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Rationalization of modes of HFC hardening of working surfaces of a plug in the conditions of hybrid processing

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ABSTRACT

Introduction. The development of a cluster of hybrid metalworking systems in the machine tool industry is associated with a number of positive consequences. First, such systems help reduce production costs by optimizing the use of resources and energy. This is especially true in the face of increased competition and a trend towards savings. Secondly, hybrid systems enable the production of quality products with increased efficiency. By integrating various functions in one process equipment, metalworking processes become more efficient and precise. This reduces the amount of defective products and improves the quality of the final ones. In addition, hybrid metalworking systems have autonomous functionality, which is especially important in flexible engineering production, where rapid changeover and adaptation to various production tasks is required. Thus, hybrid metalworking systems represent an important step in the development of modern mechanical engineering, helping to reduce costs, increase efficiency and ensure high product quality. *The purpose of this work* is to increase efficiency and reduce energy consumption during surface-thermal hardening of machine parts through the use of concentrated energy sources under integral processing conditions. **Theory and Methods.** To achieve this purpose, studies were carried out on the possible structural composition and layout of hybrid equipment integrating mechanical and surface-thermal processes. When developing the theory and methods, the main provisions of the structural synthesis and components of metalworking systems were taken into account. Theoretical research is based on the application of system analysis, geometric theory of surface formation and design of metalworking machines. The experiments were carried out on a modernized multi-purpose machining center *MS 032.06*, equipped with an additional energy source, which was a microwave thyristor-type generator *SHF-10* with an operating frequency of 440 kHz, which implements high-energy heating by high-frequency currents. Structural studies were carried out using optical and scanning microscopy. The stress-strain state of the surface layer of the part was evaluated by mechanical and X-ray methods for determining residual stresses. The microhardness of the hardened surface layer of the parts was evaluated on a *Wolpert Group 402MVD* instrument. **Results and discussion.** An original method for conducting structural-kinematic analysis for pre-project studies of hybrid metalworking equipment is presented. Methodological recommendations were developed for the modernization of metal-cutting machine tools, allowing high-energy heating with high-frequency currents (*HEH HFC*) on a standard machine tool system and creating high-tech technological equipment with enhanced functionality. It has been experimentally confirmed that the introduction of the proposed hybrid machine into production in combination with recommendations for the appointment of high-frequency electric power units for integral processing of punch-type parts allows increasing the productivity of surface hardening by 36–40 times and reducing energy costs by 6 times.

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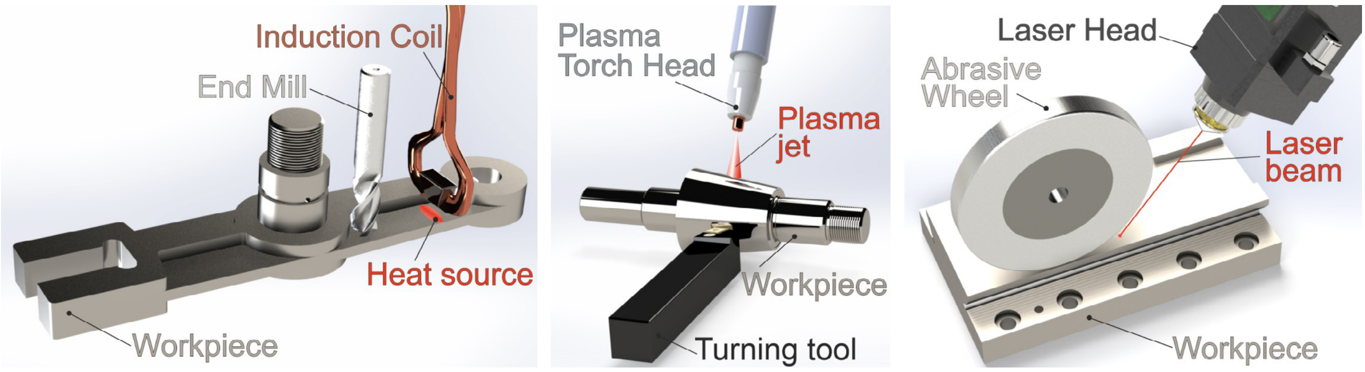
Introduction

In industrialized countries, the volume of metalworking products is in the range from 35 % to 40 % of the total production [1–3]. In turn, the industrial sector accounts for more than 50 % of global energy consumption, of which countries outside the Organization for Economic Co-operation and Development (*OECD*) account for up to 67 %. The use of energy and resources in the manufacturing sector is about 40 % and 25 % of world consumption, respectively. Recently, the concept of ensuring sustainable production is gaining momentum due to the awareness of this enormous ecological impact on the environment through the significant use of energy and resources [1–6]. There is a clear understanding that sustainable growth in production is possible only if the conditions for manufacturing products are realized, under which processes are used that minimize the negative impact on the environment, conserve energy and natural resources, are safe for employees, the public and consumers and are economically justified. Consequently, the success of the development of a particular production largely depends on the effective use of metalworking machines.

In this regard, in the strategically important and basic branch of mechanical engineering – machine tool industry – a cluster of hybrid metalworking systems has formed, in the design and creation of which the developers adhere to the principle of multifunctional integration [4, 7–18]. One of the options for this high-tech integral equipment is machine tools that combine several technological processes of different nature (fig. 1) (e.g. milling, turning or grinding using various additional energy sources [7, 14, 17, 19–70]). The designers' pursuance of increasing the technological potential of machine tools and ensure autonomous operation of hybrid equipment in adaptable production has led to the emergence and development of this class of equipment [7–9, 14, 16–21, 32–37, 47]. Industrial testing showed positive results, confirming the production cycle reduction for the manufacture of machine parts and a resource costs decrease when using such systems [7, 10, 14, 20–74].



a *b* *c*

Fig. 1. Varieties of hybrid metalworking machines that combine machining with various heat sources: *a* – Induction Assisted Milling (*IAM*); *b* – Plasma Assisted Turning (*PAT*); *c* – Laser Assisted Grinding (*LAG*)

The current investigation is concerned with the technological process of manufacturing a press brake plug, which includes the following operations: 1) machining, 2) milling and surface hardening, 3) high-energy heating by high-frequency currents (fig. 2). When developing a classical technological process for manufacturing this part, the operations of surface thermal hardening and milling are traditionally carried out on different equipment and in different workshops of a machine-building enterprise. As a result, at the thermal operation it is necessary to obtain a hardened layer of greater thickness than specified by the detailed drawing, and then, at the finish mechanical operation, remove the most effective part of the surface layer. Due to this approach, there is a decrease in efficiency both in the surface thermal and mechanical operations, as well as an increase in energy consumption at both stages of the technological process [7, 14, 17, 21, 47, 61, 71–75].

To solve this problem, it is proposed to combine two operations on one metalworking machine. Taking into account the modern development of microprocessor technology in the field of high-frequency thyristor-

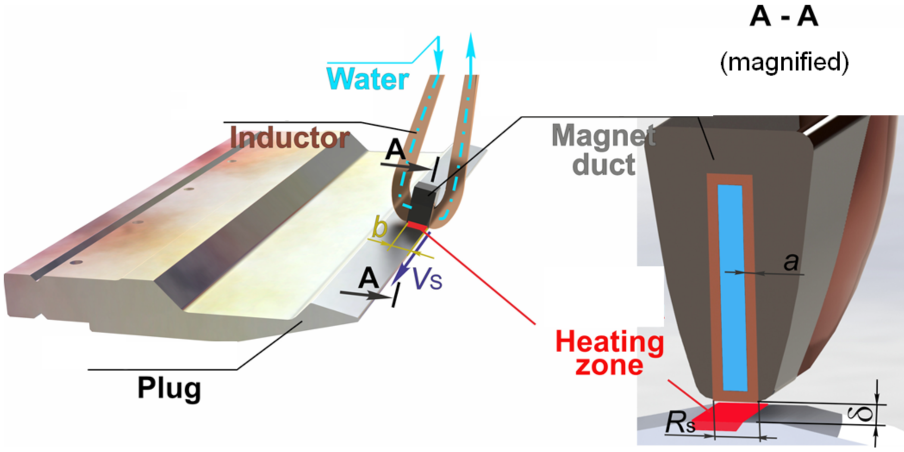


Fig. 2. Pattern of *HEH HFC* hardening of a punch

type industrial installations [76–81], as well as the principles of convenient integration into a hybrid machine tool system, in our work we consider the use of high-frequency generators of the *SHF-10* type with a power of 10 kW [7, 14, 61, 82].

The development of new methods for assigning processing modes, which will take into account the relationship between the combined operations of the technological process, is an urgent task. These technological recommendations should ensure the production of parts with a predetermined accuracy and certain physical and mechanical properties of its working surfaces [7, 14, 17, 47, 61, 71–75, 83].

The purpose of the work is to develop a methodology for assigning rational modes of *HEH HFC* hardening, which, under conditions of integral processing, increase productivity and reduce energy consumption during surface-thermal hardening of the working surfaces of the plug.

To achieve this purpose, it is necessary to solve the following **tasks**:

1) to develop a structural analysis methodology that that enables an effective pre-project research in the process of developing hybrid metalworking equipment. This methodology should take into account the possibility of integrating a source of concentrated energy into a standard machine tool system.

2) practical testing of the equipment complex that implements the *HEH HFC* technology in order to prove the effectiveness of its manufacturing application. During the testing process, the effectiveness of the technology under study will be evaluated in accordance with the specified criteria.

Methodology of experimental research

The executive movements of the *hybrid metalworking system* (*HMS*) and the required number of its adjustable parameters were determined by applying the structural-kinematic synthesis of the mechanisms of metal-cutting equipment [14, 82, 84–87]. The main provisions of the structural synthesis and components of the systems under consideration, given in [14, 82, 84–96], were used to study the proposed structural composition and layout of *HMS*, in which surface heat treatment and mechanical operations are integrated.

Materials and methods of full-scale experiments

For full-scale experiments, a press brake plug (fig. 3) made of *U10A* steel (Table 1) was chosen. The composition of the starting material was determined on an *ARL 3460* optical emission spectrometer.

To determine the linear dimensions, taking into account the required thickness of the heat-strengthened layer, we used the theory of dimensional chains and the method presented in the relevant works [97, 98].

The experiments were carried out on a modernized multi-purpose machining center *MS032.06*, equipped with an additional energy source, which was a microwave thyristor-type generator *SHF-10* with an operating frequency of 440 kHz, which implements high-energy heating by high-frequency currents.

Structural studies of the samples were carried out using a *Carl Zeiss Axio Observer Z1m* optical microscope and a *Carl Zeiss EVO 50 XVP* scanning electron microscope equipped with an *INCA X-ACT* energy dispersive analyzer (Oxford Instruments). The microstructure of the samples was revealed using

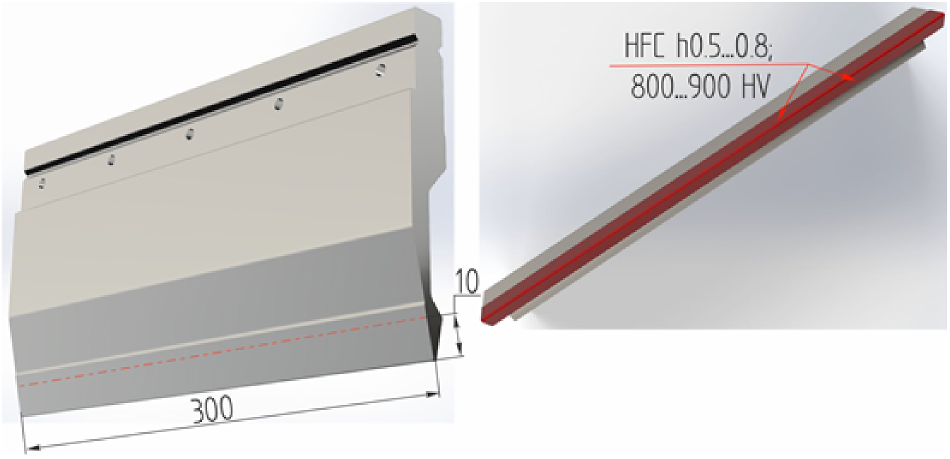


Fig. 3. Press brake plug

Table 1

Chemical compositions of initial material

Steel	Mass content of elements, [%]							
	C	*Si*	*Mn*	*S*	*P*	*Cr*	*Ni*	*Cu*
U10A	1.01	0.25	0.21	0.017	0.022	0.18	0.17	0.15

a 5 % alcohol solution of nitric acid and a saturated solution of picric acid in ethanol with the addition of surfactants [99].

The microhardness of the hardened surface layer of the parts was evaluated using a *Wolpert Group 402MVD* instrument. Residual stresses were measured using the X-ray method on an *ARL X'TRA* high-resolution diffractometer and the mechanical destructive method – layer-by-layer electrolytic etching of the sample [100, 101]. To detect defects in the surface layer, a visual-optical method was used using a *Carl Zeiss Axio Observer A1m* microscope, a capillary method, and an eddy current method using a *VD-70* eddy current flaw detector.

Statistical processing of the experimental studies results was carried out in the software products *Statistica*, *Table Curve 2D* and *Table Curve 3D*.

Results and discussion

In the process of developing integral metalworking equipment, it is planned to introduce the method of high-energy heating by high-frequency currents on a hybrid machine at one of the technological stages. Taking into account the design features of inductors for this process, the treated surface heating is carried out by localized areas, the dimensions of which are determined by the width of the active wire of the inductor and the length of the ferrite magnetic circuit (fig. 2). To ensure surface hardening, coordinated movements of the workpiece and tool are required, similar to those used in milling [7, 14, 17, 47, 82, 87]. Structural-kinematic analysis showed that at all stages of integral processing (pre-milling, hardening with high-frequency currents and finish milling), a similar set of executive movements and adjustable parameters is required.

Subsequent synthesis of the generalized kinematic structure of the developed hybrid metalworking system based on the five-coordinate machining center *MS 032.06* with a *CNC* control system, designed for high-performance processing of randomly located surfaces of parts installed on the worktable (fig. 4). With this method, the layout formula can be represented as follows:

$$[CAY0XZ]\left\{\left[\widehat{D}_h\right]+[d]\right\},$$

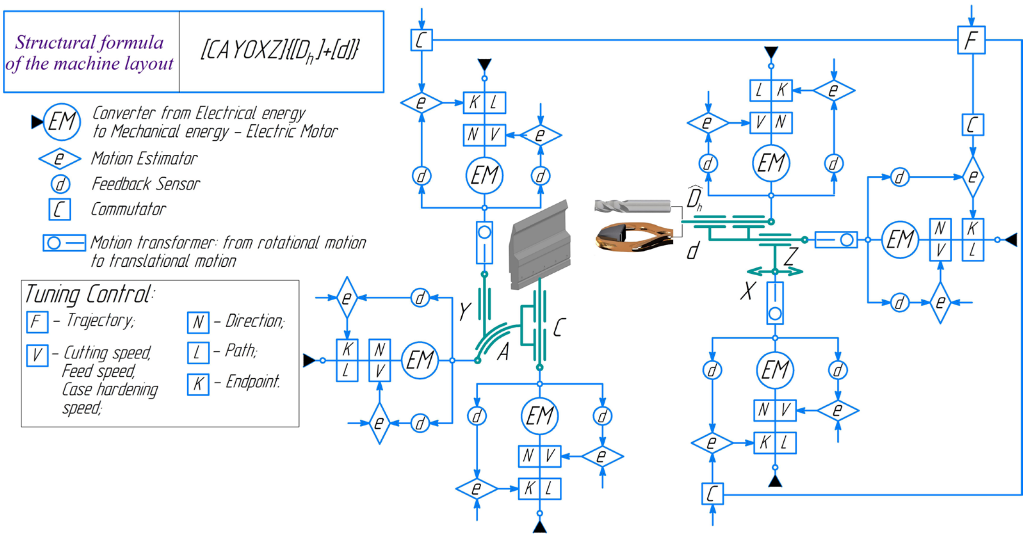


Fig. 4. Block schematic diagram of the hybrid metalworking machine

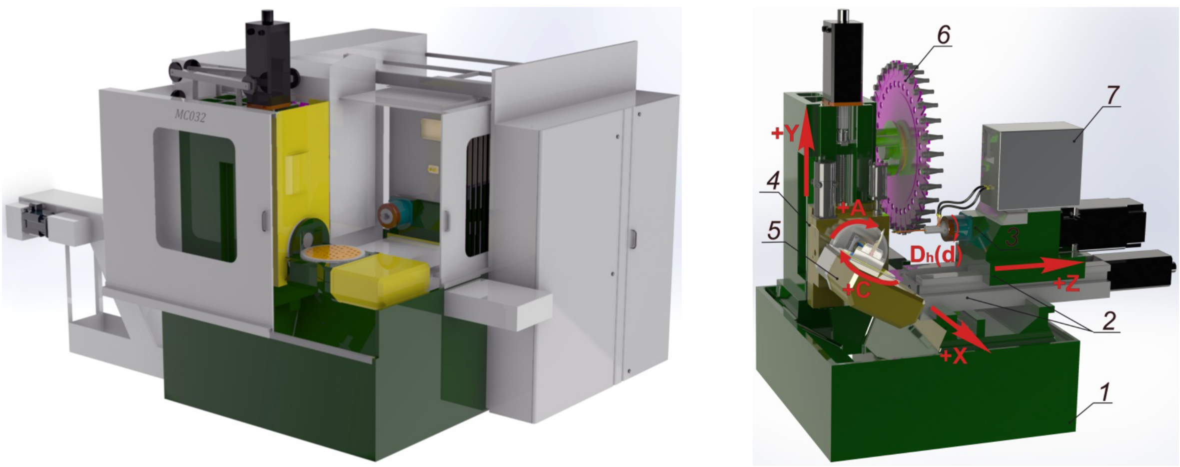
where A and C – degree axes of the worktable; Y – vertical movement of the worktable with the workpiece; X and Z – linear tool movements; $\widehat{D}_h$ – spindle rotation with cutting tool; d – setting rotational motion of the inductor.

Block D_h, which performs the main cutting motion during milling, is additionally marked with a $\wedge$.

After a comprehensive analysis of the required structural formula for the layout of hybrid equipment, the kinematic structure of the *MS 032*.06 machine and the rigidity of its base units, the main directions for upgrading the specified model of metalworking equipment were identified. The complex of pre-project studies carried out made it possible to prepare working documentation for the implementation of hybrid technological equipment that combines mechanical and surface-thermal treatments (fig. 5).

As a result of calculations of the technical characteristics of hybrid metal-working equipment, it was recorded that in order to ensure a level of shaping productivity comparable to mechanical operations, it is necessary to carry out *HEH HFC* hardening at speeds of the order of $V_S \in [50, 100]$ mm/s. Conducting full-scale experiments made it possible to determine the range of specific power of the source q_S (h, V_S), which it is required to *HEH HFC* hardening: $q_S \in [1.5; 4.0]\ 10^8$ W/m^2.

To confirm the effectiveness of the implementation of the developed hybrid equipment, let's consider a specific example – the final stage of the plug processing (fig. 3). In this example, two different processing



a *b*

Fig. 5. Hybrid metal-working machine:

a – general view of the machine; b – basic layout of the integral machine tool complex: 1 – machine bed; 2 – dual slides; 3 – spindle assembly; 4 – vertical slide; 5 – turntable; 6 – tool magazine; 7 – microwave thyristor-type generator SHF-10 patterns are considered: using standard factory technology and using the proposed integrated processing. An analysis of the presented data will confirm the effectiveness of the introduction of the developed hybrid metalworking equipment and demonstrate the advantages that it can bring compared to traditional processing methods.

According to the factory manufacturing process of the plug, after pre-machining, the operation "Surface *HFC* hardening" is performed. In this operation, it is necessary to take into account the technological depth of hardening, taking into account the subsequent finish machining (grinding). The technological depth of hardening in this case should be $AT = 0.84 + 0.1$ mm [97, 98]. However, it should be noted that according to the data of the enterprise, approximately 7 % of manufactured parts are subject to rejection due to the presence of burns and microcracks on the surface, which are formed during the "grinding" operation.

To achieve the specified thickness of the hardened layer using a generator with a frequency of 440 kHz, it is required to implement a surface heating scheme. In such a scheme, the specific power and speed of the heating source will be lower compared to the volumetric scheme. The active wire of the inductor has a width $R_S = 4$ mm and its length $b = 15$ mm, which corresponds to the specific power $q_S = 1.2 \cdot 10^7$ W/m^2 and the speed $V_S = 2$ mm/s.

To harden the part, it is necessary to process two sections with a total length of 300×2 = 600 mm. Both sections are processed for two longitudinal movements of the loop inductor relative to the workpiece. The total length of the tool stroke (displacement along the X axis), taking into account the entry and exit of the inductor with a continuous-sequential heating scheme, is $l = (300 + 8 + 4)2 = 624$ mm. With these parameters, the basic time is $T_b = l/V_d = 312$ s. In accordance with the general engineering standards for heat treatment at *HFC* installations, the auxiliary time for basing a part of the plane type is $T_{np.} = 15$ s. Thus, the single-piece productivity is equal to

$$P_{sp} = \frac{1}{T_b + T_{np}} = \frac{1}{312+15} = 0.003\, s^{-1}$$

and energy demands are equal to

$$E = \frac{q_i\, b\, R_s\, l}{V_d} = \frac{1.2 \cdot 10^7 \cdot 0.015 \cdot 0.004 \cdot 0.624}{0.002} \approx 0.062\, kW \cdot h\,.$$

The final stage of the technological process of manufacturing a part using hybrid metal-working equipment was carried out on a modernized multi-purpose machining center *MC032*.06 and consisted of three transitions: preliminary (rough) and semi-finish machining, surface *HFC* hardening, and fine milling. The machine tool system was equipped with an additional power source, which was a microwave thyristor-type generator *SHF-10* with an operating current frequency of 440 kHz. To measure and control the operating frequency of the induction heater, a *Hantek DSO 1000S Series* digital oscilloscope was used.

Based on the dimensions of the part 25×160×300 mm made of steel *U10A*, a following blank was taken: a sheet 30×170×310 mm. For referencing in the machine, a pair of special self-centering vice chuck with a jaw section of 40×100 mm was used. The first stage of manufacturing was the shaping of the connecting base of the punch, which included roughing and finishing with face and end mills with carbide indexable insert. Based on the technical characteristics of the machine and the material being processed, a tool was selected and cutting conditions were calculated. For roughing, an *IE21-90.11A16.040.05* end mill with a diameter of 40 mm was used with *APKT113508R-GL IA6330* inserts designed for milling carbon and stainless steel, and hard materials. Cutting modes: $V_C = 200$ m/min; $ap = 5$ mm; $ae = 30$ mm; $V_f = 800$ mm/min. The same tool was used for finishing the plane in the following modes: $V_C = 350$ m/min; $ap = 0.15$ mm; $ae = 30$ mm; $V_f = 500$ mm/min. To form the connecting grooves, a solid carbide cutter with a diameter of 4 mm with an edge radius of 0.2 mm and a ball cutter with a diameter of 2 mm were used, in the following modes: $V_C = 50$ m/min; $ap = 0.5$ mm; $ae = 4$ mm; $V_f = 500$ mm/min.

During the hardening process, a loop-type inductor equipped with *N87* ferrite was used (fig. 2) [7, 14, 17, 21, 47, 61, 71–73, 75, 82–83, 87]. The inductor is installed in an adapter mandrel made of *ZX-324 GF30 PEEK* glass-filled plastic, capable of operating at elevated temperatures and securely fixed in a tool chuck with a collet (fig. 6). The studies were carried out using intensive water circulation cooling of the inductor (fig. 2).

Finish milling of the working profile was carried out in the following modes: V_C = 370 m/min; *ap* = 0.05 mm; *ae* = 20 mm; V_f = 250 mm/min. During machining, a universal cutting fluid (coolant) *TECHCOOL 1000* with mineral oils was used.

In the process of integrated workpiece processing, when its relocations between mechanical operations and surface heat treatment are leveled, the technological depth of hardening at the operation *"Surface HEH HFC hardening"* is $A_T = 0.52^{+0.28}$ mm (finish allowance $z_{min} = 0$). The absence of an additional workpiece positioning, and the fact that the pre-machining is carried out on non-hardened material, milling is carried out in a more intensive mode than with standard technology. Moreover, the use of hybrid technology makes it possible to intensify the cutting process of the workpiece during machining due to additional heating by a concentrated energy source. Preheating the product with high-frequency currents before using the cutting tool reduces the resistance during processing and makes the workpiece more conformable for shaping. Thus, an additional effect is achieved, which makes it possible to enhance the operation conditions during preliminary (rough) milling. At the same time, by the subsequent operation *"Surface HEH HFC hardening"* due to heating of the *U10A* carbon tool steel for hardening, it will be possible to balance the dangerous level of the stress-strain state of the workpiece surface layer.

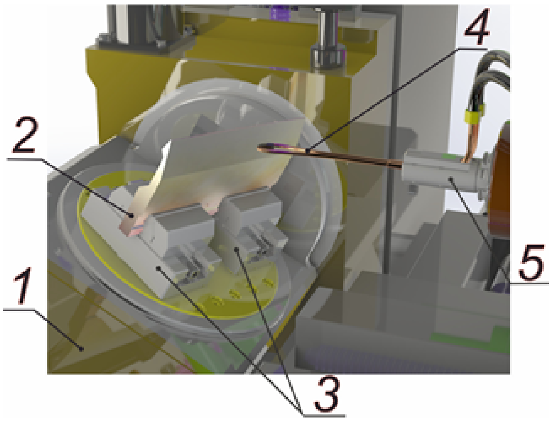


Fig. 6. Processing area with high-energy heating by high-frequency currents:
1 – turntable; *2* – workpiece; *3* – self-centering vice chuck; *4* – loop inductor; *5* – adapter mandrel

To determine the most effective modes of surface hardening in the framework of the use of hybrid processing, the relationship between the depth of hardening and process-dependent parameters for a given steel grade was established:

$$h(q_S, V_S) = a + bV_S + cq_S + dV_S^2 + eq_S^2 + fV_Sq_S + gV_S^3 + xq_S^3 + iV_Sq_S^2 + jV_S^2q_S, \qquad (1)$$

where for *U10A* steel the coefficients are: $a = 0.906184$; $b = -12.343186$; $c = 1.851541 \cdot 10^{-9}$; $d = 24.621030$; $e = 4.103625 \cdot 10^{-18}$; $f = -1.571684 \cdot 10^{-8}$; $g = -66.067377$; $x = -4.851607 \cdot 10^{-28}$; $i = -2.040626 \cdot 10^{-17}$; $j = 6.052463 \cdot 10^{-8}$.

Fig. 7 shows the results of the research. Experimental data processing was performed using *STATISTICA 6.0* and *Table Curve 3D v 4.0* software products. It is important to note that the maximum error does not exceed 5 %, which indicates the reliability and accuracy of the results. This confirms the reliability of the study and allows taking its results into account when making decisions.

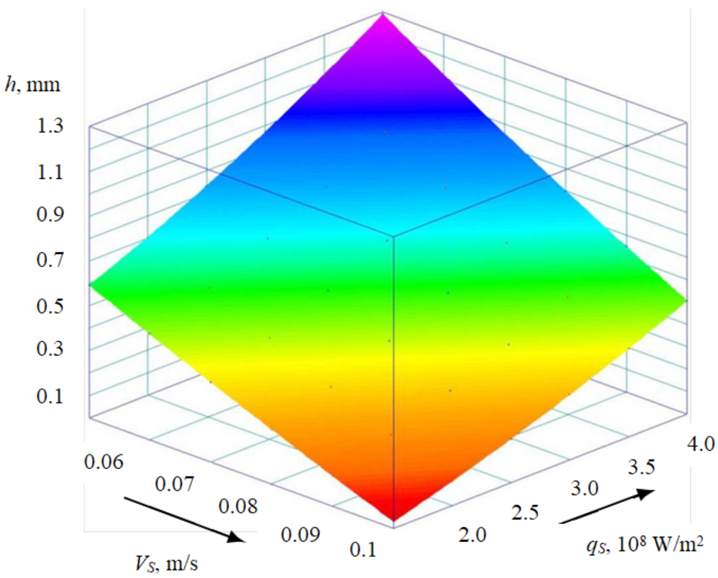


Fig. 7. Functional dependence $h(q_S, V_S)$ for *U10A* steel

When using *HEH HFC*, changing the geometric parameters of the source in the process of manufacturing a new inductor is a complex and spending process. In this regard, the specific power of the heating source and the speed of its movement were chosen as variable parameters. When applying induction heating, the size of the source is usually determined first, and then the other two process parameters. However, the results of mathematical and experimental studies [7, 14, 17, 21, 47, 61, 71–73, 75, 82–83, 87] showed that the obtained ranges of hardening modes do not guarantee the formation of a hardened layer without the appearance of hardening cracks. The main reason for the appearance of such microcracks is the internal stress-state of the material.

In the case of surface hardening, special attention is paid to the depth of hardening, as this is the main parameter in the process. To achieve the desired level of hardness, it is necessary to choose the optimal steel grade. In this case, the effect on the magnitude and distribution of residual stresses is possible only by changing the size of the transition zone.

Taking into account the fact that the location of the maximum tensile stresses is the fracture nucleus of the part during operation, it is advisable to move the dangerous zone deeper from the surface of the product. In this case, the greatest depth of occurrence is achieved if the thickness of the transition layer is maximum. However, a balance needs to be found, because as the depth increases, the level of compressive stresses on the surface also decreases. Studies have shown that the optimal size of the transition layer should be approximately 25–33 % of the depth of the hardened layer. If this requirement is met, a balance is achieved between the transfer of stresses into the deep layers of the material and the reduction of compressive stresses on the surface, not exceeding 6–10 %. It is especially important to provide a larger transition layer when hardening steels with a high carbon content. This makes it possible to control the mechanical properties and fracture resistance of parts effectively [7, 14, 17, 21, 47, 61, 71–73, 75, 82–83, 87, 102].

In the process of selecting modes of surface hardening of parts operating under cyclic loads, an additional criterion is used – the relative value of the transition zone, denoted as $\Psi(q_S,V_S)$. This criterion is defined as the ratio of the size of the transition zone to the thickness of the hardened layer.

By analyzing the experimental data, the corresponding functional dependence was established $\Psi_{U10}(q_S,V_S)$ (fig. 8), valid for the material under study and the range of processing modes:

$$\Psi_{U10}(q_S,V_S) = k + lV_S + mq_S + nV_S^2 + oq_S^2 + pV_Sq_S + rV_S^3 + sq_S^3 + tV_Sq_S^2 + uV_S^2q_S, \qquad (2)$$

where $0.25 \le \Psi_{U10}(q_S,V_S) \le 0.33$

The value of the coefficients of functional dependence for steel grade *U10A*: $k = 0.55499986$, $l = 6.376$, $m = -3{,}0969982 \cdot 10^{-9}$, $n = 2.1133193 \cdot 10^{-6}$, $o = -6.697454 \cdot 10^{-24}$, $p = -9.444857 \cdot 10^{-16}$, $r = -1.1120113 \cdot 10^{-5}$, $s = 8.2498316 \cdot 10^{-33}$, $t = 1.5500134 \cdot 10^{-24}$, $u = 1.3319075 \cdot 10^{-15}$.

The determination of the specific power and the speed of the source movement during surface hardening is carried out by solving a system of equations $\begin{cases} h_{U10}(q_S,V_S); \\ \Psi_{U10}(q_S,V_S). \end{cases}$ for given values of the hardening depth and the relative size of the transition zone. The graphical solution of this problem is shown in fig. 9. It should be noted that the resulting range of processing modes is much smaller compared to the range of modes to achieve only a given thickness of the hardened layer.

To achieve the required thickness of the hardened layer $h = 0.52$ mm in the process of surface *HEH HFC* hardening, it is necessary to select the operation parameters in the range limited by points ***A*** and ***B*** on the curve (fig. 9). These parameters include the specific power q_S, which will be in the range from $2.09 \cdot 10^8$ to $2.49 \cdot 10^8$ W/m^2, and the source travel speed V_S will be from 66 to 73 mm/s. These processing modes ensure that the required hardening depth is achieved and that the transition zone is optimally sized.

Since *HEH HFC* hardening is performed in the one workpiece location, the auxiliary time is 0 seconds. Calculation of efficiency and energy consumption at the operation *"Surface HEH HFC hardening"* is performed using the following equations:

$$E_{sp} = \frac{V_S}{L}, \quad EC = \frac{q_S b R_s}{P_{sp}} = \frac{q_S b R_s L}{V_s},$$

where $L = 614$ mm (fig. 3), $b = 10$ mm (fig. 2).

Table 2 contains the results of the calculation of energy consumption and efficiency for all combinations of operating parameters during thermal hardening of the part.

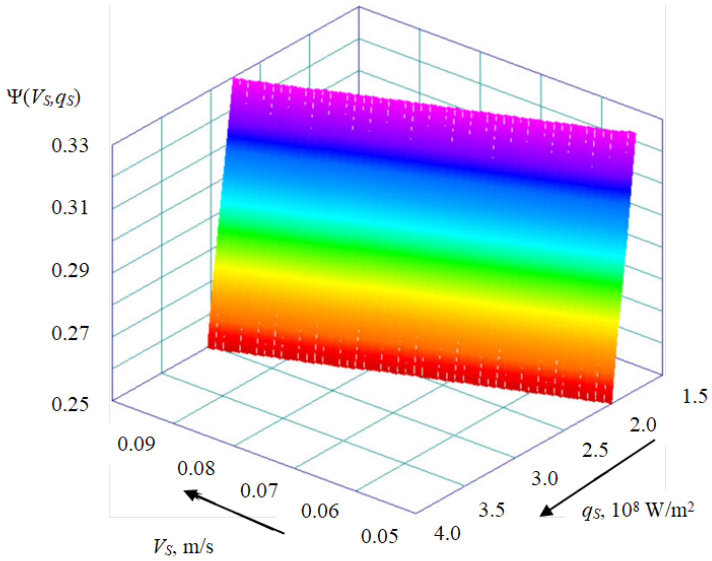


Fig. 8. Functional dependence $\Psi_{U10}(q_S,V_S)$ for *U10A* steel

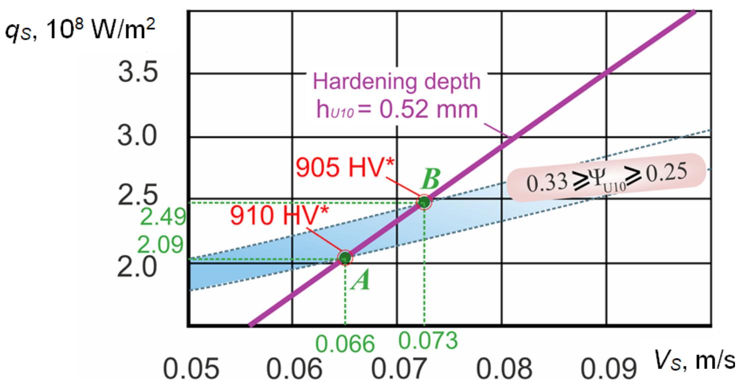


Fig. 9. The dependence of specific power of the source on its speed while *HEH HFC* hardening steel *U10* to a depth of $h = 0.52$ mm.

* The level of microhardness of the surface layer of the part, achieved after the operation *"Surface hardening by HEH HFC"*

Table 2

Calculation results of the efficiency and energy consumption in the integrated processing of surface *HEH HFC* hardening

Steel, mode		Travel speed V_S, m/s	Specific power q_S, 10^8 W/m^2	Efficiency, s^{-1}	Energy consumption, kW · h
U10A	*A*	0.066	2.09	0.108	0.011
	B	0.073	2.49	0.119	0.012

As a result of the analysis, it can be concluded that the use of integral processing allows significantly increasing the efficiency of surface *HEH HFC* hardening in comparison with the existing technology at the enterprise up to 36–40 times. In addition, energy costs are reduced by almost 6 times.

The results of optical microscopy, measurements of microhardness and residual stresses are presented in the form of graphical and numerical information in fig. 10. The presented results become the basis for a deeper analysis and interpretation of the data obtained.

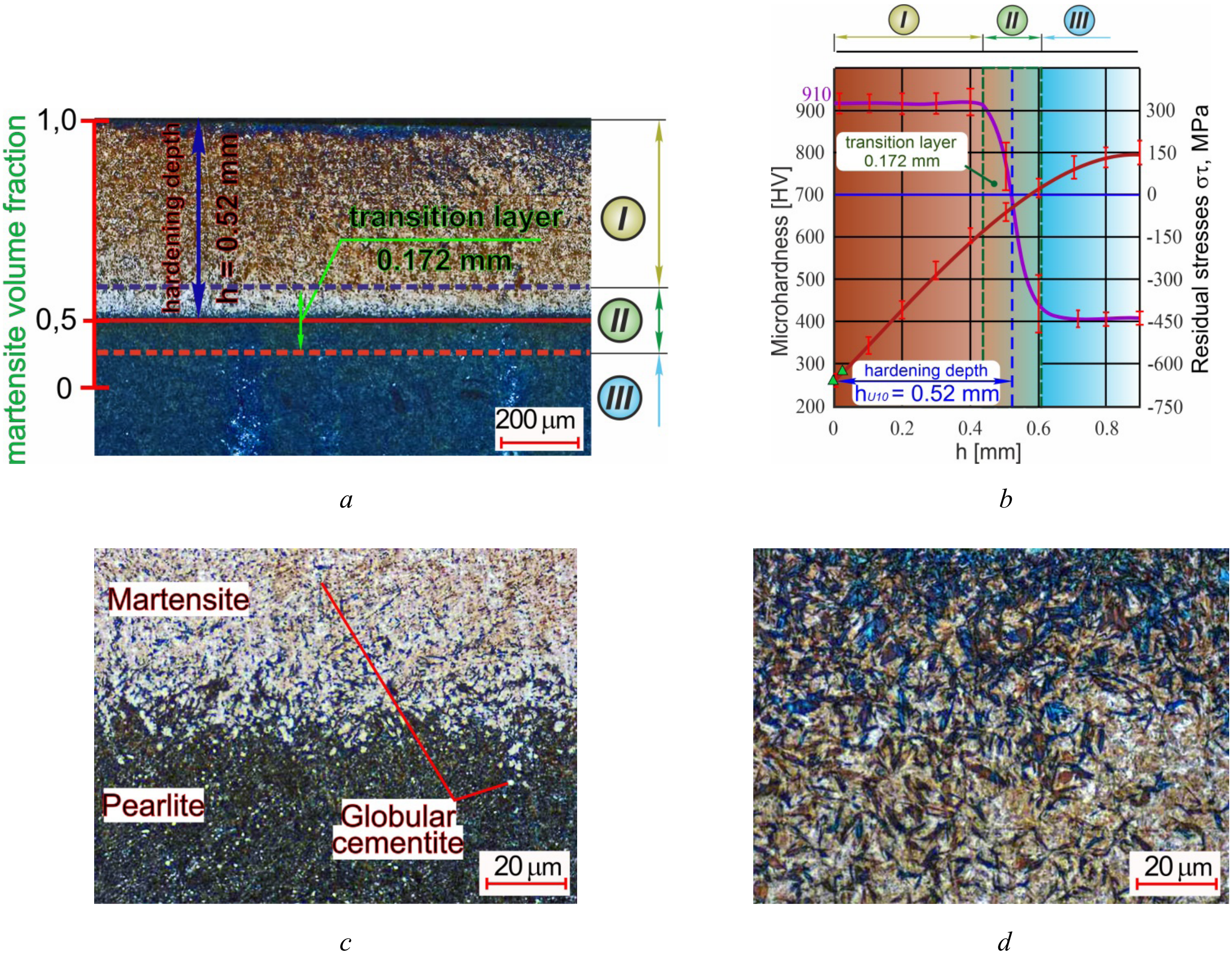


Fig. 10. Experimental results for parts made of *U10A* steel:

a – optical microscopy; *b* – the distribution of microhardness and residual stresses in the surface layer (▲ – residual stresses obtained by X-ray determination); *c* – microstructure of base metal and transition zone; *d* – microstructure of the hardened layer

Studying the graph of the microhardness distribution of the surface layer (see fig. 10a, b), three characteristic regions can be distinguished. The first region, designated as zone **I**, is characterized by a stable average microhardness value. The second region, or zone **II**, is the transition zone. Finally, the third region, or zone **III**, does not undergo structural and phase changes. The thickness of the hardened layer is defined as the distance from the surface to the area containing 50 % martensite. The transition layer is a region between the surface layer of a hardened metal with a constant average value of microhardness and a zone of material that has not undergone structural-phase transformations.

The base metal is presented by a lamellar pearlite (fig. 10c). In addition, globular cementite with sizes from 1 to 5 μm is observed in the base metal. The transition zone, with a thickness of 0.172 mm under these processing modes (fig. 10a, b), consists of martensite (light), perlite (dark) and globular cementite (fig. 10c). The presence of perlite and cementite globules indicates that the heating temperatures of this section did not exceed the **Ac3** temperature and the soaking time at this temperature was insignificant. Martensite with differently etched plates and retained austenite are observed in the hardened layer (fig. 10d). With distance from the base metal, the amount of globular cementite decreases.

The hardened layer of the studied steel grade, obtained by *HEH HFC* at a hardening depth of 0.52 mm, has a microhardness of 910 HV. In addition, the maximum value of residual compressive stresses on the working surface of the plug is approximately $\sigma_{c\,max} \approx -700$ MPa.

Conclusion

Based on the research, recommendations have been developed that are aimed at modernizing the multi-purpose five-coordinate machining center *MS 032.06*. Its execution will make it possible to carry out high-energy heating by high-frequency currents (*HEH HFC*) on a standard machine tool system and to form high-tech technological equipment with extended functionality. It was experimentally confirmed that the introduction of the proposed hybrid machine and the application of the developed recommendations for establishing rational modes of *HFC* in the process of integral machining of plug-type parts can significantly increase the efficiency of surface hardening: 36–40 times more than when using factory technology. At the same time, energy costs are reduced by 6 times. The implementation of the presented work made it possible to obtain information that can be used to solve an urgent problem in the field of mechanical engineering. This task is related to ensuring high quality products, reducing the production cycle time, minimizing the cost of manufactured products and creating new surface characteristics of machined parts. Thus, the results of the work provide valuable recommendations and approaches to address all these aspects and improve the production process in the field of mechanical engineering.

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Conflicts of Interest

The authors declare no conflict of interest.