WEB OF SCIENTIST: INTERNATIONAL SCIENTIFIC RESEARCH JOURNAL
ISSN: 2776-0979, Volume 3, Issue 3, Mar., 2022

ENSURE THE QUALITY OF THE SURFACE LAYER OF PARTS IN HIGH-SPEED END MILLING OF HARDENED STEELS

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Abstract

The article discusses With the development of technology, materials that are difficult to process using existing technologies are widely used. For example, hardened steels of high hardness are processed by grinding. This leads to the formation of a surface layer with tensile residual stresses, burns and a large inhomogeneity of the structure, which negatively affects the functional properties of the manufactured parts.

The advent of high-speed machining (HSM) has made it possible to increase cutting performance by several times. However, in order to further improve the process, it is necessary to pay special attention to the quality of the products. The leading role is played by ensuring the quality of the surface layer.

Keywords: surfaces, layers, processing, machine tool building, quality, milling, steels, face, finishing, molds, roughness, hardness.

Introduction

With the current level of development of mechanical engineering, more and more attention is paid to the quality and cost of products. The advent of high-speed blade processing has made it possible to increase cutting performance by several times. However, for further improvement of the process, it is necessary to pay special attention to the requirements for the quality of the products. The leading role is played by ensuring the specified quality of the surface layer.

With the improvement of machine tool building and the advent of new tool materials, the cutting speed increased. Currently, a new type of machining is being successfully used - high-speed blade machining (HSM). Special high-speed machines, equipment and tools have been created for it. High speed machining is a fundamentally new technology, which has its own characteristics, such as low cutting force, high temperatures, etc. The use of high-speed processing in some cases makes it possible to abandon the use of finishing operations: grinding, scraping. VSO has found wide application in the production of stamps and molds. However, the processes that take place during HSM have not yet been sufficiently studied.

Therefore, finding productive and efficient methods for ensuring the quality of the surface layer of a part during high-speed finishing face milling of hardened steels, which make it possible to obtain products with desired properties of the surface layer, is an urgent task for machining production.

With the development of technology, materials that are difficult to process using existing technologies are increasingly being used. For example, hardened steels of high hardness are processed by grinding, which leads to a surface layer with tensile residual stresses and burns, or on expensive and difficult to operate EDM machines.

Thus, there are various methods of high-performance machining, each of which has its own advantages and disadvantages.

For processing parts of dies and molds made of hardened steel, high-speed blade machining is preferable, since it provides the shaping of the surface layer of parts with optimal values of residual stresses, roughness, micro-hardness, structural-phase composition and heterogeneity of properties and does not require additional tooling and equipment.

Research Methods

For a third-party assessment of the quality parameters of the surface layer of parts after various processing methods, there are several classifications [1], which include surface roughness, residual macrostresses, depth and degree of work hardening. However, other surface quality factors often need to be taken into account. A. M. Sulima, M. I. Evstigneev [2] proposed their own classification (Table 1).

Table 1 Classification of surface layer quality parameters

Parameter group	Parameter subgroup	Name of parameters	Symbol	Measurement unit
Surface irregularities	Roughness	height of irregularities	R_z	mkm
		Arithmetic mean profile deviation	R_a	mkm
		Profile standard deviation	$R_{\text{ск}}$	mkm
		Irregularity pitch	$L_{\text{ш}}$	mkm
		roughness root rounding radius	$r_{\text{ш}}$	mkm
	waviness	Height of surface waviness	$H_{\text{вл}}$	mkm
		Surface waviness pitch	$L_{\text{вл}}$	mkm
	Lay	Angle between the direction of the unevenness and the direction of the external load	ω	radius
Physical state of the surface layer	Degree of deformation	Degree of deformation of individual grains	ε	%
		The degree of deformation of the layers	$\varepsilon_{\text{зр}}$	%
	Work hardening	Hardening depth	$h_{\text{Н}}$	mkm
		Hardening degree	$u_{\text{Н}}$	%
		hardening gradient	$u_{\text{гр.н.}}$	Kg/mm²
	Substructure	Fragment sizes	$l_{\text{ф}}$	mkm
		- blocks	$L_{\text{обл}}$	mkm
		Angle times orientation of fragments	$\alpha_{\text{ф}}$	degrees
		- blocks	$\alpha_{\text{бл}}$	degrees
	Crystal structure	Lattice parameters	a,b,c α,β,γ	A
		Dislocation density	ρ	cm^{-2}
		Vacancy concentration	C	-
Surface layer tension	Residual stresses	Technological macrostresses	σ	MPa
		Microstresses	σ'	MPa
		Stresses of the 3rd kind	σ'	MPa

The quality of the surface layer is assessed here by 23 points. A newer classification developed by A. M. Sulima together with V. A. Shulov and Yu. D. Yagodkin [3] already contains 39 parameters. Here, the phase composition, chemical composition and exoelectronic emission appeared, as well as the sections significantly improved and expanded: deformation (hardening), structure and roughness. Another important characteristic of the quality of the surface layer is the inhomogeneity of its phase structure.

One of the basic characteristics of the physical state of the surface layer is the sign and magnitude of residual stresses, m, e, stresses, which, after the removal of the load applied to the part, are balanced inside the surface layer.

Residual stresses have a significant impact on the service life of the units, changing the fatigue strength and endurance limit of parts. This is of greatest importance for products operating with alternating loads. In the presence of compressive residual stresses in the surface layer, the endurance limit, and, consequently, the service life of the unit, as a rule, increases, and residual tensile stresses usually lower it. Residual stresses affect not only the service life of parts, but can also complicate the technological process of machining, causing warping of products. This warping complicates the finishing operations quite significantly, forcing them to leave large allowances on them.

Residual stresses appear as a result of the influence of inhomogeneous fields (force, temperature, etc.) on the redistribution and orientation of dislocations in the surface layer of the part and the distortion of the crystal lattice, N.N. Davidenkov subdivides residual stresses into 3 types: the first type - those that are mutually balanced in the volume of a deformable body; the second kind or macrostresses balanced in the volume of several grains; of the third kind or submicrostresses - balanced in the volume of one grain.

Depending on the processing method, cutting mode, tool geometry, both compressive and tensile stresses are obtained. Residual stresses can be determined using various kinds of measurements (this is a rather long and laborious process, besides, only the values of the residual stresses in the product that have already been obtained can be controlled) and calculation (this allows you to obtain the desired residual stresses, influencing the processing parameters).

Residual stresses of the first kind arise due to non-uniform plastic deformation of the metal during its mechanical processing and non-uniform local heating of the surface layers of the metal. In the future, we will assume that the residual stresses of the first kind in the surface layers of the metal, their sign and magnitude depend on 3 factors: cutting forces that affect the degree of plastic deformation; heat released in the cutting zone; structural-phase transformations of the metal, the superposition of the above phenomena and predetermines the nature of the distribution of residual stresses in the surface layers.

Methods of Analysis

The development of methods for the calculation of residual stresses is a rather urgent task. To date, there are no convenient and quick ways to measure them due to the bulkiness and high cost of equipment. Therefore, the world is gaining more and more interest in the development of methods for the analytical determination of

technological residual stresses, which allow improving the quality of the surface layer of critical parts, and the creation of computer programs based on them.
A characteristic feature of the Korshunov model [4] is the determination of the magnitude of residual stresses not taking into account the physical yield strength of the material GJ, but on the basis of the true yield strength, but, i.e., stress at which there is a transition from elastic deformation of a solid body to plastic. According to the author, the error of this technique is about 10%.
Albagichev A.Yu. [1] developed a mathematical model for estimating residual stresses that form in the surface layer of machine parts, taking into account force and temperature effects, as well as structural-phase transformations. In this case, a single unevenness is modeled by a sphere. Also of interest is the mathematical model of V. F. Bezyazyachny and N.A. Tikhomirova [5]. It describes a mathematical model for calculating the total stresses from the thermal factor: temperature and the structural-phase transformations caused by it. It is based on the method of dismembering the body, which takes into account the interaction of the layers of the material being processed, based on the compatibility of the deformations of all layers of the workpiece. These techniques well describe the formation of residual stresses in traditional processing methods. However, for HSP, taking into account the peculiarities of shaping under conditions of local thermoplastic shear, it is necessary to create our own technically substantiated technique.

Experimental Research Methods

There are different methods for determining residual stresses:
1) Mechanical - based on the assumption that the removal of a part of the material from the part under study with the residual stresses present in it is similar to the application of stresses to the resulting surface of the part, which are the inverse of the residual stresses. When measuring deformations or reaction forces caused by reverse stresses, we calculate the required residual stresses.
2) X-ray methods are based on the difference in the interference effects of X-rays reflected from a surface with existing residual stresses, depending on the size of the zone in which these stresses are balanced.
3) Electrophysical methods - they are based on changing the electromagnetic properties of the surface layer in the presence of residual stresses in it.
4) Polarization-optical methods (photo elasticity and photo plasticity) – they are based on the dependence of the speed of polarized light on the orientation and magnitude of stresses (stresses are found from the interference pattern).

Methods for determining residual stresses are divided into destructive and non-destructive [6]. Table 2 shows their main types.

Table 2. Methods for determining residual stresses

Method	**Maximum depth at which measurement is possible**	**Spatial resolution**	**Accuracy**
Accuracy	~1-2x hole diameter	50 mkm to the depth	±50 MPa
Curvature method (tension or relaxation curvature)	0,1-0,5 thickness	0-0,5 thickness	limited by the minimum measurable curvature
X-ray diffraction	<50 mkm (A1) <5 mkm (Ti)	1mm thick side; to a depth of 20 microns	±20 MPa
Use of hard x-rays	150-50 mm (A1)	20mm thickness on the side; 1 mm parallel to the beam	20mm thickness on the side; 10^{-6} mm parallel to the beam
Using Neurons (Atomic Strain Gauge)	200 mm (A1); 25 mm (Fe); 4 mm (Ti)	500 mkm	±10x10^{-6} deformation
Ultrasonic	>10 cm	5 mm	10%
Magnetic	10 mm	1 mm	10%
combinational ontic	< 1 mkm	<1 micron approximately	50 mpa

The papers [7] describe a method for determining residual stresses by drilling holes, which is quite common in Europe. It is also described in the article. The monograph [8] is devoted to the measurement of residual stresses by drilling holes using a strain gauge. The article analyzes a technique based on cutting out rings from the material under study. A similar technique is presented in a publication from Switzerland. But the most interesting are non-destructive methods for determining residual stresses. Paul S. gives a description of the technology for finding residual stresses using X-rays. This method is also described in the article. A group of Japanese scientists from the Institute of Technology of Tokyo State University proposed an interesting method for determining residual stresses by X-rays, taking into account the stress gradient. German researchers proposed an original technique using diffraction. In the United States, at Los Alamos, an installation was created for measuring residual stresses using holography [9].

Over the last years, more and more demands have been made on the reliability and durability of details. In view of this, there is a need to take into account many factors that affect the reliability of their work. One of the important components on which the dynamic and static strength, manufacturing accuracy, fatigue resistance and corrosion resistance of parts and structures depend is the magnitude and sign of technological residual stresses. A. S. Gusev, in his article [10], writes that the influence of technological processing factors on the fatigue resistance of structures is currently quite well studied. In his opinion, the measures aimed at creating a favorable distribution of residual stresses turned out to be especially effective.

Under the action of alternating loads with an increase in their frequency, the plastic flow of the metal is difficult. It is believed that in this case, residual stresses have a significant effect on fatigue strength. The determining factor here is the sign of residual stresses in the surface layer. Tensile stresses reduce fatigue strength, while compressive stresses increase it.

The article [11] provides an experimental confirmation of this statement. The experiments were carried out on nickel-plated steel specimens. Depending on the coating technology, residual stresses of different signs arose on the surface of the samples. Samples with compressive residual stresses on the surface (about 42 MPa) had a higher fatigue strength than uncoated samples. Nickel plating of samples with tensile stresses (176 MPa) caused a decrease in fatigue strength by more than 30%.

Residual macrostresses also affect the resistance to brittle fracture. If technological residual stresses are not removed or weakened, then they can lead to a decrease in the margin of operational safety, and then a slight overload can cause the process of crack development. The probability of developing such cracks depends mainly on the applied forces and the energy stored in the material. It is believed that this fatigue and corrosion resistance of parts and structures is the magnitude and sign of technological residual stresses.

A. S. Gusev, in his article, writes that the influence of technological processing factors on the fatigue resistance of structures is currently quite well studied. In his opinion, the measures aimed at creating a favorable distribution of residual stresses turned out to be especially effective. There are already works that describe models for calculating loads; them on products during their operation and the effect of residual stresses on fatigue strength. Under the action of alternating loads with an increase in their frequency, the plastic flow of the metal is difficult. It is believed that in this case, residual stresses have a significant effect on fatigue strength. The determining factor here is the sign of residual stresses in the surface layer. Tensile stresses reduce fatigue strength, while compressive stresses increase it.

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There is also a relationship between the thermal expansion of the metal and residual stresses. Residual stresses have a significant effect on the corrosion resistance of metals. According to Matalin A.A., the creation of compressive stresses contributes to the closure of the pores present on the metal surface, in connection with which the sensitivity of the product to corrosion is noticeably reduced. Experimental data indicate that for parts with compressive residual stresses in the surface layer, obtained by rolling with rollers, the corrosion endurance limit increases by more than 4 times (see table 3).

Table 3. Corrosion resistance of steel specimens, rolled and not rolled

Test conditions	Samples not run in		Run-in samples	
	endurance limit			
	MPa	MPa	MPa	MPa
On air	450	1000	550	1220
In water	110	240	470	1040

Residual stresses affect not only the service life of parts, but can also complicate the technological process of machining, causing warping of products. This warping complicates the finishing operations quite significantly, forcing them to leave large allowances on them. To create a favorable stress distribution in the finished product, special operations are required: shot blasting or heat treatment.

During high-speed face milling of hardened steels, as a result of high temperatures in the cutting zone, structural-phase transformations may occur. Particularly for hardened steels, tempering or re-hardening is often observed. Thus, as a result of exposure to high temperature, secondary hardening occurs and a white surface layer is formed, which has an austenitic-martensitic structure. It is characterized by increased brittleness and hardness. A transition layer with a structure of ferrite, retained austenite and cementite follows the surface layer. The surface layer differs from conventional hardening by a higher content of retained austenite (up to 80%).

There is also a possibility of formation of local phase and structural transformations. At HSC hardened steels 60-62 HRC in the surface layer of parts under the influence of high loads and temperatures in the cutting zone, numerous defects are noted, such as microcracks (Fig. 1) and deformations of carbide inclusions (Fig. 1)

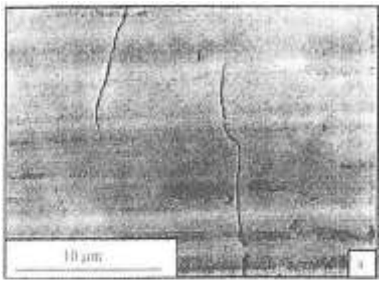

Fig.1. Microcracks in the surface layer

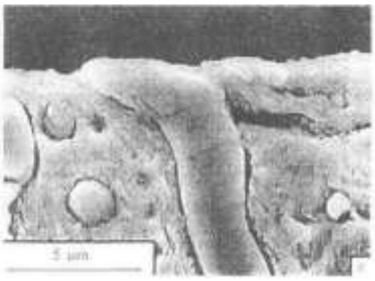

Fig. 2. Deformation of carbide inclusions

A number of authors believe that an important component of the quality of the surface layer is also the heterogeneity of the structure, microhardness, and also the magnitude of residual stresses. On fig. 3 and fig. 4 shows the unevenness of various characteristics in the aisles of the investigated surface

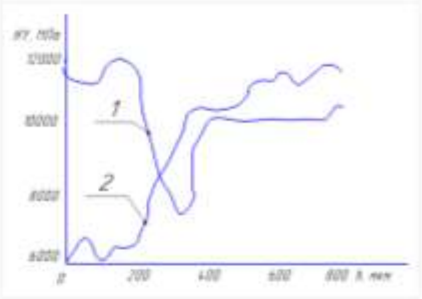

Fig. 3. Distribution of microhardness over the depth of the surface layer in the cavity (1) and on the ledge (2) of the wave (grinding condition: flat, stal SHX 15)

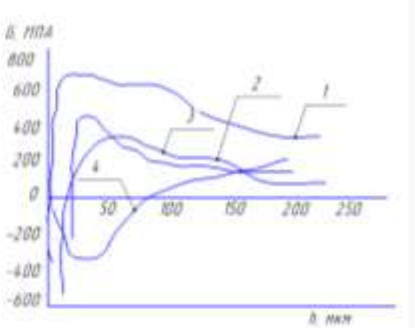

Fig. 4. Distribution of residual stresses over the depth of the surface layer during grinding with balanced and unbalanced grinding wheels (grinding conditions: 1.2 - flat, 3.4 - centerless)

The heterogeneity of the structure is determined mainly by the thermal physics of the processing process and the change in cutting forces. Metallographic studies have revealed the heterogeneity of the structural composition. This is due to the fact that tempering or secondary hardening of the surface occurs in some areas of the surface.

Since individual parts of the surface have a difference in quality, the service life of the part under variable loads is sharply reduced. Therefore, in production, various methods are used to control the heterogeneity of the surface structure. The most modern and efficient is the eddy current method. It is based on the mutual influence of the structural state of the metal on its electrical and magnetic characteristics, in particular on the electrical conductivity and magnetic permeability μ.

Hardened steels are widely used in modern industry, in particular for the production of dies and molds. The quality of their working surfaces is subject to very high requirements, the achievement of which at the lowest economic cost is an urgent task. After quenching, steels acquire high hardness and brittleness. Therefore, their processing causes many difficulties: low durability of the cutting tool, low cutting speed and unsatisfactory quality of the surface layer, which often requires a highly skilled scaler to correct the manual labor. In addition, the reliability of the resulting tooling is often low due to defects on the working surfaces. All these shortcomings can be avoided by applying highly efficient processing methods.

In recent years, for the production of parts from hardened steels, high-speed cutting (HSM) has been increasingly used.

Due to the lack of equipment operating at high speeds and having high rigidity, as well as insufficient wear resistance of tool materials, HSM could not be implemented in practice for a long time. At present, thanks to the emergence of new equipment that allows reaching speeds of the order of 500-5000 m/min, VSO has become widespread in the USA, Europe and Japan. Also significant progress is the CNC, which controls the cutting process. The problem of insufficient reliability of the cutting tool was solved thanks to the creation of fundamentally new tool materials (cubic boron nitride, diamond modifications and hard alloys with improved properties). The main idea of high-speed cutting is to switch to cutting at especially high speeds. When a certain value of speed V_{kr} is reached, the cutting temperature begins to decrease and the chip formation process changes dramatically:

1) Instead of plastic fracture, brittle fracture occurs when the material of the cut layer is separated.

2) As a result of high temperature in the cutting contact zone, the coefficient of friction between the tool and the workpiece decreases.

3) High-frequency oscillations of the technological system appear.

4) Due to the localization of plastic deformation, the confluent chip passes into the elementary.

Thus, the implementation of the HSM provides several advantages at once.:

- a short technological time for processing a part is achieved;

- The appearance of elementary chips facilitates the work of automated production, facilitating their removal;
- The quality of the surface layer of the part is higher than with other methods (due to the reduction of forces and cutting temperature).

High-speed milling is a special term denoting modern manufacturing technology, which can be attributed to the group of technological methods of manufacturing by cutting with cutters with a certain geometry. It differs in basic principle from conventional milling. It also uses a rotating cutting tool with several specific cutters (milling cutters) to remove (cut off) the material from the workpiece.

However, in high-speed milling, cutting speeds and feeds are 5 to 10 times higher than in conventional machining. For a material such as steel, they are usually 500 to 1500 m/min and higher. This high cutting speed is combined with high feed rates.

Thanks to high-speed milling, compared to conventional milling, a reduction in the main technological time is achieved, which, in accordance with the specified parameter, is 5-10 times less. One of the main advantages of high-speed milling is the reduction in the amount of heat generated during cutting, which, firstly, causes tool wear, and secondly, has a negative impact on the quality of the surface layer of the part. It is known that the temperature of the cutting surface also determines the magnitude and sign of residual stresses in the part. High thermal loads cause the appearance of tensile stresses, which are the cause of the formation of fatigue cracks on its surface.

Modern production requires obtaining parts with specified quality parameters of the surface layer. There are two types of this quality control: regulation of cutting conditions in the process of machining and provision of the required parameters by subsequent impact on the part.

Adaptive self-learning technological systems (ASLTS) for controlling technological equipment based on CNC machines. It has a mathematical model that describes the relationship between process output parameters (surface quality parameters) and control input parameters (cutting data parameters). The ASLTS operation algorithm is divided into two modes: "Training" and "Work" (Fig. 1.8). During the "Training" mode, a test part is processed on the machine, which is automatically divided into sections with specified cutting conditions (speed and longitudinal feed). Then the surface parameters are controlled. Based on the obtained data, a mathematical model (MM) is formed as follows:

$$P = C^0 S^x V^y$$

where P - controlled parameter of the quality of the machined surface; C, o, x and y - mathematical model coefficients; S - it RPM; V - at m/min.

The resulting equation and coefficients are stored in the database, and later they are used to assign cutting conditions in the manufacture of the entire batch of parts in the "Work" mode.

Currently, the Bryansk State Technical University is working on the creation of an automatic control system capable of providing the required quality of the machined surface in terms of the roughness parameter R_g.

To control the quality of the surface layer after machining, the following methods are used (on the example of regulating the magnitude of technological residual stresses): tumbling, ultrasonic relaxation, shot blasting, natural or artificial aging.

The paper describes an installation based on the use of the energy of modulated ultrasonic vibrations for the relaxation of residual stresses in the surface layer of parts. The installation effectively allows you to form the desired properties of the surface layer of machine parts at low

energy intensity. Possibility of influence of grinding modes, value and sign of residual stresses in the surface layer of hardened steel U8.

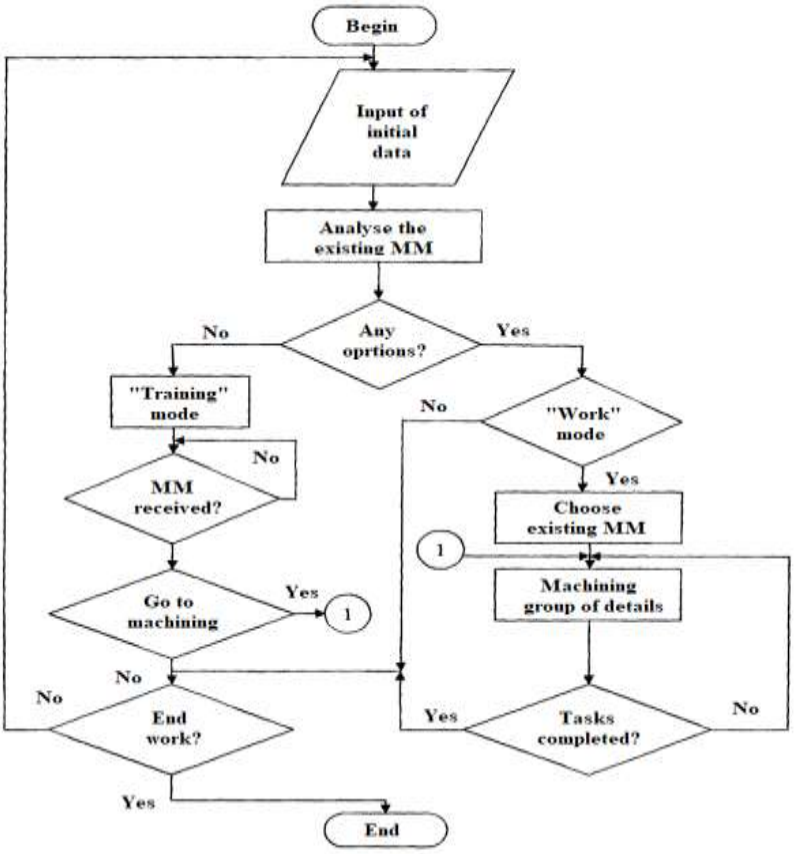

Fig. 5. Algorithm of work of automatic control system

There is also evidence of controlling the height of irregularities on the machined surface by adjusting the cutting speed, thereby changing the cutting temperature and thereby the chip formation mechanism. The control of the microhardness value of the surface layer is possible by the value of the latent energy of deformation, acting by changing the technological conditions of cutting.

Conclusion

1. A model has been developed for the formation of technological residual stresses in the surface layer of a part based on the diaphragm stress-strain, for which its own mathematical description has been found, which makes it possible to find the magnitude of residual stresses from cutting modes and properties of the material being processed. On its basis, a computer program was created.
2. A method for experimental study of residual stresses, roughness, micro-hardness, structural-phase composition and inhomogeneity of the properties of the surface layer after HSS during finishing of hardened die steels has been developed and studies have been carried out. Empirical models of roughness and micro-hardness, empirical models of roughness and micro-hardness, necessary to determine the factors affecting the quality of the surface layer of parts, are obtained.
3. An experimental-analytical thermos-physical model of the HSS process has been developed, which makes it possible to calculate the temperature on the part surface depending on the cutting conditions. This model is used to find the magnitude and depth of technological residual stresses. Empirical dependences of the value of the achieved machining accuracy (deviation from the setting size) on the cutting conditions are derived; the durability of the cutting tool is studied, the criterion of durability from a given value of roughness is determined. Based on them, technological constraints are set during optimization.

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