Development of technology and research of method of electric hydropulse hardening of machine parts

Dmytro Marchenko
Mykolayiv National Agrarian University
Mykolayiv, Ukraine
marchenkodd@mnau.edu.ua

Aleksandr Dykha
Khmelnytsky National University
Khmelnitsky, Ukraine
tribosenator@gmail.com

Victor Aulin
Central Ukrainian National Technical University
Kropyvnytskyi, Ukraine
aulinvv@gmail.com

Kateryna Matvyeyeva
Mykolayiv National Agrarian University
Mykolayiv, Ukraine
matveeva@mnau.edu.ua

Kateryna Tishechkina
Mykolayiv National Agrarian University
Mykolayiv, Ukraine
tishechkinakv@mnau.edu.ua

Viacheslav Kurepin
Mykolayiv National Agrarian University
Mykolayiv, Ukraine
kypinc@ukr.net

***Abstract*—The article presents studies of dynamic processes that occur during an electrohydropulse discharge. A method and design of a device for hardening parts by an electrohydropulse high-voltage discharge in a liquid has been developed. The proposed method allows to obtain a depth of the hardened layer up to 30 mm with compressive stresses throughout its depth and a uniform microscopic relief of the working surface.**

Keywords—high-voltage discharge, pulse current generator, electromechanical hardening, electric discharge chamber.

I. INTRODUCTION

Currently, in the repair industry, the technology is most widely used, in which the restoration of the dimensions of the part occurs through distribution. However, the parts restored using this technology have a number of significant drawbacks, the main of which is the large residual stresses in the material of the sleeve, which, in the end, leads to the destruction of the part.

One of the promising ways to develop a technology for restoring worn-out parts such as a sleeve is using an electro-hydraulic effect for this purpose.

However, during the passage of an electro-hydraulic explosion of a metal wire, there is some uneven development of the explosion, and, accordingly, the deformation of the sleeve occurs non-uniformly. As a result, the sleeve after recovery has a large barrel-shapedness, taper, a large curvature of the axis, which leads to uneven or insufficient allowance for finishing machining. Therefore, this technology has not found wide practical application.

A method and technology for distributing bushings with mechanical shock pulses is proposed. Using a collet device, a shock pulse, which is generated by an electric-discharge generator of elastic vibrations, is transmitted to the renewable part. The large amplitude of the shock pulse, which performs the work of distributing the sleeve, is preceded by a high-speed ZAG elastic high-frequency oscillations. These vibrations excite the diffusion activity of the atoms of the deformed metal. Due to this, the friction forces between the collet and the wrought metal are reduced and its ductility increases. The uniformity of the deformation of the sleeve is ensured by the uniform distribution of pressure created by the collet on the surface of the sleeve. The increase in the distribution of the sleeve is provided by increasing the diffusion mobility of the atoms of the deformed metal.

II. ANALYSIS OF BASIC ACHIEVEMENTS

Domestic experts paid attention to the methods of electromechanical hardening of steel parts of rotation with carbide rollers by passing electric current through a contact spot for a long time - back in the 60s of the twentieth century. Studies have shown that with a current strength of I = 300–2000 A and a voltage of U = 2,5–6,0 V, the depth of the hardened (white) layer is 0,05–1,5 mm. Under this layer, residual tensile stresses most often occur, which reduce the fatigue strength of hardened parts, therefore, combined technologies are used to eliminate the negative effect of these stresses. In this case, the electromechanical treatment is carried out either before surface plastic deformation due to rolling by the rollers, or after. As a result of this, residual tensile stresses are converted to compressive ones. However, this greatly complicates the hardening technology [1-3].

It was shown in [4] that electrohydropulse treatment with a high-speed liquid jet directed normal to the machined surface of welded samples of aluminum-magnesium alloys allows not only to reduce tensile stresses in the weld, but also to make them compressive, equal in absolute value to the initial stresses. In this case, there is an increase in the hardness of the metal along the axis of the weld by 23%.

We have proposed a method and developed a design of an electromechanical hardening device for parts using a high-voltage pulse discharge in a liquid. This allows you to get the depth of the hardened layer up to 30 mm, to create residual compressive stresses in the surface layer and a regular microscopic relief of the treated surface [5].

III. PURPOSE OF THE STUDY

To study dynamic processes in an electrohydropulse discharge based on which to develop method and design of a device for hardening parts by electrohydropulse high-voltage discharge in a liquid.

IV. RESULTS OF RESEARCH

During electromechanical hardening of steel parts by rotation with carbide rollers when electric current is passed through the contact patch (current strength, I = 300-2000 A, voltage U = 2,5-6,0 V), the depth of the hardened (white) layer is 0,05-1,5 mm [5]. Residual tensile stresses most often occur under the white layer, which reduce the fatigue strength of hardened parts, therefore, combined technologies are used to eliminate the negative influence of residual tensile stresses. Electromechanical processing is preceded by surface plastic deformation (SPD) by rolling by rollers, or rolling by rollers is carried out after electromechanical processing [6, 7]. As a result of this, residual tensile stresses are converted to compressive ones. However, this greatly complicates the hardening technology.

We have proposed a method and developed a device design and technology for electromechanical hardening of parts using a high-voltage pulse discharge in a liquid, which makes it possible to obtain a hardened layer depth of up to 30 mm, to create residual compressive stresses in the surface layer and a regular microscopic relief of the treated surface [5].

A device for electromechanical processing of rotation parts is shown in Fig. 1.

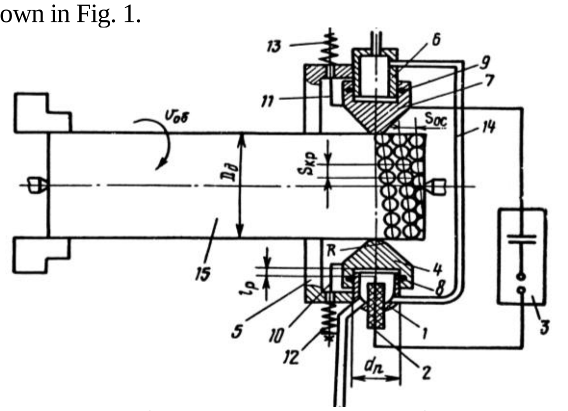

Fig. 1. Device for electromechanical hardening of rotation parts

The device consists of an electric discharge chamber 1, with a positive electrode 2 installed in it, connected to a pulse current generator 3 (PCG). The working end of the chamber 1 is made in the form of a punch 4 with a profile radius. The housing of the chamber 1 is connected to the frame 5, at the opposite end of which the chamber-hydraulic cylinder 6 is fixed, the end of which is the punch 7. O-rings 8 and 9 are installed in the bores of the punches 4 and 7. Axes 10 and 11 are attached to the punches 4 and 7, on which the springs 12 and 13 are installed. The electric discharge chamber 1 and the hydraulic cylinder chamber 6 are interconnected by a hydrochannel 14. The frame 5 is mounted on a support of the lathe, in the centers of which the workpiece 15 is installed. The punch 7 is electrically connected to the negative pole of the gas turbine 3. Electric discharge camera 1 and the camera-hydraulic cylinder 6 are filled with the working fluid (water and electric resistance of not less than 15 Om · m).

After installing the part 15 in the centers of the lathe, when the pump is turned on, water is pumped under pressure through the electric discharge chamber 1 and the chamber-hydraulic cylinder 6, which ensures the pressing of punches 4 and 7 to the workpiece. In this case, the springs 12 and 13 are compressed. Turns on the rotation of the part 15 at a speed and the feed of the machine support along the axis of the part 15. When the PCG 3 is turned on, high voltage is applied to the electrode 2, a length of water is broken, an impulse current flows between the electrode 2 and the end of the punch 4 and a discharge channel is formed, which is a low-temperature plasma, and gas-vapor cavity. The pulsed current flows through the contact surface of the punches 4 and 7 with part 15 and the electrical connection with the negative pole of PCG 3. In this case, the pulsed current heats the surface layer of the part to ≈ 900^0C and the surface layer is quenched by heat removal to the mass. When expanding the vapor-gas cavity, a quasistatic pressure is created, transmitted through the punches 4, 7 and the workpiece 15. Plastic deformation of the surface layer of the part to depth is carried out. High-voltage pulses follow with a frequency, the part rotates for each pulse by an amount. At the end of processing, PCG 3 and the pump for supplying water to the discharge chamber are turned off, the rotation of part 15 and the feed of the machine support are stopped. Using the springs 12 and 13, the punches 4 and 7 are retracted from the part 15.

First, a thermal pulse is created on the surface of the hardened part due to the passage through the surface of contact with the part of the pulse current that occurs during high-voltage breakdown in the discharge chamber. Due to the abrupt heat removal to the mass of the part, a thermally hardened layer with depth is created on its surface. Then, due to the expansion of the vapor-gas cavity in the discharge chamber, a shock pulse is generated and transmitted to the end of the punch by pressure, which provides plastic deformation of the surface layer of the component to a depth, the material of the component undergoes cold hardening, residual compressive stresses occur in the surface layer, and the surface of the component is circular and axial The feed creates a regular surface microrelief.

The depth of thermal hardening δ_T is calculated by the formula

$$\delta_T = (1{,}8-3{,}0)10^{-4} U_O^{2/3} C^{1/2} R_K^{1/3} L^{-1/6}\text{, m,} \qquad (1)$$

where U_O - PCG charging voltage, V; C - the capacity of the capacitors PCG, F; L - inductance of the discharge circuit, G; R_K - electrical resistance of the contact surface of the punch with a hardened part, Om.

When the radius of the sphere is 0,03 m of the punch 7 and the force of pressing the punch to the part P_1 = 500 N, the electrical resistance of the contact of the punch with the part is determined from the ratio

$$R_K = \frac{U}{I}.$$

With voltage U = 2,5 V, current I = 470 A

$$R_K = \frac{2{,}5}{470} \approx 5 \cdot 10^{-3} \text{ Om.}$$

The depth of mechanical hardening and occurrence of residual compressive stresses is determined by the dependence

$$\delta_M = 10^2 C^{-1/24} U_O^{1/6} L^{-1/8} \eta^{1/4} d_n \sigma_T^{-1/2}\text{, m,} \qquad (2)$$

where η - electro-acoustic efficiency of the high-voltage discharge, = 0,01 – 0,05; d_n - diameter of the punch, m; σ_T - yield strength of hardened metal, Pa.

The amount of heat released on the contact surface of the punch with the part when passing through the contact of the pulse current for the pulse duration t according to the Joule – Lenz law

$$Q = 0{,}24 I_{avg}^2 R_K t\text{, cal,} \qquad (3)$$

where I_{avg} - the average value of the current in the pulse.

Taking the curve of the current in the form of a sinusoid, we have

$$I_{avg} = \frac{I_{max}}{\pi}\int_0^{\pi} \sin t dt = \frac{I_{max} 2}{\pi}.$$

Substituting the value I_{avg} in (3) we obtain

$$Q = 0{,}097 I_m^2 R_K t\ . \qquad (4)$$

Taking into account the values of the coefficients $\mu = 0{,}6$ and $K = 0{,}234$, taking into account the part of the heat generated in the contact zone, which is removed to the part, and the part of the heat released in the part, which is absorbed by the ultra-high temperature volume, we obtain the expression for the heat going to heat a thin layer of the part

$$Q_1 = 0{,}6 \cdot 0{,}234 \cdot 0{,}097 I_{max}^2 R_\kappa t = 0{,}0136 I_{max}^2 R_\kappa t \cdot \qquad (5)$$

The amount of heat released in the contact zone of the punch with the part due to their mutual friction during rotation of the part is neglected, since under pulsed loading the friction coefficient is small.

Given L, C, U_0 and the length of the interelectrode gap l = (80 - 90) mm, we take

$$I_{max} = 0{,}4 U_0 \sqrt{\frac{C}{L}}\,, \qquad (6)$$

and

$$t = 2\pi\sqrt{LC}\,. \qquad (7)$$

Substituting (6) and (7) into (5), we obtain

$$Q_1 = 0{,}00218 \cdot 2\pi U_0^2 R_k C^{3/2} L^{-1/2} = 0{,}0137 \cdot U_0^2 R_K I^{3/2} L^{-1/2}\,. \qquad (8)$$

Taking the minimum temperature of phase transformation for this steel equal to 900^0C and heat capacity at a temperature of 400^0C, we obtain

$$\gamma\, C = 7{,}8 \cdot 0{,}16 = 1{,}25 \text{ cal/cm}^3 \cdot \text{grad},$$

where C, γ - are the specific heat and density of the metal, respectively.

Taking the volume of the heated metal layer in the form of a hemisphere of radius δ_T, we determine the amount of heat required to heat this volume to 900^0C,

$$Q_2 = \gamma\, C 900 \frac{2}{3} \pi \delta_T^3 = 1{,}25 \cdot 900 \frac{2}{3} 3{,}14 \delta_T^3\,;\ Q_2 = 2355 \delta_T^3\,. \qquad (9)$$

Given $Q_1 = Q_2$, we obtain in accordance with (8)

$$\delta_T = 1{,}8 \cdot 10^{-2} U_0^{2/3} C^{1/2} L^{-1/6} R_K^{1/3}\text{, cm} =$$
$$= 1{,}8 \cdot 10^{-4} U_0^{2/3} C^{1/2} L^{-1/6} R_K^{1/3}\text{, m.}$$

For given values U_0 = 50 kV, C = 1 mkF, L = 1 mkG, R_K = 5 · 10^{-3} Om, we obtain

$$\delta_T = 1{,}8 \cdot 10^{-4} (50 \cdot 10^3)^{2/3} (10^{-6})^{1/2} (10^{-6})^{-1/6} (5 \cdot 10^{-3})^{1/3} =$$
$$= 4{,}3 \cdot 10^{-4} \text{ m} = 0{,}43 \text{ mm.}$$

The feed per axial pulse per revolution $S_{\kappa p}$ of the part in the axial S_{oc} directions is taken equal to $2\delta_T = 0{,}85$ mm. This ensures that at a pulse repetition rate of $f_И = 50$ Hz, the peripheral speed of rotation of the part is obtained

$$V_{OK} = f_И 60 \cdot 2\delta_T = 2{,}5 \text{ m/min.}$$

We calculate the depth of mechanical simplification (hardening) and the propagation of compressive residual stresses in the surface layer δ_M. The pressure in the electric discharge chamber can be calculated by the formula [3]

$$P_m = \frac{314{,}48}{R_1} \cdot \sqrt{\eta W / t_p}\text{, Pa,} \qquad (10)$$

where R_1 - radius of the development of the gas-vapor cavity, m; t_p - discharge time, s; W - stored energy in the capacitors PCG, J; η - electro-acoustic efficiency of the electric discharge chamber, R_1^* = 0,032 mm at W_1 = 312,5 J.

Accepting the condition that for such high-voltage discharges in chambers of a closed volume, the specific volume energy is constant, we obtain

$$R_1^3 = \frac{R_1^{*3} W}{W_1} = \frac{0{,}032^3}{312{,}5}\,,\ R_1 = 4{,}7 \cdot 10^{-3} W^{1/3}\text{, m.} \qquad (11)$$

From (10) and (11) we have

$$P_m = \frac{314{,}48}{4{,}7 \cdot 10^{-3}} W^{-1/3} \eta^{1/2} W^{1/2} t_P^{-1/2} = 67 \cdot 10^3 W^{1/6} t_P^{-1/2} \eta^{1/2}\,. \qquad (12)$$

Punch Force

$$P = P_m \frac{\pi d_n^2}{4}\,.$$

In view of (12), we obtain

$$P = \frac{67 \cdot 10^3}{4} \pi W^{1/6} t_P^{-1/2} \eta^{1/2} d_n^2\,. \qquad (13)$$

The depth of hardening and the depth of compressive residual stresses when exposed to a spherical punch on a steel part will be calculated according to [4]

$$\delta_M = \sqrt{\frac{P}{2\sigma_T}}\text{, m,}$$

where σ_T - yield strength of the metal, Pa; P - force, N.

In view of (13), we obtain

$$\delta_M = 162 W^{1/2} t_p^{-1/4} \eta^{1/4} d_n \sigma_T^{-1/2}\,, \qquad (14)$$

where $t_P = 2\pi\sqrt{LC}$;

$$W = \frac{C U_0^2}{2}\,.$$

After substituting these expressions in (14), we obtain

$$\delta_M = 10^2 C^{-1/2} U_0^{1/6} L^{-1/8} \eta^{1/4} d_n \sigma_T^{-1/2}\,. \qquad (15)$$

With values C, L, U_0, and the length of the interelectrode l_P = (80 - 90) mm; η = 0,05.

At d_n = 0,16 mm; $\sigma_T = 4 \cdot 10^8$ Pa get

$$\delta_M = 10^2 (10^{-6})^{-1/24} (50 \cdot 10^3)^{1/6} (10^{-6})^{-1/8} (0{,}05)^{1/4} 0{,}16 (4 \cdot 10^8)^{-1/2} =$$
$$= 0{,}0225 \text{ m} = 22{,}5 \text{ mm.}$$

Select [δ_M] ≥ 0,05 D_∂. In this case, [δ_M] = 20 mm.

For the experimental determination of the impact force of the vibrator plate on the hardened part, we use the elastic-contact method based on the measurement of elastic local deformations upon impact of hardened bodies against spherical and flat ends (Fig. 2) [5].

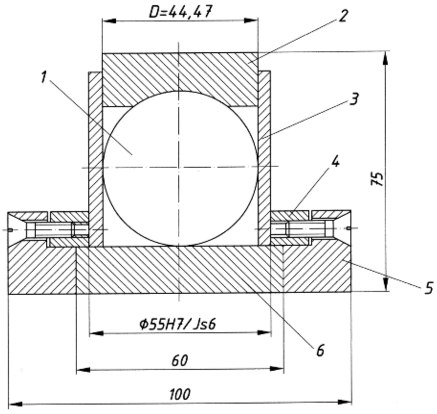

Fig. 2. Scheme of a device for measuring impact force by the elastic contact method: 1 - ball; 2 - a punch; 3 - sleeve; 4 - case; 5 - emphasis; 6 - plate

Therefore, the values of the hardening depth and the depth of residual compressive stresses obtained during processing according to the proposed method guarantee an effective increase in the fatigue strength of a part with a diameter of 500 mm, and the thickness of the white layer δ_T = 0,43 mm will provide a long service life of the part from the point of view of its wear resistance.

The radius of the spherical tip was calculated according to the recommendations of [6] to exclude plastic deformation in the contact zone according to the formula

$$P = \frac{E_y d_k^3}{(1-\mu^2)D_ш}, \qquad (16)$$

where E_y - modulus of elasticity, for steel E_y = 2 · 10^5 N/mm^2; μ - Poisson's ratio, for steel μ = 0,3.

The appearance of the device for measuring the impact force by the elastic contact method is shown in Fig. 3.

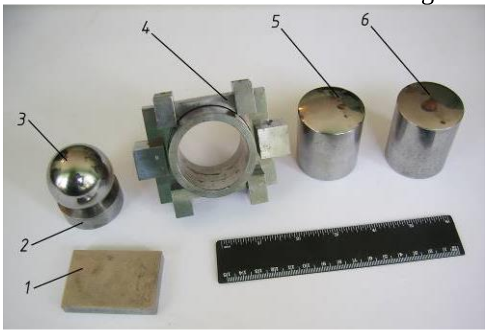

Fig. 3. Appearance of a device for measuring impact force by the elastic contact method: 1 - plate; 2, 5, 6 - punches; 3 - ball; 4 - case

The registration of readings comes down to measuring under the microscope the diameter of the circle, which is the boundary of the surface of the elastic touch of the bodies upon impact. So that this boundary is visible, one of the surfaces that come into contact is covered with a layer of a substance (for example, a three percent solution of paraffin on gasoline), which exhibits an elastic contact zone. The solution was applied with a brush to a flat plate, with the evaporation of benzene a thin layer of paraffin was formed on the plate.

Static calibration of the device was carried out on a Brinell press with 10 measurements at a force of 2,5; 5,0; 10; 15 kN. The confidence interval for the value of the imprint diameter is calculated with a confidence probability of 0,95. The dispersion did not exceed the value of $S \leq 0{,}05$. The accuracy of measuring force increases with its growth. For a force of 2,5 kN - $\varepsilon = 16\%$, for a force of 10 kN - $\varepsilon = 8\%$. The accuracy of measuring the force of impact can be increased to $\varepsilon = 3\%$ [5], if calibration is done on a more accurate press.

A calibration curve for determining the impact force by the diameter of a print of a ball with a diameter of 44,47 mm is shown in Fig. 4.

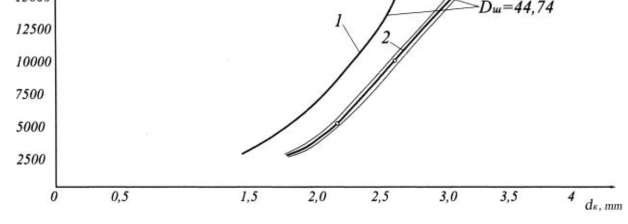

Fig. 4. Dependence of impact force on imprint diameter: 1- theoretical curve calculated by the formula (16); 2- calibration curve

In order to exclude plastic deformation in the contact of the ball with the plane, the force should be limited to [*P*] ≤ 490$D_ш^2$, where $D_ш$ - in cm according to [6].

For a ball with a diameter of 44,47 mm, the allowable force, [*P*] = 10 kN. In order to measure large forces, larger diameter balls or punches with increased radii of curvature were used.

V. CONCLUSION

A numerical analysis of the dynamic processes occurring in the plate-rod system confirmed the order of the mean pressure values measured by the Hopkinson method.

As a result of the calculations, the maximum value of the efficiency of converting electric energy into mechanical energy was obtained due to the following parameters of the discharge circuit:

- inductance of the discharge circuit L = 10 mkH;
- capacitance of the capacitor bank C = 0,3; 0,5 mkF;
- voltage in the discharge circuit U = 50 kV;
- interelectrode gap lp = 30 mm.

An analysis of the data obtained on the breakdown losses showed that in some cases they can reach more than 50% of the stored energy. From this it follows that the selection of the optimal parameters of the circuit and the geometry of the electrode system must be carried out necessarily taking into account the breakdown losses. Thus, it becomes necessary to conduct a comprehensive study of all stages of a discharge under conditions of a limited volume of electric discharge chambers and increased hydrostatic pressure. Only on the basis of the results of such a study, it is possible to develop practical recommendations for choosing the parameters of the electric circuit and the geometry of the electrode system to ensure optimal operating conditions of the device for electromechanical hardening of rotation parts.

REFERENCES

[1] V.M. Grabovy. The science and technology foundations of electric power pulses for the structure and power of the alloys for alloying the basis for aluminum and aluminum: Abstract. dis. ... Dr. tech. Sciences / FTIMS NAS of Ukraine. Kyiv, 2007. 42 p.

[2] G.V. Volkov. Peculiarities of the morphology of intermetallic inclusions in a liquid aluminum alloy during processing by an acoustic field // Casting processes. 2006. No. 3. pp. 8–12.

[3] V.M. Tsurkin, G.V. Volkov, A.V. Sinchuk. Injection of electrohydroimpulse rosmelt sampling on elements of structural elements in metals. MOM. 2004. No. 4. pp. 10–14.

[4] B.I. Semenov, V.S. Ivanova. The concept and controls of the formation of the crystalline structure of castings in new casting methods. Foundry. 2001. No. 5. pp.20–25.

[5] B.I. Butakov. Basic principles of the technology of pulsed and low-speed mechanical action on the structure and properties of metals and alloys: Abstract. dis. ... Dr. tech. Sciences: 05.02.01 / NAS of Ukraine. Kyiv, 1992. 52 p.

[6] A.V. Dykha, D.D. Marchenko, V.A. Artyukh, O.V. Zubiekhina–Khaiiat, V.N. Kurepin Study and development of the technology for hardening rope blocks by reeling. ISSN 1729–3774, Eastern–European Journal of Enterprise Technologies. Ukraine: PC «TECHNOLOGY CENTER», 2018. №2/1 (92) 2018. pp. 22–32. https://doi.org/10.15587/1729-4061.2018.126196.

[7] A.V. Dykha, D.D. Marchenko. Prediction the wear of sliding bearings. ISSN 2227–524X, International Journal of Engineering and Technology (UAE). India: "Sciencepubco–logo" Science Publishing Corporation. Publisher of International Academic Journals, 2018. Vol. 7, No 2.23 (2018) pp. 4–8. https://doi.org/10.14419/ijet.v7i2.23.11872.