

Plates of carbon and alloy steels, both in the annealed and hardened state, are able for qualitatively explosion cladding with both copper and aluminum. The Rockwell hardness of the surface layer of metals after explosion cladding increases significantly: copper becomes 10...30 times harder, manganese steels without quenching and tempering – 2...2.5 times, manganese steels after quenching and tempering – 1.5...1.6 times, carbon steels – 2...2.7 times.

The obtained results are not limited in application only by explosion welding processes. They also can be used for stress evaluating in profiled and sheet blanks calibrating and in the process of step strain by the explosive forming.

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