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Excavator bucket teeth strengthening using a plastic explosive deformation

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Relevance of the work

Elements of mining equipment parts of ball mill stone crushers, rock cutting tools, grinding device hammers, pneumatic and hydraulic hammers, drill bits, bucket teeth of excavators and rippers operating under excavation of steel rocks are subjected to shock-abrasive wear. The reason for the short life of the units (less than one shift) is not breakage but wear. Repairs and restoration of these parts are extremely expensive and significantly increase production costs and reduce the efficiency of enterprises. A premature wear of these parts is most often the result of an ill choice of a hardening treatment method excluding the impact of the abrasive nature and operational loads. Therefore, solving the ways of increasing operational life time and durability of parts of mining equipment is extremely important and offers significant economic benefits.

To improve the durability or performance of the parts, constructive and technological methods are used. The most wearable surfaces of excavator buckets and teeth are reinforced by welding of studs [1], as well as through creation of conditions for self-sharpening. Among the technological methods of surface hardening of parts the most commonly used are: plastic deformation, thermal and thermo-mechanical treatment, chemical and heat treatment, welding and spraying, laser irradiation, sintering powders, electro-explosive alloying, etc. Among the methods of plastic deformation the explosive hardening and explosive and heat treatment [2] are the most effective ones. These methods of hardening give the best combination of part mechanical properties for decreasing an impact-abrasive wear [2].

The researches results and materials

The purpose of the research is to find reserves to enhance the wear resistance of teeth of excavator buckets by the explosive hardening which would ensure the required combination of properties of parts after the hardening treatment for maximum durability of excavator bucket teeth. The choice of materials and methods of the hardening treatment is largely dependent on the operating conditions, which are mainly determined by the form of wear. When classifying types of wear by the degree of the abrasive fixation and the nature of its impact on the wearable parts [1], the predominant type of wear of excavator bucket teeth in a steel rock excavation (Poltava GOK) is the wear by a stiffly fixed abrasive, namely the fraying against the monolith [1]. In this case the largest pieces of rock are considered as monolith. [1]

The choice of a method of increasing wear resistance should be made in the same manner as of the material for parts working in the conditions of the abrasive wear [1]. At first the multiplicity of the necessary part life n is determined [1]. It should be borne in mind that the life of the excavator bucket teeth depending on the manner of work and skills of the excavator operator is different. We focus on the most wearable teeth, using the diagram of the resource of excavator bucket teeth efficiency. The durability is desirable to be increased by 15% or 1.15 times; 2.15, etc.

The next step is to determine the type of wear. It has been determined earlier and corresponds to the impact-abrasive wear by a stiffly fixed abrasive. In this case the wear of excavator bucket teeth occurs when the shock interaction of particles or abrasive projections with the wearable surface takes place. The excavator bucket teeth are made of high manganese austenitic G13L steel. In the hardened state the steel has an austenitic structure, high stiffness and wear resistance under shock loads and high pressures. The wear of this steel is the result of the plastic shift, brittle spalling and micro-macro-scratching. The analysis of the worn surfaces shows that micro- and macro- scratches with the depth of $2.5\cdot10^{-7}$ to $500\cdot10^{-7}$m, micro- and macro-tear-offs with the area from $3\cdot10^{-4}$ to $100\ 10^{-4}$ m^2 at a depth of up to $6\cdot10^{-2}$m appear on the teeth and bucket in the working conditions at Poltava GOK. Thus, the durability of components under a shock-abrasive wear is affected by the hardness of the wearable surface, strength and ductility. The hardness increases the scratch resistance and strength, and the ductility increases resistance to the chipping and plastic shift.

According to the modern wear theory, the latter in conditions of the impact-abrasive wear by a fixed abrasive is determined by the dependences obtained by G.M. Sorokin [3]

$$u = f\frac{H_a}{H_t}\frac{A}{\sigma_t\psi}\beta\gamma \quad (1)$$

where u - wear by weight; f - coefficient of friction; A- work done by external forces of friction, ψ - relative narrowing; σ_t- temporary fracture resistance; γ - density of steel; H_a, H_t - hardness of the abrasive and tooth.

However, if you previously thought that the minimal wear by weight corresponds to the maximum intensity of strain, according to the more recent data the minimal wear corresponds to the limit uniform strain. Therefore, in dependence (1) the expression $2\psi - \psi_{eq} + (\psi_{rel} - \psi_{eq})$, where $2\psi - \psi_{eq} + \Delta$, ψ_{rel} - limit uniform relative narrowing, and $\Delta = \psi_{rel} - \psi_{eq}$, where ψ_{rel} - maximum relative narrowing, is more preferable to be used instead of ψ. Furthermore, the expression $\Delta = H_{rel} - H_{eq}$, where H_{rel} - hardness, corresponding to a limit relative narrowing, should be used instead of $H_m + 2H_m - H_{eq} + \Delta$, where H_{eq} - hardness corresponding to the maximum uniform strain.

In turn, the coefficient of friction and work performed by the external friction forces are also functions of hardness and plasticity. Establishing the wear depending on a complex of parameters finally gives the universal criterion of durability, i. e. the product of the tensile strength σ_{rel} by the relative reduction ψ. However, the dependence of steel wear-resistance on simultaneous influence of strength and ductility does not have the optimum ratio of these quantities.

Some parameters, which are represented in dependence (1), can be expressed in terms of relative deformation, they are:

- relative reduction $\psi = \varepsilon/(1+\varepsilon)$; (2)

- friction coefficient $f = \left(\frac{\lambda}{\sigma_s} + \beta\right)$, (3)

where σ_s - yield strength; λ, β – constants.

- friction forces work $A = f\sigma_p \cdot u \cdot F$, (4)

where σ_p - normal pressure in the contact plane; *F*- area of the tooth surface.

Also it was established [4] that when the relative deformation $\varepsilon = 0{,}2 - 0{,}3$ reaching, the connection between the hardness and stress intensity is nearly linear and has the form

$$HBu = K_1\varepsilon \quad (5)$$

$$\sigma_{rel} = K_2\varepsilon\ , \quad (6)$$

wher K_1, K_2 - proportionality coefficient; for the Hadfield steel $K_1 = K_2 = K$ =0,67.

Taking this into consideration, the equation is reduced to the form:

$$u = H_a\sigma_p Fu \cdot K^{-4}\varepsilon^{-5}\left[\lambda^2 + 2\beta\lambda\varepsilon + K^2\beta^2\varepsilon^2 + \lambda^2\varepsilon^2 + 2\beta\lambda K\varepsilon^3 + K^2\varepsilon^4\beta^2\right]$$
(7)

The dependence $u = F(\varepsilon)$ (Fig. 1) has an extreme point when compressive deformation. When the abrasive hardness limit values and normal pressure in the contact plane, the mass wear is minimum if deformations are close to the uniform.

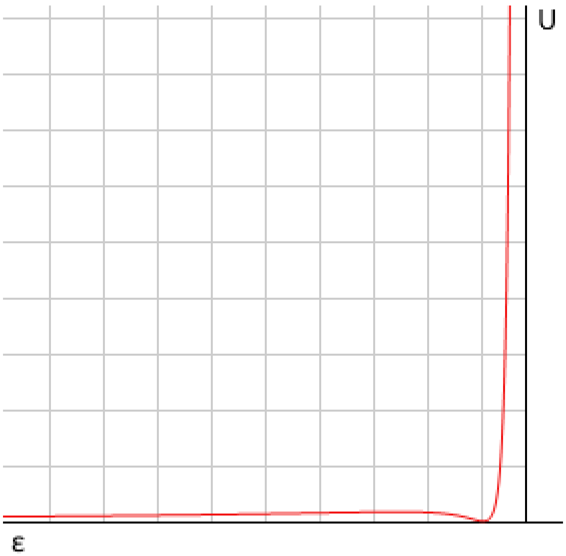

Figure 1. The character of mass wear change caused by deformation

Among the methods of hardening of high-manganese steel the explosive method provides high strength and ductility. The theory and practice of the explosive treatment is being developed and not all the features and aspects of the action of the explosion are revealed and found the proper application. Improving the efficiency of the existing technologies, in particular, the explosive hardening can occur in the following areas:

- optimization of the parameters of the explosive hardening;
- development of combined methods of treatment;
- creation of new methods of the explosive treatment.

The optimal regime of the explosive loading of a work-piece surface in terms of strengthening and maximum wear resistance is the one which provides the maximum increment of tensile strength σ_{rel} (or hardness) while minimizing disruption of plasticity, as compared to their initial values. The physical aspect of the optimization process is to select and justify the optimization parameters, and the technological one is to ensure the conditions of loading (deformation) of the surface part layer corresponding to the selected values of these parameters. For a material with specified physical and mechanical properties, the value $\Delta\ \sigma_{rel}$ (increment of tensile strength) due to the impulsive loading depends on the following basic physical factors: the velocity of the shock front shifting (with a cap charge of the explosive, i.e. the detonation velocity), the pressure at the front of the shock wave, residual stress distribution after a pulse loading. The optimal physical state is determined by the competing influence of two processes of physical hardening (work hardening), on the one hand, and a loss of strength or increasing the ductility due to formation of micro-defects and fragmentation of structural components of a hardenable material, on the other hand. Currently it is found [3-6], the degree of the physical hardening to improve the wear resistance of parts is optimal at the maximum intensity of deformation. The maximum intensity of deformation under the shock-wave loading occurs at the critical impact velocity, when the sample is destroyed at the point of impact. According to Karman and Taylor [2]

$$u_{cr} = \int_0^{\varepsilon_м} \left(\rho^{-1} d\sigma / d\varepsilon\right)^{0,5}, \qquad (8)$$

where ρ - density of the material; $\varepsilon, \varepsilon_м$ - degree of current deformation and deformation corresponding to yield strength; $d\sigma / d\varepsilon$; $d\sigma / d\varepsilon$ - tangent of the slope to the curve of hardening of the material.

According to the experimental data of D.S. Kladko and D.S. Vud given in [2], for the Hadfield manganese steel $u_{кр} = 230$ m/s.The calculated values (2) exceed these values 2.5 times.

The relative deformation along the normal to the shock front [2] is

$$\varepsilon_r = u / D = 1 - \rho_0 / \rho = 1 - v / v_o \qquad (9)$$

where ρ, ρ_0 - initial and final (after the passage of the shock front), density of the metal; v_0, v - initial and final volume of the metal.

For RDX D=6200 м/с, $\varepsilon_r = 3{,}7$ %, v / v_0=0,963.

The total strain is

$$\varepsilon_n = \frac{4}{3} v / v_0 = 0{,}050$$

For ammonite 6GV D=3600 м/с; $\varepsilon_r = 6{,}4$ %, v / v_0=0,936; $\varepsilon_n = 0{,}088$.

These data correspond to the regimes of the explosive hardening recommended for the industrial use [2].

As for the next direction, currently the most high wear resistance of Hadfield steel is achieved by the explosive heat treatment [4]. The latter includes the strengthening by the explosion, followed by the re-crystallization annealing, which provides a fine-grained structure of the equilibrium. However, the use of an additional heat treatment of parts is costly and unproductive in an open cut. In this case, it is more effective to use an additional explosive treatment, which leads to the formation of fine dispersion structures with the implementation of a non-dislocation plasticity mechanism [5]. It is possible with an additional hardening of surfaces by converging shock waves [5] through the intervening medium for which, as a rule, water is used. In the open cut production it is more technologically to use small fractions of the produced products. Another option would be to strengthen a surface by the "traveling" oblique shock wave by collision with a technological plate, being thrown. The hardening process parameters correspond to the parameters of the explosive welding, specifically the upper boundary of the explosive welding. In this case, the melt formed at the interface does not have time to harden and the weld joint collapses. In the surface layer the microcrystalline structure is formed as a result of a rapid cooling. The tests have shown that the combination of operations of the explosive hardening by a plane shock wave with the hardening by converging shock waves reaches such wear of teeth, as when hardening by the explosive heat treatment. When combined hardening processes of a "traveling" oblique wave or a plane wave with hardening by shock waves because of the collision with the plate being thrown the wear resistance is increased by 25-30% compared with the explosive heat treatment. To improve the performance of the combined treatment, the processes of hardening can be combined as follows Fig. 2. At the first stage the contact hardening of excavator bucket teeth takes place. At the second stage the hardening is carried out as follows. Untreated teeth 4 are placed fan-like (Fig. 2a). The explosive charge 1 is placed on the hardenable surfaces. Between adjacent teeth charges pre-hardened teeth 5 are placed.

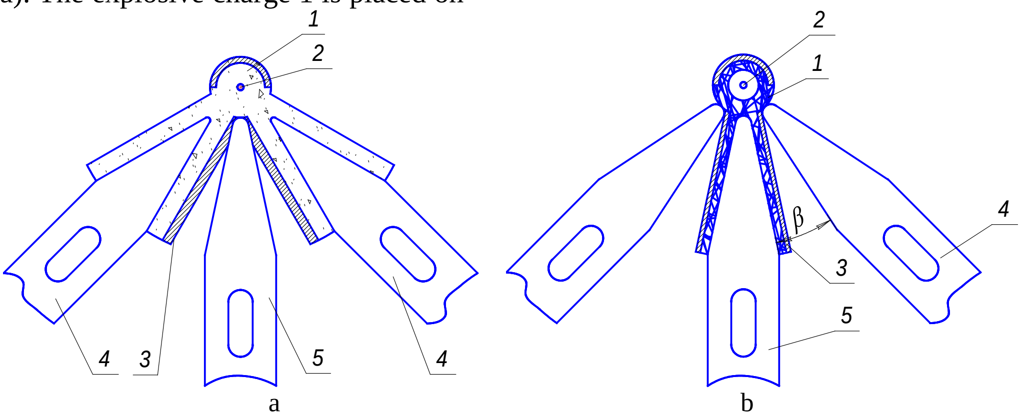

Figure 2. Diagram of multiple hardening of excavator bucket teeth 1 – an explosive; 2 - electric detonator; 3 - striker plate; 4 - excavator bucket teeth subjected to primary hardening; 5 –an excavator bucket tooth subjected to secondary hardening

Depending on the re-loading scheme the following can be implemented: 1) strengthening teeth 4 by the hurlled oblique impact plate; 2) strengthening by converging shock waves; 3) loading providing intensive plastic deformation of the surface layer of the hardenable surfaces. In this case (Fig. 2b) a striker plate 3 is mounted between the overlaid explosive charge 1 and the surface.

The last line seems to be associated with the formation of chemical elements in commercially pure iron and carbon steels in the ultra-deep penetration of micro-particles and the reactions of the "new class" (nuclear) in the shock-compressed materials. Developed in works by V.K. Borisevich and V.V. Sobolev [5] the method of dynamic effects and the results may be used in the development and creation of fundamentally new technologies of explosive metalworking in the future.

Thus, the first step is hardening of Hadfield steel by plane shock wave, and on the second step by traveling shock wave. Additional shift under repeated loading reinforces the material more quickly than under plane dynamic compression. Under the same level of pressure, the hardening parameters by traveling wave pressure are increases by 6 ÷ 9%. The same phenomenon is observed when high-speed rolling [7]. Also in this case, plasticity is increased.

At secondary loading, an angle between the surface of the explosive charge and the surface of the tooth has the major effect on the degree of hardening. Therefore, the experiments in the angle influence on Hadfield steel hardening were performed. The angle varied from 5º to 45º every 5º. During the experiments and their statistical processing, it was found that the maximum hardening is achieved at the angle = 16º30'moreover in these experiments the explosive distance was varied. It allowed building of the ratio of surface hardness after HB hardening to the initial HB_0 from the explosive distance.

In addition it should be noted that the cutting edge of a tooth is subjected to an extremely uneven wear. The edges adjacent to the side faces of the tooth are particularly wearable. It is possible to further improve the hardness and wear resistance of these areas in case the flat overlaid explosive charge is initiated from three points by linear charges located along the axis of the tooth. One point is in the center of the edge of the tooth and the other two edges are at sides. At undermining the linear charges the counter detonation wave fronts are formed. This doubles the pressure at the lateral edges of the tooth and accordingly to improving the hardness and wear resistance of these areas.

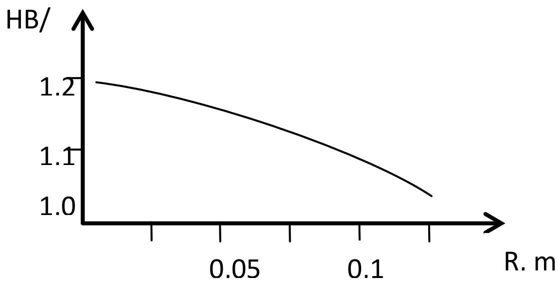

Figure 3. The ratio of hardness before and after hardening to the initial from the explosive distance

Conclusions

The reserve for increasing the wear resistance and durability of components of mining equipment subjected to the explosive hardening is the optimization of the process parameters to ensure high levels of hardness and ductility of the hardenable material and the development of combined methods of the explosive treatment. The most high durability under the impact-abrasive wear, more than 3 times, is provided by using a combination of hardening by a plane shock wave with the shock waves from the collision of the impact plate with the hardenable surface and a three-point initiation of the overlaid explosive charges.

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