Efficiency of hybrid equipment combining operations of surface hardening by high frequency currents and abrasive grinding

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Abstract. The methods of different processing steps concentration on the same equipment have been gaining wider application at the current stage of cutting machining development. It allows improving performance and reducing energy costs in the processing of machine components. The paper considers the finishing stage of the manufacturing process of a machine critical part. In comparison with the standard technology, the integrated treatment applied at the finishing stage of the manufacturing process is proved to improve the performance by the factor 3.5 for the main processing time and reduce energy consumption by the factor 5.7.

1. Introduction
The object of these studies is the finishing stage of the manufacturing processes comprising the operations of rigid steel components surface hardening by high frequency currents (HFC) and abrasive grinding.

These operations are traditionally separated in the machine components manufacturing process. Taking into account of the errors arising at the previous stage of the manufacturing process, the deformation of the material during thermal hardening and the components installation errors, the machining allowance for final treatment should be significant. Therefore, the thermal operation must provide a deeper hardening than that specified by the design, and the finishing mechanical operation must remove the most effective part of the surface layer [1, 2].

One of the main limitations in the intensity of the metal removal rate at grinding hardened steel workpieces is the high heat release rate. It leads to the formation of defects (burns and residual tensile stresses), with the probability of these defects occurrence growing with the increase in the allowance for this operation.

The most simple and reliable means to lessen the heat release rate at the grinding process is to reduce the depth of cut by decreasing the general allowance for final treatment. The achievement of the maximum effect becomes possible with the use of hybrid processing that combines the operation of surface thermal and mechanical finish treatment at one process equipment [3 - 8].

The aim of the work is to show the efficiency of combining surface hardening by HFC and grinding operations in one process equipment.
2. Theory and methods
We selected plain bearing used in process equipment (Figure 1) made of steel 60 as a sample for field experiments.

Figure 1. Bearing model for loom

The finishing stage of the manufacturing process was performed at a 3M151V circular grinding machine. Surface hardening was executed at a VChG 6-60/0.44 industrial tube generator with a current operating frequency of $440 \times 10^3$ Hz [9-11]. The workpiece dimensions control in the manufacturing process was performed by the Form Talysurf Series 2 surface profiler.

The theory of dimensional chains and the methodology presented was selected to determine the linear operational dimensions conditioned by the required depth of the thermo-hardened layer [12].

3. Results and discussion
The achievement of the set aim is exemplified by the manufacturing process finishing stage of the bearing for the SULZER RUTI loom (Figure 1) processed according to two different schemes: by standard technology and by the proposed integrated treatment.

The finish stage of the standard manufacturing process of this component provides for the following operations: turning, hardening by HFC and grinding (Table 1). According to the design conditions, the outer cylindrical surface 1 must have a hardened layer with the depth of $0.8...1.2$ mm and hardness $60+4$ HRC. The values to define are the dimension $D_1$ whose tolerance is specified; the manufacturing depth of the hardening by HFC $A_T$ and tolerance for it $\delta_T$; minimum allowance for final processing $z_{min}$.

This task was accomplished by the methodology presented in [12], according to which $D_1 = D_{e1}$ and $\delta_{e1} = 0.12$ mm, $A_K = 0.8...1.2 = 0.8$ mm $^{0.4}$, master link tolerance $\delta_K = 0.4$ mm.

1. The tolerance on the depth of HFC hardening $\delta_T$ (which is determined on the basis of experimental data, as a rule) must be known to determine the allowed fluctuations in the depth of cut $\delta_c$. HFC hardening is performed with the stabilization of input power. In this case, the main criterion for determining the change in the depth of the hardened layer is the constant gap between the inductor and the heated surface.

According to the standard technology, the workpiece is based on the surface 2 by the hard fixture installed in the centers. Hardening is performed in a sequential progression by the ring inductor $D_1^{0.87}$ (Figure 2). The manufacturing clearance between the inductor and the workpiece is 3 mm. In this case, the clearance variation is due to the displacement of the workpiece rotation center which is determined by the form error of the inductor and the installation error of the workpiece.
Table 1. The initial data on the allowances and operating dimensions calculation for the processing of the hardened surface

| Number of the operation | Draft | The operation and technical requirements for its implementation |
|-------------------------|-------|---------------------------------------------------------------|
|                         | ![Diagram](image) | Turning the surface 1. Ellipticity within tolerance on diameter $D_1$ which is to be determined. |
| 24                      | ![Diagram](image) | Surface 1 hardening by HFC at the depth $A_T$. The hardness of the hardened surface is $HRC_{60..64}$. Increase in $D_1$ diameter caused by the $8 \ldots 10 \mu m$ swelling per each millimeter of the hardened layer thickness. |
| 27                      | ![Diagram](image) | Finish grinding of the surface 1. |
| 30                      | ![Diagram](image) | |

Figure 2. Diagram of workpiece HFC hardening by standard technology

The workpiece is rotated to obtain a symmetrical circumferential hardened layer. The experimental data demonstrated that under these conditions of HFC hardening, provided the inductor is adjusted relative to the centers axis, $\delta_T = 0.1 \text{ mm}$. In this case, $\delta = 0.4 - 0.1 = 0.3 \text{ mm}$. 
2. The allowed value of the total spatial displacement $\sum \delta_{ei}$ is determined taking into account the operating tolerances for axis misalignment $\delta_{ei}$, the sequence of operations, methods of location and installation.

According to [13] the increase in the specific volume of the hardened surface is 0.5% for steel 60. The expected increase in diameter at surface hardening with limited directions of free extension is $8 \ldots 10 \ \mu m$ per each millimeter of the hardened layer thickness. In this case, the depth of hardening according to the standard technology is $1.25\ldots1.35 \ mm$, therefore the value of $A_p = 0.01\ldots0.0135 \ mm$, $\delta_p = 0.0035 \ mm$. On this basis, the tolerance $\delta_{i-1}'$ is defined:

$$\delta_{i-1}' = \delta_i + \delta_p = 0.12 + 0.0035 = 0.1235 \ mm.$$ 

In this case, $2\delta_{iA} = \delta_i - \frac{\delta_i + \delta_{i-1}'}{2} = 0.3 - \frac{0.015 + 0.1235}{2} = 0.23075 \ mm$.

3. The possible value of the total spatial displacement $\sum \delta_{ei}$ is determined taking into account the operating tolerances for axis misalignment $\delta_{ei}$, the sequence of operations, methods of location and installation.

The finishing operations 27 and 30 of the standard technology provide for a set of three rigid fixtures, which allows breaking the tolerance of the surface 2 into three regions. In this case, the error of the workpiece location on rigid fixture is:

$$\epsilon_{L1} = \delta_0 + \delta_1 + \delta_2 = 0.03 + 0.1 + 0.03 = 0.16 \ mm,$$

where $\delta_0$ is the minimum clearance, $\delta_1$, $\delta_2$ are the hole and fixture tolerances, mm.

The error of the fixture location in the centers is $\epsilon_{L2} = 0.02 \ mm$. The error of the workpiece and fixture setting is $\epsilon_S = 0.03 \ mm$. The general workpiece installment error:

$$\epsilon_{i} = \epsilon_{L1} + \epsilon_{L2} + \epsilon_S = 0.16 + 0.02 + 0.03 = 0.21 \ mm.$$

In addition to the installment error, the value of the total spatial displacement is influenced by the magnitude of deformation $\delta_i$ (bent, warping) of the hollow cylinder after surface hardening. The deformation occurs due to the uneven depth of hardened layer and depends on the wall thickness, on the ratio of the wall thickness and diameter of the cylinder, on the relative depth of hardened layer. The hardening of the outer surface results in the emergence of "barrels". In this case the value $\delta_1 = 0.014 \ mm$. Then $2\Sigma \delta_{ei} = \epsilon_i + \delta_i = 0.21 + 0.014 = 0.224 \ mm$. In this case, the condition $\sum \delta_{ei} \leq \delta_{iA}$ is observed.

4. The desired dimension, i.e. the manufacturing depth $A_T$ of the thermo-hardened layer is determined. Limiting values of the closing dimension are:

$$A_{Kmax} = A_{Tmax} - t_{min} \quad \text{and} \quad A_{Kmin} = A_{Tmin} - t_{max}.$$ \hspace{1cm} (1)

High quality final surface treatment after thermo-hardening is possible provided $t_{min} \geq (R_z - T)_{i-1}$, where $R_z$, $T$ is the surface roughness and depth of the defect layer in the preceding processing. This minimum allowance should also be provided at unfavorable combination of the parameters that affect its value: at $D_{1-1max}$ and $D_{j-1max}$. The operation 24 is a semi finish turning $R_z = 0.06 \ mm$, $T_{i-1} = 0.06 \ mm$. Hence $t_{min} = 0.06 + 0.06 = 0.12 \ mm$ and $t_{max} = t_{min} + \delta_i = 0.12 + 0.3 = 0.42 \ mm$.

Solution of the equations (1) regarding the desired dimension yields:

$$A_{Tmax} = A_{Kmax} + t_{min} = 1.2 + 0.12 = 1.32 \ mm;$$
5. The allowance for the final processing is defined by the equation:

\[ z_{imin} = 2(R_i + T_i)_{i-1} + 2\sum\delta_{ii} = 2 \times 0.12 + 0.224 = 0.464 \text{ mm}. \]

6. In this case, the dimension of the surface \( j \) pretreatment taking into account the swelling equals

\[ D_{i-1} = D_i + z_{imin} + \delta_{i-1} - A_{pmin}, \]

and then \( D_i = 85 + 0.464 + 0.12 - 0.00976 = 85.57424 \text{ mm}. \) According to the standard technology \( D_i \) is assumed to be 85.6 mm.

Thus, the required parameters are: the manufacturing depth of hardening \( A_T = 1.22 \pm 0.1 \text{ mm}; \) the dimension of the pretreatment \( D_i = 85.6 - 0.12 \text{ mm}; \) the allowance for final machining \( z_{imin} = 0.464 \text{ mm}. \) It should be noted that 10% of the workpieces are rejected because of burns and microcracks on the surface (according to the data from the plant).

The surface heating scheme which is characterized by lower values of power density and the heat source speed in comparison with the volumetric scheme must be implemented to provide this depth of the hardened layer by using the 440 kHz generator. At the inductor active wire width \( R_i = 12 \text{ mm} - q_i = 1.2 \times 10^7 \text{ W/m}^2, V_i = 2 \text{ mm/s}. \)

Two sites of the workpiece with a total length of 103 mm must be hardened. Both sites are processed in one axial movement of the workpiece relative to the ring inductor. Total workpiece stroke length taking into account the 6 mm grooves and the inductor entry and exit at the sequential progression of heating is \( l = 125 \text{ mm}. \) In this case, the main time is \( T_m = l/V_i = 62.5 \text{ s}. \) According to the HFC heat treatment engineering standards at the specified workpiece location method (Figure 2) the auxiliary time is \( T_{aux} = 20 \text{ s}. \) Thus, the unit performance is:

\[ P_u = \frac{1}{T_m + T_{aux}} = \frac{1}{62.5 + 20} = 0.0121 \text{ s}^{-1}, \]

and energy consumption is:

\[ E = \frac{q_i \cdot \pi \cdot D_i \cdot R_i \cdot l}{V_i} = \frac{1.2 \times 10^7 \cdot \pi \cdot 0.0856 \cdot 0.012 \cdot 0.125}{0.002} = 0.68 \text{ kW per hour}. \]

Finishing mechanical operation is performed according to the scheme of the infeed grinding. The processing cycle includes three phases: pregrinding, finish grinding and sparking-out. Since the hardened surface is processed, the grinding is performed on “soft” modes to avoid changes in the properties of the surface layer.

The auxiliary time for the installation on rigid fixture and centers adjustment is \( T_{aux} = 90 \text{ s}. \)

The modes of prerinading are: the removed allowance value is \( t = 0.2 \text{ mm}, \) speed of workpiece is \( V_w = 30 \text{ m/min} \) \((n_w \approx 110 \text{ rpm}), \) radial feed is \( S_r = 0.004 \text{ mm/rev}, \) the main processing time is \( \tau_{1p} = 60 \times 0.2/(110 \times 0.004) = 27.27 \text{ s}. \)

Finish grinding modes: \( t = 0.1 \text{ mm}, V_w = 30 \text{ m/min}, S_r = 0.001 \text{ mm/rev}, \) the main processing time is \( \tau_{2p} = 60 \times 0.1/(110 \times 0.001) = 54.55 \text{ s}; \) sparking-out time is \( \tau_{3p} = 10 \text{ s}. \)

The total processing time \( \tau_p \) is:

\[ \tau_p = \tau_{1p} + \tau_{2p} + \tau_{3p} = 27.27 + 54.55 + 10 = 91.82 \text{ s}. \]

Thus, unit performance is:
The effective power at infeed grinding by the wheel periphery is calculated by the dependence:

\[ P_u = \frac{1}{\tau_p + T_{aux}} = \frac{1}{91.82 + 90} = 0.0055 \text{ s}^{-1}. \]

The effective power at infeed grinding by the wheel periphery is calculated by the dependence:

\[ N = C_N V'_w S'_v d q b^y r^z, \quad (2) \]

where \( C_N = 0.14, r = 0.8, y = 0.8, q = 0.2, z = 1.0, d \) is the diameter of the workpiece \( b = 52 \text{ m} \) is the width of grinding. According to the dependence (2), the efficient power of pregrinding \( N_1 = 0.14 \cdot 30^{0.8} \cdot 0.004^{0.8} \cdot 85.6^{0.2} \cdot 52 = 3.25 \text{ kW}; \) finish grinding \( N_2 = 0.14 \cdot 30^{0.8} \cdot 0.001^{0.8} \cdot 85.2^{0.2} \cdot 52 = 1.07 \text{ kW}. \)

Effective capacity of the sparking-out process is negligible due to its smallness. Then the energy consumption for the grinding operation is:

\[ E = N_1 \tau_{p1} + N_2 \tau_{p2} = 3.25 \cdot 27.27 + 1.07 \cdot 54.55 = 0.04 \text{ kW-hour}, \]

and for the processing of two sites \( E = 0.08 \text{ kW-hour}. \)

The average temperature on the surface during pregrinding in the treatment area is estimated to be 435 °C [5, 7, 10].

The finishing stage using the proposed integrated processing. In this case, the three finishing operations are replaced by a single integrated one consisting of three transitions: smooth grinding, hardening by HEH HFC and finish grinding (sparking-out) (Table 2).

**Table 2.** The initial data on the allowances calculation and operational dimensions for treating the hardened surface using integrated processing

| № transition | Draft | The operation and technical requirements for its implementation |
|--------------|-------|---------------------------------------------------------------|
| 1            |       | Surface grinding. Ellipticity within tolerance on diameter \( D_1 \) which is to be determined. |
| 2            |       | Surface 1 hardening by HFC at the depth \( A_T \). The hardness of the hardened surface is HRC 60...64. Increase in \( D_1 \) diameter caused by the 8 ... 10 µm swelling per each millimeter of the hardened layer thickness. |
| 3            |       | Finish grinding of the surface 1. |
1. Hardening by HEH HFC is performed according to the scheme (Figure 3). In this case, the irregularity of the hardened layer depth is determined by the precise manufacturing of the inductor active wire and its position relative to the axis of the workpiece. Based on the experimental results and using the alignment of the inductor active wire according to the indicator $\delta_T = 0.05$ mm. Therefore, $\delta_t = \delta_K - \delta_T = 0.4 - 0.05 = 0.395$ mm.

![Figure 3. Scheme of combined workpiece machining](image)

$$\delta_{t-1} = \delta_t + \delta_p = 0.015 + 0.0055 = 0.0205 \text{ mm.}$$

Then the allowed value of the total spatial displacement is

$$2\delta_{\Delta t} = \delta_t - \frac{\delta_t + \delta_{t-1}}{2} = 0.395 - \frac{0.015 + 0.0205}{2} = 0.36975 \text{ mm.}$$

3. The proposed finishing stage of the manufacturing process is performed without reinstalling the workpiece; therefore, despite using the same fixture, the installment error $\varepsilon_Y = 0$. The first transition, i.e. surface grinding, eliminates the errors incurred at the previous stage of the manufacturing process and workpiece installment errors. This in turn ensures that the clearance between the inductor and the treated surface is constant. Hence, the uniformity of the hardened layer depth is achieved. In this case, the amount of warping after surface hardening $\delta_t = 0$. Then $2\Sigma\delta_{\Delta i} = 0$.

The real value of $\delta_t$ is $\delta_t = \sum \delta_{\varepsilon i} + \frac{\delta_t + \delta_{t-1}}{2} = 0 + \frac{0.015 + 0.0205}{2} = 0.01775 \text{ mm.}$

4. Finish grinding is executed after hardening; therefore, $T_{i-1} = 0$. Achieving the designed surface roughness $R_s = 0.8 \mu m$ is expected due to the use of the sparking-out process, since surface hardening is performed without changing the surface roughness and machining is carried out by one grinding wheel. Consequently, the value of $R_s = 0$, and therefore, $t_{\text{min}} = 0$, $t_{\text{max}} = t_{\text{min}} + \delta_t = 0 + 0.01775 = 0.01775 \approx 0.018 \text{ mm.}$

Solution of the equations (1) regarding the desired dimension yields:

$$A_{T_{\text{max}}} = A_{K_{\text{max}}} + t_{\text{min}} = 1.2 + 0 = 1.2 \text{ mm;}$$
$$A_{T_{\text{min}}} = A_{K_{\text{min}}} + t_{\text{max}} = 0.8 + 0.018 = 0.818 \text{ mm.}$$

5. The allowance for the final processing is defined by the equation:
\[ z_{\text{min}} = 2(R_z + T)_{i-1} + 2 \Sigma \delta_i = 0. \]

6. In this case, the dimension of the surface \( I \) pretreatment in view of the swelling is:
\[ D_{i-1} = D_i + z_{\text{min}} + \delta_{i-1} - A_{p_{\text{min}}} = 85 + 0 + 0.015 - 0.0065 = 85.0085 \text{ mm}. \]

Thus, the required parameters are: the manufacturing depth of hardening \( A_T = 0.82 + 0.38 \text{ mm}; \) the dimension of the pretreatment \( D_i = 85 - 0.003 \text{ mm}; \) the allowance for final machining \( z_{\text{min}} = 0. \)

According to a proposed processing scheme, the first transition is a workpiece pregrinding to the dimension \( D = 85 - 0.003 \text{ mm}. \) The processing cycle includes two phases: pregrinding and smooth grinding. Since the ground material is raw (unhardened), the modes of machining are "harder" than those of the standard technology.

The modes of pregrinding are: the removed allowance value is \( t = 0.29 \text{ mm}, \) speed of workpiece is \( V_w = 25 \text{ m/min} \) \( (n_w \approx 95 \text{ rpm}), \) radial feed is \( S_r = 0.015 \text{ mm/rev}, \) the main processing time is \( \tau_{1p} = \frac{60 \cdot 0.29}{95 \cdot 0.015} = 12.2 \text{ s}. \)

Smooth grinding modes: \( t = 0.01 \text{ mm}, \) \( V_w = 25 \text{ m/min}, \) \( S_r = 0.001 \text{ mm/rev}, \) the main processing time is \( \tau_{2p} = \frac{60 \cdot 0.01}{95 \cdot 0.001} = 6.3 \text{ s}. \)

Finish grinding is performed after surface hardening without resetting the workpiece. In this case, the allowance for finish grinding is formed by increasing the specific volume of the hardened surface, which occurs in the process of the steel structural, and phase transformations. With surface hardening depth being 0.82 mm, the expected value of the removed allowance is \( t = 7 \mu \text{m}. \) In this case, the grinding cycle is performed according to the scheme: finish grinding, sparking-out. Finish grinding modes are the same as for smooth grinding which precedes the transition to the surface hardening: \( t = 0.01 \text{ mm}, \) \( V_w = 25 \text{ m/min}, \) \( S_r = 0.001 \text{ mm/rev}. \) Therefore, the main processing time is \( \tau_{3p} = 6.3 \text{ s}. \)

The sparking-out process in the proposed processing scheme aims not so much at eliminating elastic deformations, but rather at increasing surface hardness and compressive residual stress in the surface layer of the material [5]. In this case the sparking-out time is increased at the expense of performance up to \( \tau_{3p} = 25 \text{ s}. \) Thus, the level of residual compressive stress is 12% higher.

The total main time of the two grinding transitions is:
\[ \tau_m = \tau_{1p} + 2\tau_{2p} + \tau_{3p} = 12.2 + 12.6 + 25 = 49.8 \text{ s}. \]

Thus, the piece productivity is:
\[ P_u = \frac{1}{\tau_m + T_{\text{aux}}} = \frac{1}{34.8 + 90} = 0.007 \text{ s}^{-1}. \]

According to the dependence (2), efficient pre-grinding power is \( N_1 = 8 \text{ kW}, \) smooth and finish grinding power is \( N_2 = 0.93 \text{ kW}. \) The time of finish grinding for removing the allowance of 7 \( \mu \text{m} \) is \( \tau_{3p} = 4.42 \text{ s}. \) Then the energy consumption for grinding operations, taking into account the two sites:
\[ E = 2(N_1\tau_{1p} + N_2\tau_{2p} + N_2\tau_{3p}) = 16 \cdot 12.2 + 1.86 \cdot 6.3 + 1.86 \cdot 4.42 = 0.06 \text{ kW-hour}. \]

The average temperature on the surface during pregrinding in the treatment area is estimated to be 640 °C [5, 7, 10]. During raw material grinding, it can lead to the emergence of significant tensile stresses in the surface layer of the material. However, in the subsequent transition of thermo-hardening these stresses are eliminated in the process of material heating and do not influence the final state of the material.

Surface hardening is performed between two grinding transitions, which means that the processing of each of the hardened cylindrical surfaces is carried out separately. The developed technique [10, 14] is used to assign the surface hardening modes for steel 60. The accepted heating power density value is
\( q_i = 2.6 \times 10^8 \text{ W/m}^2 \), the speed of the source is \( V_i = 55 \text{ mm/s} \) to ensure the depth of the hardened layer is \( h = 0.82 \text{ mm} \). Since hardening is performed in one workpiece set-up, \( T_{aux} = 0 \text{ s} \). In this case unit performance is equal to technological performance. Considering the two sites to be thermo-hardened on one workpiece, the unit performance \( P_u \) is:

\[
P_u = \frac{V_i}{2\pi D} = \frac{55}{(2\pi \times 85)} = 0.103 \text{ s}^{-1},
\]

and energy consumption

\[
E = \frac{2q_i \cdot b \cdot R_i \cdot \pi \cdot D}{V_i} = \frac{5.2 \times 10^8 \cdot 0.052 \cdot 0.002 \cdot \pi \cdot 0.085}{0.055} \approx 0.073 \text{ kW-hour}.
\]

4. Conclusion
In comparison with standard technology, the proposed treatment of this workpiece allows one to reduce the minimum technological depth of hardening from 1.22 mm to 0.82 mm, i.e. by the factor 1.5, with all subsequent advantages:
- improving the performance of surface hardening by factor 8.5 and reducing energy consumption by factor 9.3;
- increasing the grinding performance by factor 1.27 and reducing energy consumption by factor 1.3;
- excluding the possibility of wastage at finish grinding;
- improving performance properties.

On the whole, the performance of the main processing time increases by factor 3.5 and energy consumption is reduced by factor 5.7 in comparison of these indicators for the finishing stages of the manufacturing process.

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References
[1] Lobanov D V et al. 2017 IOP Conf. Ser.: Earth and Environ. Sci. 87(8) 082029
[2] Lobanov D V et al. 2017 Key Engineering Materials 736 81-85
[3] Rao S B 1997 Journal of Manufacturing Science and Engineering 119(4B) 713-716
[4] Lauwers B et al. 2014 CIRP Annals-Manufacturing Technology 63(2) 561-583
[5] Skeeba V Yu et al. 2015 Materials and Manufacturing Processes 30(12) 1408-1411
[6] Makarov V M 2011 RITM: Repair. Innovation. Technologies. Modernization 6(64) 20–23
[7] Ivancivsky V V, Skeeba V Y 2006 Obrabotka metallov 1 16-18
[8] Moriwaki T 2008 CIRP Annals -Manufacturing Technology 57(2) 736-749
[9] Ivancivsky V V et al. 2016 IOP Conf. Ser.: Mater. Sci. Eng. 156(1) 012025
[10] Skeeba V Y 2014 Obrabotka metallov 3 90-102
[11] Plotnikova N V et al. 2016 IOP Conf. Ser.: Mater. Sci. Eng. 156(1) 012022
[12] Ivashchenko I A 1975 Technological dimensional calculations and methods of their automation (Moscow: Mashinostroenie Publ.)
[13] Golovin G F, Zamyatnin M M 1990 High-frequency heat treatment: Problems of metallurgy and technology (Leningrad: Mashinostroenie Publ.)
[14] Ivancivsky V V et al. 2005 Obrabotka metallov 3 22-24