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Simulation of Grinding with Wear of the Abrasive Grains

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Abstract—A geometric model of grinding is developed. For the first time, this model takes account of wear of the abrasive grain. That permits prediction of the surface roughness at any time of tool operation. The wear is taken into account in terms of the physicochemical and mechanical interaction of the abrasive and the workpiece. This is of great importance for multiproduct manufacturing.

Keywords: simulation, grinding, wear, abrasive grains, surface roughness, multiproduct manufacturing

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INTRODUCTION

Simulation is a general approach to understanding practical systems. It permits analysis of the external and internal relations and the improvement of system performance on that basis. Information technology provides a powerful basis for simulation.

Refining the models of any process permits improvement in the technology. The development of high-precision models of production processes is an important step toward industrial advancement.

In investigating the shaping of surfaces and the resulting roughness in grinding, simulation is of great value. Numerous models already exist [1–5]. They permit the determination of the surface relief (Figs. 1a–1e) and calculation of the corresponding roughness.

A model of plane grinding by the periphery of a wheel was proposed in [6]. This model characterizes the mechanical (Fig. 1f), thermophysical, and energetic interaction of the tool and workpiece. It describes with high precision the physical phenomena in grinding and, on that basis, permits prediction of the output parameters: the surface roughness, the scorch depth, the dimensional precision, etc. The model of plane grinding includes several interrelated modules: the grinding wheel, the workpiece, the mechanical interaction, the thermophysical interaction, and the cutting forces.

In the development of the model, it is assumed that the size of the abrasive grain remains constant in machining—in other words, that the grain is not worn. This assumption prevents us from taking account of the wheel wear. In addition, it reduces the precision when the thermophysical parameters and the cutting forces are calculated on the basis of data from the geometric module of the model.

Accordingly, in predicting wheel wear and improving the precision of the calculated temperatures and cutting forces, we need to take account of the wear of the abrasive grain in the model. We turn our attention to the geometric module of the model, which is where the mechanical interaction is taken into account.

GEOMETRIC MODULE OF THE MODEL

The geometric module is based on a discrete description of wheel–workpiece contact. In other words, we consider repeated cutting by individual abrasive grains, resulting in the formation of a set of scratches that constitute the relief of the machined surface. Each abrasive grain is represented as a truncated paraboloid of revolution (Fig. 2); the truncated plane surface represents the blunting area.

The relief due to a single scratch is considered as follows. The scratch is divided over its length into a set

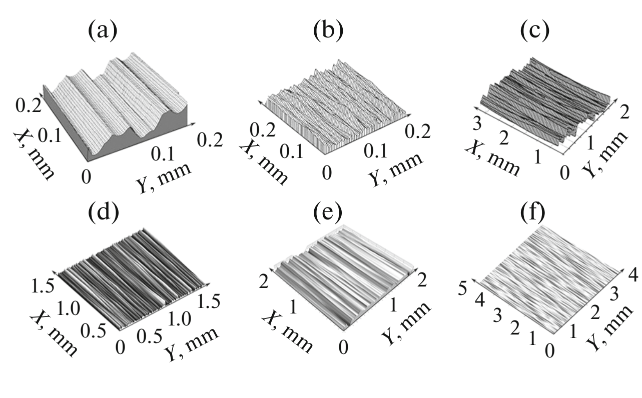


Fig. 1. Ground surfaces according to the models in [1] (a), [2] (b), [3] (c), [4] (d), [5] (e), and [6] (f).

of cross sections at intervals of δ. In each cross section, the null position of the abrasive grain may be found by means of the equation of a circle

$$z_0(y) = \frac{D_{wh}}{2} - t - \sqrt{\left(\frac{D_{wh}}{2}\right)^2 - (y - y_0)^2}; \quad y \in \left(y_0 - \frac{L_{co}}{2}; y_0 + \frac{L_{co}}{2}\right). \tag{1}$$

Here D_{wh} is the wheel diameter; t is the cutting depth of the grain; y is the coordinate of the cross section over the length of the scratch; y_0 is the coordinate of the center of the scratch along the Y axis; L_{co} is the length of the wheel–workpiece contact arc.

Then, in each cross section, we calculate the scratch profile by means of the system of equations

$$z(x,y) = \begin{cases} z_0 + h + \dfrac{4x^2}{b}, & \text{when } x_0 - \dfrac{b}{2} < x < x_0 - \dfrac{l}{2}; \\ z_0 + h, & \text{when } x_0 - \dfrac{l}{2} \le x \le x_0 + \dfrac{l}{2}; \\ z_0 + h + \dfrac{4x^2}{b}, & \text{when } x_0 + \dfrac{l}{2} < x < x_0 + \dfrac{b}{2}, \end{cases} \tag{2}$$

where x_0 is the coordinate of the center of the scratch along the X axis; l and h are, respectively, the diameter of the worn area on the grain and the linear wear of this grain in comparison with an ideal parabola. The width and height b are assumed equal to the mean size of the fraction. Since the grain is regarded as a paraboloid of revolution, the relation between the diameter of the blunting area and the linear wear of the idealized grain is as follows

$$h = \frac{4l^2}{b}. \tag{3}$$

Note that the diameter of the blunting area and the linear wear of the grain are regarded as constant in the existing geometric model [6]; they are assumed equal to the mean values. In reality, however, the abrasive grains are constantly subject to wear as they interact with the workpiece surface. Thus, to take account of the wear, we need to select a mathematical relation describing the change in the blunting area as a function of the time or the number of interactions with the workpiece.

WEAR OF THE ABRASIVE GRAIN

We assume that various factors are responsible for the wear of the abrasive grain. In particular, we single out the mechanical and physicochemical wear. The mechanical wear develops over time with a cyclic load on the abrasive grain and is analyzed on the basis of the kinetic theory of strength [7]. The physicochemical processes in the cutting zone were considered in [8].

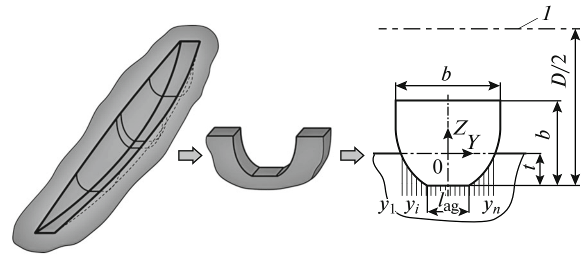


Fig. 2. Calculating the profile of a single scratch: (*1*) grinding-wheel axis; ag, abrasive grain.

Generalizing those results, the following formula for the mass of the abrasive grain as a result of mechanical and physicochemical wear was derived in [9]

$$M_{ag} = \frac{60 v_{wh} \rho_a W_{ag}^{ma} T \exp \dfrac{\dfrac{q m_{AL}}{6\rho_a 10^{23}} \sigma}{2k\theta}}{n_{wh} \sqrt{D_{wh} t} \left(1 + \dfrac{v_{wo}}{60 v_{wh}}\right) I_0 \left(i, \dfrac{\dfrac{q m_{AL}}{6\rho_a 10^{23}} \sigma}{2k\theta}\right)} + 0.08 \rho_{ma} \frac{m_{AL}}{m} \frac{L_k T C_0}{D_{wh}} \sqrt{K v_{wh} l^3}, \tag{4}$$

where v_{wo} is the workpiece velocity; v_{wh} is the wheel velocity; n_{wh} is the speed of wheel rotation; I_0 is the Bessel function of imaginary argument i; q is the overload of the atomic bonds; ρ_a is the density of the abrasive; W_{ag}^{ma} is the elementary volume of the abrasive material experiencing stress σ in the abrasive grain; k is the Boltzmann constant; θ is the absolute temperature of the abrasive grain (the temperature in the contact zone); ρ_{ma} is the density of the machined material; m_{Al} is the atomic weight of Al_2O_3; m is the atomic weight of FeO; C_0 is the limiting solubility of electrocorundum in the solvent; l is the length of the blunting area on the abrasive grain before contact with the workpiece; K is the chemical affinity of the abrasive and machined materials; T is the operating time of the abrasive grain.

For the grinding of steel 45, we assume the following values in Eq. (4): $W_{ag}^{ma} = 4.03 \times 10^7$ mm^3; $q = 10$; $\sigma = 417$ MPa; $\theta = 600$ K; $m_{AL} = 101.96$; $m = 71.85$; $C_0 = 0.41$; $K = 1.9 \times 10^{-9}$ mm^2/s [8].

WEAR OF AN IDEALIZED GRAIN

Thus, on the basis of Eq. (4), we may determine the mass of the worn part of the abrasive grain. Then, knowing the mass that is worn in one interaction and the diameter of the blunting area before that interac-

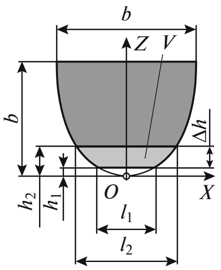


Fig. 3. Calculation of the wear of an abrasive grain.

tion, we may determine the diameter of the area after interaction (Fig. 3).

To that end, we use the equation for the volume V of a paraboloid of revolution truncated on two sides

$$V = \frac{1}{2}\pi h\left(R^2 + r^2\right). \quad (5)$$

Switching to the parameters from Fig. 3 in Eq. (5), we obtain

$$V = \frac{\pi}{2}(h_2 - h_1)\left(\frac{l_2^2}{4} + \frac{l_1^2}{4}\right). \quad (6)$$

Using Eq. (3), we write Eq. (6) in the form

$$V = \frac{\pi}{2b}\left(l_2^4 - l_1^4\right). \quad (7)$$

From Eq. (7), we write the blunting area on the abrasive grain after interaction with the workpiece in the form

$$l_2 = \sqrt[4]{\frac{2bV}{\pi} + l_1^4}. \quad (8)$$

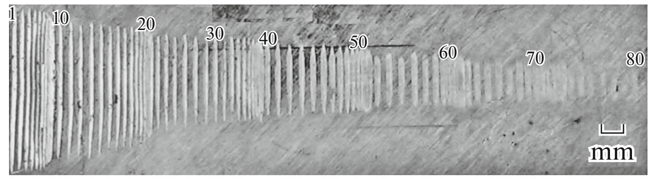
Finally, knowing the mass of the worn section of the abrasive grain after a single interaction with the workpiece from Eq. (4), the density of the abrasive material, and the dependence of the blunting area of the given grain on the worn volume in Eq. (8), we find that

$$l_2 = \sqrt[4]{\frac{2bM_{\text{ag}}}{\pi\rho_{\text{a}}} + l_1^4}. \quad (9)$$

Thus, on the basis of Eq. (9), we may determine the length of the grain's blunting area after a single interaction with the workpiece. Using Eq. (3) to calculate the length of the blunting area, we may determine the linear wear of the abrasive grain.

The wear of the abrasive grain is taken into account as follows in the geometric model. After each interaction of the grain with the workpiece, the mass of its worn section is calculated from Eq. (4), the length of the wear area from Eq. (9), and the linear wear after interaction from Eq. (3). In calculating the relief of the scratch in the next wheel rotation, the new parameters of the grain are taken into account on the basis of Eqs. (1) and (2); the form of the scratch is slightly changed. In particular, linear wear of the grain reduces the length and depth of the scratches. On account of increase in the blunting area, the bottom of the scratch becomes smoother.

(a)



(b)

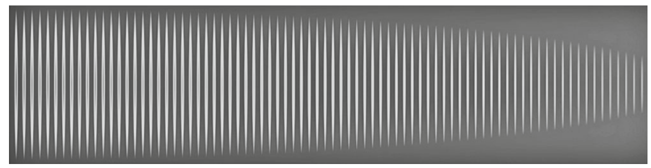


Fig. 4. Surface microrelief after cutting by a single abrasive grain: (a) experiment; (b) simulation.

TESTING OF THE GEOMETRIC MODEL

Taking the wear of the abrasive grain into account, we verify the model as follows. A single abrasive grain is attached to a specially constructed metallic disk. Then, transverse supply on a shortened path is organized on a plane grinding machine with the longitudinal supply of the table switched off. Thus, we form a number of individual scratches on the workpiece (experimental sample), as shown in Fig. 4a. For the same parameters, we plot the surface relief on the basis of the model, with visual indication of the height of the relief after machining (Fig. 4b).

We conduct several experiments by this method. The table presents the results of two experiments for different cutting depths. Note that, without taking the wear into account in the model, all the scratches in Fig. 4b would have the same height.

Comparison of the model with experimental data on the basis of the table permits the following conclusions. The initial and final scratch lengths obtained in the model and in the experiment are comparable: the error is no more than 10%. The lengths of scratches 10–60 obtained by simulation differ considerably from the experimental values: the error reaches 102%. The mean variation in scratch length for a single grain–workpiece interaction in the model and in the experiment is comparable: the error is no more than 7.5%.

Comparison of model and experimental results

Results	Scratch length (mm)								l_{me}, mm
	1	10	20	30	40	50	60	70	
Cutting depth 0.070 mm									
Experiment 1	8.5	5.0	4.5	3.9	4.5	3.5	3.3	3.1	0.077
Experiment 2	8.4	4.0	2.9	2.8	2.8	2.6	2.6	2.7	0.081
Mean	8.5	4.5	3.7	3.4	3.6	3.0	3.0	2.9	0.080
Simulation	8.3	7.9	7.5	6.8	5.9	4.8	3.8	3.2	0.074
Error, %	2.4	76	102	100	64	60	27	10	7.5
Cutting depth 0.035 mm									
Experiment 1	6	4.5	2.8	3	3	3	2.3	2.1	0.055
Experiment 2	6	4	3	2.5	3	3	3.3	3.2	0.040
Mean	6	4.6	3.3	3.1	3.3	3	2.8	2.6	0.047
Simulation	6	5.8	5.7	5.5	5.2	4.8	3.9	2.5	0.050
Error, %	0	26	73	77	58	60	39	4	6

Here l_{me} is the mean change in scratch length per interaction.

CONCLUSIONS

(1) By analysis of the physicochemical and mechanical wear, we derive a formula for the mass of the worn material after a single interaction of the grain with the workpiece. On that basis, we obtain the relation between the time, the operating conditions of the abrasive grain, and its wear.

(2) We employ the formula in developing a model of the wear of an abrasive grain. Written in programming language C#, the model constitutes a module within a more complex model [6]. By means of this module, the wear of the abrasive grain and the blunting of the wheel may be taken into account in calculating the roughness, temperature, and cutting forces in the complex model.

(3) The results of the geometric model are compared with experimental data. We find good agreement for the initial and final scratch lengths. However, significant discrepancy is noted for the scratch length in the central region. At the same time, the change in scratch length after a single interaction with the workpiece is similar according to the model results and the experimental data. The error observed in the central region may be due to the model's disregard of peeling and macroscopic failure of the grains.

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