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Deformation Wave Hardening of Metallic Materials

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The article deals with the machine parts hardening by means of deformation waves generated by the impact system with a waveguide as an intermediary member. The conditions for the efficient use of impact energy for elastoplastic deformation of the processed material and creation of the deep hardened surface layer.

Keywords: Hardness, Head, Waveguide, Hardening, Plastic deformation, Impact, Impact wave, Resistance to penetration.

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1. INTRODUCTION

Hardening by means of surface plastic deformation (SPD) is widely used to increase the component life and load-carrying capacity of the machine parts working under cyclic loading. PDP processing has low energy intensity and does not require the use of complex technological equipment.

During SPD a strong work-hardened surface layer is formed; its parameters depend largely on the deformation force. Depending on the type of deformation force the SPD methods are divided into static and impact. Impact loading is energetically more favorable than the static one, so it is more often used when it is necessary to create deep hardened surface layer [1]. However, impact methods of SPD are not so widespread as static ones. This is largely due to the fact that to control the impact energy during elastoplastic deformation is much more complicated than to control the static loading, because in the case of the same kinetic energy of impact, the energy consumed by plastic deformation can be different. It is difficult to predict the parameters of hardened surface layer obtained under the influence of impact loading, especially when deep and intense hardening is necessary.

The conducted research shows that the results of hardening using impact methods depend significantly on the form and the duration of the impact pulses [2]. Impact pulse duration determines the lead time of the processes of elastoplastic deformation of hardenable material. Previously, short pulses generated by primitive impact systems were used for hardening. When exposed to short pulses the processes of microstructure transformation do not take place to the full extent. Pulse rise and pulse tail characterize the change of the deformation force of the processed material in the deformation zone (pulse form) and determine the impact energy share consumed during elastoplastic deformation. Therefore, to achieve high efficiency of hardening it is necessary to select the form and duration of a pulse for each processed material. The general guideline is the necessaty to increase the impact pulses duration with the increase of the initial hardness of the material.

Controlling the pulse parameters in the deformation zone, it is possible to increase significantly the efficiency factor of the process and to predict with greater accuracy the necessary parameters of surface layer hardening.

2. DESCRIPTION OF THE OBJECT AND THE RESEARCH METHODS

It is possible to control pulse parameters by deformation waves arising in the impact system at impact. To obtain prolonged pulses in the deformation zone it is rather efficient to use the head –-waveguide system (Fig. 1).

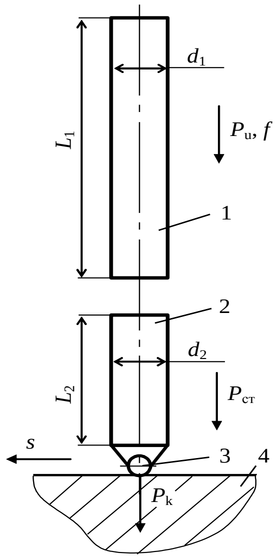

Fig. 1 – The scheme of material hardening by impact deformation waves: 1 – head, 2 – waveguide, 3 – tool, 4 – hardenable material;
P_u – pulse force, f – impact pulses frequency, P_{st} – static force, P_k – contact force in the deformation zone, s – feeding; L_1, L_2 – length of the head and the waveguide, respectively, d_1, d_2 – the diameter of the cross section of the head and the waveguide, respectively

While hardening the head periodically hits the statically pressed against the hardenable surface waveguide with the tool at the end. Preliminary static load-

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ing of the waveguide does not allow it to stop contacting with the hardenable surface after hitting, providing the recovery of the reflected deformation waves [3, 4].

At hitting, forward and backward deformation waves are formed in the head and the waveguide, accordingly. Forward wave reaches the loading surface and is distributed to the passing into the hardenable material, and reflected waves. When keeping the impact system in contact with the hardenable surface during the time exceeding the deformation wave period, backward and reflected waves with the frequency determined by the parameters of the impact system will reach the deformation zone and further affect the hardenable material, prolonging deformation impact.

The parameters of the head − waveguide impact system influencing the formation of the impact pulse in the deformation zone are: the material and the geometric shape of the elements of the impact system; the ratio of masses, cross-section areas, and the lengths of the head and the waveguide. To obtain different variants of energy states of head and waveguide after the impact, they can be made from materials with different speed of propagation of an impact wave. However, due to high-energy of the transmitted impact waves, tool or die steels, having high-strength level, are usually used for their manufacturing. Waveguide most often has the shape of a smooth cylindrical rod. The head also has a cylindrical shape with small joggles; the sizes of these joggles depend on the type of impact pulses generator drive. Therefore, the regulation of deformation waves propagation in the impact system is usually carried out by changing the ratio of cross-section areas r and the ratio of lengths n of head and waveguide.

A distinctive feature of the deformation wave hardening is the possibility of adapting the form of impact pulses to the physical and mechanical properties of the loading material, as well as to the degree of the curvature of the tool and the loading surface so that to transfer the greatest amount of kinetic energy of impacts to the material. The characteristic of the resistance of the material to penetration of the tool, expressed in terms of coefficient k is used for this purpose.

Along with the ratio of geometric parameters of the head and the waveguide, the coefficient of the resistance to penetration k plays an important role in the formation of the impact pulses in the deformation zone. To determine the characteristic of the resistance of the loading material it is appropriate to use the dependence 'force – penetration'. A model in the form of a broken line with a monotonically decreasing inclination of segments to the x-axis can be used as an approximate model 'force – penetration' for materials with elastoplastic properties, (Fig. 2).

Mathematically, this model is written as follows

$$P_1(\alpha) = k_1\alpha ;$$

$$P_2(\alpha) = k_2\alpha + P_1 ;$$

$$P_n(\alpha) = k_n\alpha + P_{n-1} .$$

This model allows approximating any real dependence 'force – penetration' to the required accuracy by a number of straight-line segments, and for adequate representation eight segments are usually enough [5].

This approach was used for describing impact deformation waves which are used for elastoplastic deformation when hardening metallic materials.

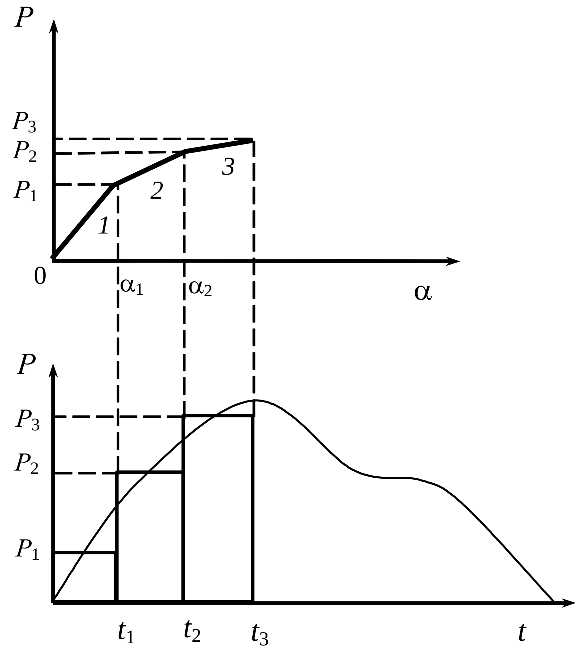

Fig. 2 – The influence of the characteristic force (P) – penetration (α) on the impact pulse form, i.e. change of force (P) according to time (t)

3. DESCRIPTION AND THE RESULTS ANALYSIS OF THE

When hardening metallic materials using SPD, elastoplastic deformation α occurs in the contact patch of the tool and the loading surface; it includes elastic α_e and plastic α_p components. The force required for the partial crush of the tops of microroughnesses of the loading surface, for the initial and subsequent elastic deformation at the penetration of the tool, is less than force required for plastic deformation, and is 3...8 % [6]. In this regard, at a certain approximation, the dependence $\alpha = f(P_u)$ can be replaced by $\alpha_p = f(\phi P_u)$, where ϕ is the plasticity coefficient, $\phi = 0,92 ... 0,97$; P_u is the impulse force.

According to [7] the dependence 'force – penetration' for the depth of plastic deformation $\alpha_p \le 0,7…1$ mm and the impact velocity $v = 1…10$ m/s can be represented as follows

$$\alpha_p = \frac{P_u}{2\pi R_r n_d} , \tag{1}$$

where R_r is the equivalent radius of the curvature of the tool and the hardenable surface, mm; HD is the processed metal plastic hardness, MPa

$$HD = \left(\frac{HB}{1,96}\right)^{\frac{1}{0,89}},$$

where HB is the hardness, measured by Brinell method, MPa; n_d is the plastic hardness dynamic coefficient

$$n_d = 0,5(1 - 137\frac{v}{HD} + \sqrt{1 + 2250\frac{v}{HD}}) .$$

Therefore, the coefficient of the resistance to penetration is written as follows

$$k = \varphi P_u / \alpha_p ,$$

or, taking into account formula (1)

$$k = 2\pi R_r HD n_d \varphi , \qquad (2)$$

From formula (2) it follows that the values of k are determined by the curvature of the tool and the loading surface, characterized by R_r, the material properties of the loading surface, characterized by HD, and impact velocity v. It has been found that k is to greater degree influenced by the equivalent radius and plastic hardness, and this influence is approximately the same.

As the tool penetrates into the material, the hardness of the last, as well as the equivalent radius of the curvature (due to the deformation of the hardenable surface) will increase, and, correspondingly the coefficient of the resistance to penetration will increase. Therefore, the new conditions arisen during the process of deformation will be described by a new coefficient of the resistance to penetration.

To set a dependence of $k(t)$ (where t is the coordinate of impact pulse time in the range 0 ... T) the following assumptions are admitted. The initial plastic hardness of the material HD_0 and the initial equivalent radius of the curvature of the tool and the hardenable surface $R_{пр\,0}$ will correspond to the initial value $k_0 = k(0)$; the hardness of the material, which can be achieved under these conditions of deformation hardening HD_{max} and the final equivalent radius of the curvature of the tool and the hardenable surface $R_{r\,max}$ will correspond to the final value $k_{max} = k(T)$.

$$k_{max} = 2\pi R_{rmax} HD_{max} n_d \varphi^1 .$$

When calculating the dependence $k(t)$ it is necessary to take into account that the value of HD_{max} must not exceed the maximum hardness of the material achieved in the process of deformation hardening. For some most frequently subjected to deformation hardening steel grades it was experimentally found out the following values of the maximum achievable degree of hardening: for steel 45 this value is 90 %, for steel 9ХС it is 20 %, for steel 110Г13Л it is 200 %, for steel 40Х it is 90 %, for steel 30ХГСА it is 35 %, for steel ШХ15 it is 25 %.

The initial value of the coefficient of the resistance to penetration significant for creating work-hardened surface layer during the deformation hardening has been experimentally defined $k_0 = (2,5…7,5)\cdot 10^8$ N/m.

A number of guidelines for hardening the surfaces of parts with different curvature from different materials with a characteristic value of the coefficient of the resistance to penetration have been obtained as a result of studying the efficiency of the impact systems with the intermediary member with different geometric parameters of head and waveguide.

It has been found out that the change of cross-section area of the head and the waveguide r has the greatest influence on the share of impact energy transferred to the deformation zone of the processed workpiece. Less significant is the ratio of the lengths of the head and the waveguide n.

For hardening with a small coefficient of resistance to penetration which is close to $k_0 = 2,5\cdot 10^8$ N/m the maximum transmission of impact energy to the hardenable material occurs at $r = 1…2$. With the increase of k_0 it is advisable to select heads and waveguides with cross-section area close to one (Fig. 3).

Since the ratio of the lengths of a head and a waveguide has little effect on the amount of energy transferred by impact pulses to the deformation zone, to reduce the overall dimensions of the pulse generator, for the reasons of design, it is advisable to shorten the length of a waveguide. It is also necessary to take into account the recommendations on the geometry of a waveguide ($L_2/d_2 > 3$, where L_2 and d_2 are the length and the diameter of the waveguide), when the laws of wave theory of impact come into force [1, 3]. On this basis, the recommended range of the geometric parameters of the impact system 'head – waveguide' used for deformation wave hardening is: n = 3...5, r = 1...2.

To carry out the process of hardening by deformation waves pulses a special design of the pulse generator is used; the basic element of the pulse generator is an impact system 'head – waveguide' [8]. The transfer of the energy of impact waves is performed due to the condition of obtaining the maximum efficiency of the process. The necessary form of impact pulses is selected according to the physico-mechanical characteristics of hardenable metal and the geometry of the tool and the hardenable surface. The adjustment of the form of impact pulses takes place at the stage of pre-production, while adjusting the pulse generator changing the geometric parameters of its impact system 'head – waveguide'.

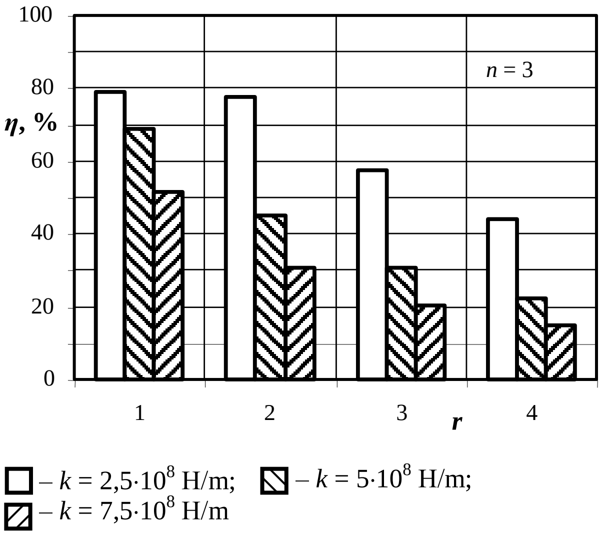

Fig. 3 – The amount of impact kinetic energy η, transferred to the hardenable material when loading by impact system 'head – waveguide' depending on the changes in cross-section areas of the head and the waveguide r and the coefficient of resistance to penetration k

As a result of pulse actions plastic impressions of a certain size − single tool marks are formed on the hardenable surface. Hardened surface layer is formed in the result of multiple pulse actions, the zones of which have relative displacement adjusting impressions overlapping and defining the uniformity of hardening.

The depth and uniformity of the hardened surface layer are determined by the energy and frequency of impact deformation waves, the shape and size of the deforming tool, workpiece feeding relative to the tool [9-11].

High energy of deformation impact waves (10 ... 200 J), and conditions facilitating its penetration to a great depth, allow creating a deep hardened surface layer of 6...10 mm. Adjustment of the displacement of impact waves application to the hardenable surface allows obtaining different overlapping of deformed areas and, thus, heterogeneously hardened structure providing several-fold increase in contact endurance.

4. CONCLUSION

The possibility of material hardening by means of deformation waves generated by impact system with a waveguide as an intermediary member has been determined. The system of guidelines on setting the parameters of the impact system 'head – waveguide' with regard to the maximum efficient use of the impact energy and ensuring the high efficiency of the process has been worked out.

The technological possibility of obtaining a deep hardened surface layer as a result of the impact of deformation wave has been established. It is significantly higher compared to the processing using other known methods of surface plastic deformation.

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