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COMPUTER THERMAL MODEL FOR HARDENING GRINDING

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A mathematical model of heat transfer in steel parts under force grinding is considered that allows one to determine the grinding parameters at which a steel layer of prescribed thickness is heated up to hardening temperatures. Results of numerical simulation of the process of hardening grinding are compared with experimental data. The internal structure of the material after hardening grinding is analyzed.

Intense heat release in grinding exerts a significant influence on the quality of the part surfaces formed. Here not only the contact temperature but also the entire space-time temperature field is of special importance. Use of the energy capabilities of grinding for simultaneous hardening of the surface treated is very urgent and enables one in certain cases to eliminate operations of thermal treatment with the provision of the required geometric accuracy. However, widespread introduction of the method of hardening grinding (HG) [1, 2] is restrained by insufficient investigation of the intense thermal fields formed on exposure to the treatment conditions, which affect substantially the degree and depth of the hardened zone. The majority of the well-known mathematical models of grinding provide calculation of contact temperatures [3, 4]. Some authors present relations that make it possible to establish the character of the distribution of these temperatures over the depth of the part under grinding [5, 6]. In these relations, mainly the high traverse speed of the part under the abrasive disk is taken into account, which does not allow one to perform a calculation for the HG regime, since this requires allowance for very low traverse speeds of the part, large depths of treatment, the effect of boundary surfaces, their mutual arrangement, the conditions of heat transfer with the surrounding medium, and other factors. In [7], some of the indicated conditions are considered as applied to parts with a wedge-shaped body type with a limited heat-removing volume of metal. However, in relation to parts with a semi-infinite volume and with preceding chemical thermal treatment, the investigation presented in this work is carried out for the first time and is of particular scientific interest.

Consideration of the necessary conditions and regimes of treatment with the possibility of wide variation of their limits, prompt intervention in the course of calculation, a change in initial data, and a clear representation of the process in dynamics with output of results in tabular or graphical form are by far not a complete list of the advantages of using computer mathematical models. The simplicity, the compactness of storage, and the possibility of repeated application of information are also of great importance.

Determination of the Temperature Parameters of the HG Process. The mathematical model for determining the temperature fields in a material subjected to the action of an abrasive disk is based on the solution of a widely known heat conduction equation that, on the assumption of heat supply only from the material surface, has the form [8]

$$c_p(T)\,\rho(T)\,\frac{\partial T(\mathbf{r},\tau)}{\partial \tau} + \nabla\left(-\lambda(T)\,\nabla T(\mathbf{r},\tau)\right) = 0\,. \qquad (1)$$

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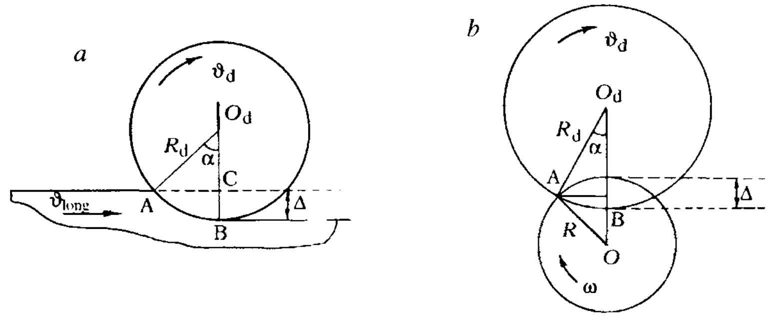

Fig. 1. Computational scheme for the length of the contact of the disk with the part in grinding of a plane (a) and a cylinder (b).

The boundary conditions to Eq. (1) that take into account the convective and radiative mechanisms of heat transfer from the body surface and the heat supply due to the cutting and frictional forces on the material surface can be written as follows:

$$-\lambda(T)\left.\frac{\partial T(\mathbf{r},\tau)}{\partial \mathbf{n}}\right|_{\mathbf{r}\in B}=\alpha(T)\,(T(\mathbf{r},\tau)-T_{\mathrm{med}})+\varepsilon\sigma\,(T^4(\mathbf{r},\tau)-T^4_{\mathrm{med}})+q_{\mathrm{gr}}(\mathbf{r},\tau)\,. \tag{2}$$

At the initial instant of time the temperature of the part is taken to be uniform:

$$T(\mathbf{r},\tau)\,|_{\tau=0}=T_0\,. \tag{3}$$

Equation (1) with boundary (2) and initial (3) conditions is solved by the widely known method of finite elements [9], which is described in detail in [10].

Determination of the Heat-Flux Density in the Zone of Contact of a Disk with a Part. The algorithm described allows us to evaluate the temperature field in the ground part for a known value of the heat source, i.e., of the surface density of the heat flux $q_{\mathrm{gr}}(\mathbf{r},\tau)$ caused by the cutting and frictional forces.

To determine the heat-flux density, we consider the schemes of motion of an abrasive disk along the surface of a plane part (Fig. 1a) and a circular part (Fig. 1b). The additional heat flux $q_{\mathrm{gr}}(\mathbf{r},\tau)$ appears only at the place of contact of the abrasive disk with the part (arc AB) and can be expressed by the relation

$$q_{\mathrm{gr}}(\mathbf{r})=\left[\frac{F_{\mathrm{cut}}\vartheta_{\mathrm{d}}}{LB}-q_{\mathrm{d}}-q_{\mathrm{m}}\right]\delta(\mathbf{r},L,B)\,, \tag{4}$$

where

$$\delta=\begin{cases}1\,, & \mathbf{r}\in[\text{zone of contact}]\,,\\ 0\,, & \mathbf{r}\notin[\text{zone of contact}]\,.\end{cases}$$

As shown in [11], q_{d} does not exceed several percent of the heat released due to the cutting and frictional forces, i.e., it can be assumed that $q_{\mathrm{d}}=0$. The heat flux going with the removed metal will comprise

$$q_{\mathrm{m}}=\frac{c_pM}{LB}\,(T-T_0)\,,$$

where $M=\rho\Delta\vartheta_{\mathrm{long}}B$ is the flow rate of the removed metal per second, kg/sec.

At the present time, the cutting force F_{cut} is determined mainly from experiment. Here it is written in the form of empirical formulas of the type [11]

$$F_{\mathrm{cut}}=A\Delta^aS^b\vartheta^c_{\mathrm{long}}\,\vartheta^d_{\mathrm{d}}\,, \tag{5}$$

where A, a, b, c, and d are coefficients selected empirically; S is the area of the zone of contact between the disk and the part. Experiments show that in the range of disk-periphery velocities from 15 to 35 m/sec the cutting force decreases with increase in the velocity and $d \approx -0.33$ [11]. Besides, from physical considerations it follows that the cutting force is directly proportional to the width of capture of the disk (B), since as the width increases, an increasing number of grains enter into operation. The same cannot be said of the influence of the contact-zone length (L), since, despite the increase in the number of operating grains, a situation is possible where the grains fall into grooves already cut by previously going grains. However, as a first approximation it can be assumed that $F_{cut} \sim L$, while the coefficient A includes a correction for the contact-zone length. With allowance for the aforesaid we have

$$F_{cut} = A\Delta^{a}\vartheta_{long}^{c}\,\vartheta_{d}^{-0.33}LB\,. \tag{6}$$

Let us consider the length of contact of the disk with the metal in plane grinding (Fig. 1a):

$$L = |AB| = R_d \arccos\left(1 - \frac{\Delta}{R_d}\right) \approx \sqrt{2R_d\Delta}\,. \tag{7}$$

Then $F_{cut} \sim \Delta^{a+0.5}$ and $F_{cut} \sim \vartheta_{long}^{c}$. In [12], Osipenko and Shpir'kov present an empirical formula according to which the cutting force $F_{cut} \sim \Delta^{0.62}$ and $F_{cut} \sim \vartheta_{long}^{0.31}$. Thus, $a \approx 0.12$ and $c \approx 0.31$. Taking into account the aforesaid, for the surface density of the heat flux in grinding, we may suggest the following formula:

$$q_{gr}(\mathbf{r}) = \left[A\Delta^{0.12}\vartheta_{long}^{0.31}\vartheta_{d}^{0.67} - \frac{\rho\Delta\vartheta_{long}c_p}{L}(T - T_0)\right]\delta(\mathbf{r}, L, B)\,, \tag{8}$$

where T_0 is the initial temperature of the part; A is a correction factor. As the experiments carried out in [13] showed, $A \approx 1.40 \cdot 10^7$. For plane grinding, the length of contact of the disk with the part is determined by expression (7), which is obtained from known geometric relations (see Fig. 1). From these relations we can obtain an expression for the contact length in grinding a cylinder (Fig. 1b):

$$L = R_d \arccos\left(\frac{R_d^2 - R^2 + (R_d + R - \Delta)^2}{2R_d(R_d + R - \Delta)}\right). \tag{9}$$

The speed of feed of the disk onto the part in plane grinding is prescribed, whereas in grinding of a cylinder it is calculated from the cyclic rotational speed of the part (ω) and the speed of its longitudinal feed (ϑ'_{long}), which lead to screw motion of the disk periphery relative to the part:

$$\vartheta_{long} = \sqrt{\left((\omega R)^2 + (\vartheta'_{long})^2\right)}. \tag{10}$$

Test Equipment and Determination of the Temperature in Hardening Grinding. In order to provide regimes of hardening grinding for a circular grinding machine of model 3132 [14], the main-motion drive and the drives of circular and longitudinal feed were modernized [14]. Here the motor for the main motion was replaced by a more powerful one. Apparatuses for uncontrolled and controlled circular feed of a billet were designed, manufactured, and tested [14]. The longitudinal-feed drive involved improvement of the hydraulic cylinder [15] and the hydraulic-control circuit [16].

A modernized hydraulic drive controls the traverse speed of the table in the range of "creeping" and "fast" feeds, providing two-cycle treatment: single-pass hardening grinding and multipass bringing up. This makes it possible to obtain the necessary degree and depth of the hardened zone and the required parameters of the microgeometry and waviness of the surface. In hardening grinding, use is made of cooling agents that ensure the required heat-removal rate established for the hardening of the treated grade of steel. Multipass grinding (bringing up) was performed using conventional cooling liquids.

TABLE 1. Experimental (T_{ex}) and Theoretical (T_t) Values of the Temperatures in Hardening Grinding

Rotational speed n, min^{-1}	Depth of grinding Δ, mm	Temperature (T_{ex}/T_t, °C) at a distance (a, mm) from the zone of contact of the grinding disk with the part						
		0.3	0.6	0.9	1.2	1.5	1.8	2.1
3	0.5	975/830	880/765	740/940	680/580	510/430	440/375	365/310
	1.0	1150/980	1090/860	980/860	810/690	745/640	680/580	590/500
	1.5	–	1130/930	1080/930	945/830	860/730	790/675	745/640
6	0.5	930/790	820/700	695/610	615/530	475/400	415/360	370/320
	1.0	1110/940	1030/880	940/810	820/710	735/660	620/550	445/380
	1.5	1200/1060	1110/950	1020/880	900/780	805/735	780/670	630/535
9	0.5	880/770	740/635	610/560	580/500	440/387	365/310	285/240
	1.0	920/820	865/740	815/710	720/635	615/545	525/450	460/400
	1.3	1050/930	930/800	890/765	810/690	740/695	670/580	560/495
12	0.5	760/720	705/610	580/515	490/420	310/278	270/230	185/167
	1.0	835/780	785/670	740/667	580/508	425/383	305/265	215/194
	1.5	960/910	825/700	805/715	695/605	610/574	475/400	310/290

To investigate the temperatures, we used a thermoelectrode method. Measurement was performed by means of artificial Chromel–Alumel thermocouples with an electrode diameter of 0.2 mm. The temperature was recorded using an NO-43-1 light-beam oscillograph. The thermal signal was picked off in the form of recording of characteristic oscillograms of the thermal cycle under the HG conditions. The slowed rotation of the part within the limits of 3–9 min^{-1} allowed us to pick off the thermal signal directly from the thermocouples onto the oscillograph without intermediate current collectors, which simplifies considerably the measurement scheme and increases the accuracy of the indications.

Testing of the Mathematical Model of HG. Experimental investigations were conducted as applied to the front-spring pins of an MAZ truck [14] after carburization to a depth of 1.8–2 mm. Results of the experimental investigation of the temperatures in hardening grinding of carburized steel 45 and the temperatures obtained using the mathematical model described above are given in Table 1. As is seen from the table, the deviation between the theoretical and experimental values of the temperatures does not exceed 15% and is sufficient to recognize the fact that the mathematical model developed is adequate for the actual process and is suitable for investigating the regularities and seeking for the optimum regimes of the HG process.

Results of Metallographic Investigations of Specimens after HG. The depth and hardness of the layer hardened by grinding were determined by means of a PMT-3 device on microsections obtained from cut-out specimens. In preparing a microsection we filled the specimen in a ring with Wood's alloy. To eliminate clogging up of the microsection edges, before the filling we laid a strip made of chilled steel alongside the surface investigated.

The specimens were cut out on a special cutting machine with a rocker under mild conditions and with abundant cooling in order to preclude the appearance of searings. Table 2 presents the depth of the hardened layer after the HG and the hardness and structure in the zones. The total depth of the preliminarily carburized layer is 2.2 mm. After the hardening grinding the hardened layer comprises 3.15 mm with a hardness up to HRC_{ex} 58. Here an upper sublayer with a thickness of 2.1 mm has a hardness up to HRC_{ex} 63. The hardness was determined on each of the cuts at four points in mutually perpendicular directions.

The hardening of a commercial specimen of a front-spring pin for an MAZ truck (after chemical thermal treatment (CTT) with heating by high-frequency currents (HFC)) has hardness limits from 45 to 63 HRC_{ex}, or a mean hardness of 55 HRC_{ex}. The total depth of hardening varies within the limits of 1.4–3 mm (Table 2).

After the HG the specimens have a hardness limit over depth from 56 to 64 HRC_{ex} in zones I and II, or a mean value of HRC_{ex} 60, which is 1.3–1.4 times higher than the hardness of the commercial specimen.

Figure 2 presents the structure of the hardened layer after the CHT with the HFC heating (the commercial specimen). The depth of hardening is 2.8 mm for zone I and 1.0 mm for zone II.

TABLE 2. Structure, Thickness, and Hardness of the Metal Hardened by Grinding

Zone	Structure	Depth, mm	H_μ, MPa
Structural state of the hardened layer			
I	Martensite	0.85	6810
II	"–"	0.85	8940
III	Troostite	0.375	6800
IV	Perlite, cementite	0.360	5290
V	Perlite	0.720	2150
Initial	Perlite, ferrite	0.750	1900
Structural state of commercial specimens			
I	Martensite fine-needle, residual austenite (RA) – 15%	1.4–3.0	6278
II	Troostite	1.0	4258
III	Sorbite-shaped perlite, ferrite	0.5	2127
Core	Ferrite, perlite		1951

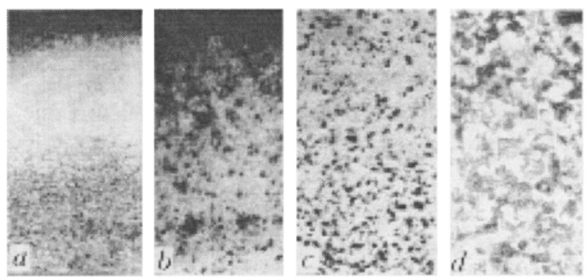

Fig. 2. Structure of the hardened layer of a commercial specimen (after CHT with HFC heating): a) ×20; b) structure of zones I-II, ×100; c) same for zone III, ×100; d) same for the core, ×200.

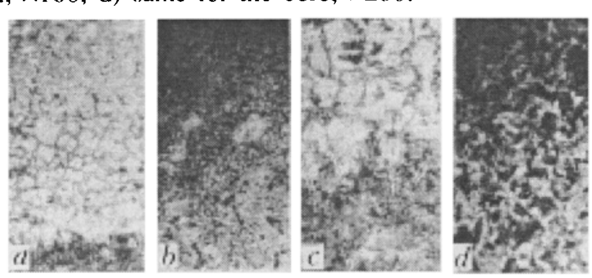

Fig. 3. Microstructure of specimens after hardening grinding: a) ×200; b) microstructure of zones I-II, ×500; c) same for zones II-III, ×500; d) same for the core, ×200.

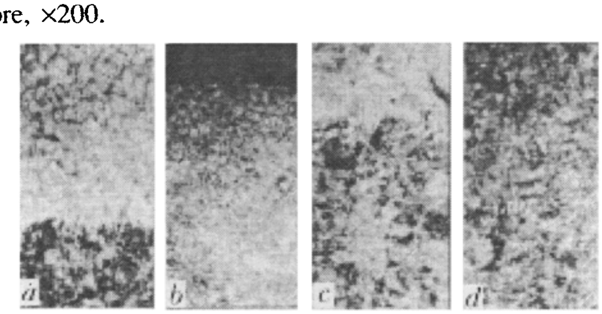

Fig. 4. Microstructure of specimens after hardening grinding and bringing up: a) ×200; b) microstructure of zones I-II, ×500; c) same for zones II-III, ×500; d) same for the core, ×200.

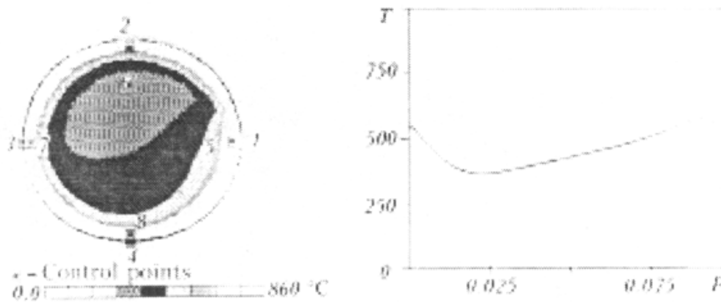

Fig. 5. Field of temperatures over the cross section and a graph of the temperature dependence at a depth of 1.2 mm in a complete revolution of the part. T, °C; P, m.

Figure 3 shows the microstructure of a specimen hardened by grinding. The hardening of zone I is H_μ = 6761 MPa; of zone II, H_μ = 7220 MPa; of zone III, H_μ = 3991 MPa. The total depth of the hardened zone is 1.4 mm.

Figure 4 presents the microstructure of the hardened zone of a specimen after the HG and bringing up with a total depth of hardening of 1.35 mm, in which zone I has a hardness H_μ = 6760 MPa; zone II, 7719 MPa; zone III, 2678 MPa.

The somewhat lower hardness of zone I compared to the hardness of zone II is characteristic of the structure of the zone hardened by grinding. This is attributable to a certain burning of the carbon on exposure to the temperatures formed due to the plastic deformation of the metal by grains of the abrasive disk and to other factors.

Simulation of the Thermal Regime of Parts in HG. In simulating the thermal processes of hardening grinding, it is necessary to assign the thermophysical properties of the material, introduce the dimensions of the part and construct its cross section, determine the removed stock and the number of passes, prescribe the diameter and rotational speed of the disk, introduce a longitudinal feed, and, on the basis of these data, calculate the temperature field at assigned points of the product over its surface and cross section.

Below we present the initial data for the calculations of the temperature dependence in a treated cylindrical specimen:

Material	steel 45
Number of calculation nodes	462
Diameter, mm	31.9
Emissivity	0.8
Temperature of the part, °C	20
Temperature of the environment, °C	20
Rotational speed, rpm	6
Diameter of the disk, mm	400
Stock, mm	0.5
Longitudinal feed, mm/sec	3
Rotational speed of the disk, rpm	2800

Figure 5 presents the field of the maximum temperatures and a graph of the temperature change at selected points at a depth of 1.2 mm under the product surface in a single pass of the disk over the cylindrical specimen. For the prescribed regimes of mechanical treatment of the part of cylindrical shape the surface temperature reaches the hardening temperature (points 1-4); however, the depth of the hardened layer is small, since at a depth of 1.2 mm (points 5-8) the temperature hardly reaches 550°C. Therefore, in order to obtain the desired results over the depth, it is necessary to decrease either the rotational speed of the part or the longitudinal speed or to increase the removed stock and to carry out repeated calculations.

Figure 6 presents a graph and the field of temperatures in the zone of contact with the grinding disk (control point 4) on removing a stock of 2 mm and the temperature change over the cross section under grinding.

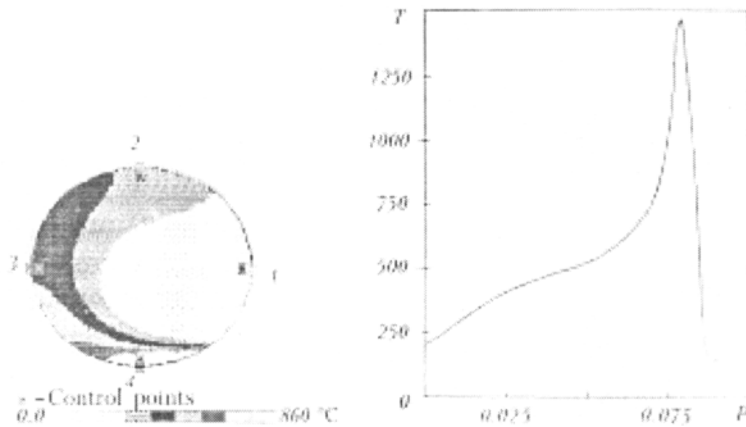

Fig. 6. Field of temperatures over the cross section and a graph of the temperature change at point 4 of the surface.

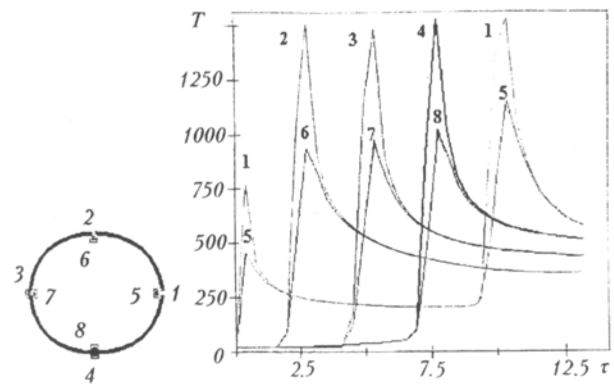

Fig. 7. Graph of the temperature change on the surface (at points 1-4) of the specimen and at a depth of 1.2 mm (at points 5-8). τ, sec.

Beginning with points 2-4, the temperature on the surface reaches 1350°C, and at point 1, only on a repeated pass of the grinding disk (Fig. 7). The temperature at a depth of 1.2 mm reaches the hardening temperature at points 6-8 in the first pass and at point 5 in a second pass of the grinding disk.

With each successive revolution the mean temperature of the specimen increases, and to obtain the prescribed hardness on the surface and over the depth a process of surface cooling is needed in which, for different articles, the corresponding cooling rate is selected.

CONCLUSION

The results of the mathematical model were checked in introducing a technology of hardening grinding on spring pins of the MAZ truck.

The technological process of manufacturing front-spring pins that exists at the Minsk Automobile Plant involves a route of treatment consisting of ten operations. The employment of HG technology makes it possible to reduce the route by four operations. The intermediate grinding operations and the HFC heating for surface hardening are eliminated.

By means of the results of comparative investigations of the hardness and structure of the layer hardened by grinding, the treatment conditions under which a commercial lot of parts was produced are refined and optimized.

Sampling investigations of the hardness and depth of the hardened zone of a commercial lot of parts showed that they correspond to the required specifications.

Comparative bench trials of spring pins for a truck showed that the wear resistance of the surface layers of pins hardened by grinding exceeds by a factor of 1.3-1.5 the wear resistance of commercially produced 45-steel pins after CHT with HFC heating.

The roughness of pins hardened by grinding is approximately 2.5 times higher than for commercial ones, which is a favorable factor that increases the service life of conjugation.

NOTATION

$T(r, \tau)$, temperature of the body at the point with radius-vector $\mathbf{r}$ at the instant of time τ, $^{\circ}$C; c_p, ρ, and λ, heat capacity, density, and thermal conductivity of the material; $\mathbf{n}$, outward normal to the boundary; ε, emissivity of the surface; $\sigma \approx 5.67 \cdot 10^{-8}$ W/(m$^2 \cdot$K^4), Stefan–Boltzmann constant; α, heat-transfer coefficient in the system of part surface–surrounding medium, W/(m$^2 \cdot {}^{\circ}$C); T_{med}, temperature of the cooling medium; $q_{\text{gr}}(\mathbf{r}, \tau)$, heat-flux density attributable to the cutting and frictional forces on the material surface in grinding; Δ, depth of grinding (of the removed stock), m; ϑ_{long}, speed of longitudinal feed of the part, m/sec; R_{d}, radius of the grinding disk, m; R, radius of the treated part, m; ϑ_{d}, velocity of the disk periphery ($\vartheta_{\text{d}} = 2\pi R_{\text{d}} n$, where n is the rotational speed of the disk), m/sec; F_{cut}, cutting force, N; L, length of the contact of the disk with the part, m; B, width of the cutting edge of the disk, m; q_{d}, heat flux going into the grinding disk; q_{m}, heat flux going with the removed metal; P, coordinate of the treated boundary of the body (from left to right), m.

REFERENCES

1. M. S. Naerman and V. D. Kal'ner, *Vestn. Mashinostr.*, No. 1, 64-66 (1977).
2. V. D. Efremov, P. I. Yashcheritsin, and A. A. Savkov, *Method for Manufacturing Cutting Elements*, Inventor's Certificate No. 1481036 USSR, Byull. Izobret., No. 19 (1989).
3. P. I. Yashcheritsin, A. K. Tsokur, and N. P. Eremenko, *Thermal Phenomena in Grinding and Properties of Treated Surfaces* [in Russian], Minsk (1973).
4. A. M. Isaev and S. S. Silin, *Procedure for Calculating Temperatures in Grinding* [in Russian], Moscow (1952).
5. S. G. Red'ko, *Processes of Heat Generation in Metal Grinding* [in Russian], Saratov (1962).
6. M. S. Zheludkevich and P. S. Gurchenko, *Vestsi Akad. Navuk Belarusi, Ser. Fiz.-Tékh. Navuk*, No. 1, 51-57 (1999).
7. V. D. Efremov and P. I. Yashcheritsin, *Technological Provision for the Quality of the Cutting Edges of Tools and Parts* [in Russian], Minsk (1997).
8. V. P. Isachenko, V. A. Osipov, and A. S. Sukomel (eds.), *Heat Transfer: Textbook for Institutions of Higher Education*, 4th rev. and augm. edn. [in Russian], Moscow (1981).
9. O. Zenkevich, *Method of Finite Elements in Engineering* [Russian translation], Moscow (1975).
10. M. L. German, M. S. Zheludkevich, and V. D. Efremov, *Inzh.-Fiz. Zh.*, **72**, No. 4, 715-720 (1999).
11. V. A. Sipailov, *Thermal Processes in Grinding and Control of Surface Quality* [in Russian], Moscow (1978).
12. V. F. Osipenko and F. M. Shpir'kov, *Vopr. Lokomotivostr. Tekhnol. Mashinostr.*, No. 12, 82-87 (1967).
13. Report No. 19972844. Assignment No. 5.16 of RNTP "Tekhnologii": *To Develop and Introduce a Technological Process for Hardening Grinding (HG) of Spring Pins for an MAZ Truck* [in Russian], Minsk (1998).
14. V. D. Efremov and P. I. Yashcheritsin, *Hydraulic Drive*, RB Patent 1475, Minsk (1997).
15. V. D. Efremov and V. M. Kuchenkov, *Hydraulic Drive*, Inventor's Certificate No. 1807252, Byull. Izobret., No. 13 (1993).
16. P. S. Gurchenko, *Development and Introduction of Methods for Nitrocementation in Inductive Heating of Heavily Loaded Parts of an MAZ Truck*, Dissertation for Candidate of Technical Sciences, Minsk (1986).