Assessing Cutting Force: A Study of Varying Internal Grinding Wheels

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Abstract. We developed a cutting force model which takes into account the kinematics and features of internal grinding. Our model also lays out the relationships between cutting force, cutting modes, and other technological factors which have a significant impact on its value, including the concept of "wheel dulling degree." The degree of wheel dulling (η) is equal to the relation of the total area of the abrasive grain dulling to the geometric area of the entire working surface of the wheel. η determines the relative base surface of the wheel on the dulling areas of the wheel grains. Our proposed cutting force model will further serve as the foundation for a stock removal model for internal grinding, which in turn will allow for the optimization of internal grinding cycles. This will ensure the precise accuracy and quality of the treated surface under variable technological conditions. This article presents experimental confirmation of the mathematical model of interrelation between the cutting force and parameters of the wheel performance indicators through the complex parameter "degree of wheel dulling."

Keywords: Grinding · Wheel · Wheel performance indicators · Grains dulling

Nomenclature

V_{soc}	Speed of wheel axial speed, mm/min
S_{rad}	Program value of the radial component of the cutting force, mm/double stroke
S_f	Actual radial feed, mm/stroke
V_W	Speed of part rotation, m/min
V_{GW}	Speed of wheel rotation, m/sec
$M_{3,}\ M_4$	Coefficients determined by formulas (2) and (3)
σ_i	Intensity of the stress condition, N/mm^2
d	Workpiece diameter, mm
D	Wheel diameter, mm
T	Height of the grinding wheel, mm
η	Degree of wheel dulling
P_y	Radial component of the cutting force, N
Q	Stock removal rate in one working stroke, mm^3/min

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1 Introduction

The performance indicators of the abrasive wheel are the most important technological factors affecting the cutting force, and therefore the quality of the treated surface of the workpiece after internal grinding. However, the analytical interrelation between the wheel performance indicators, cutting modes, and quality of the treated surface has still not been determined entirely. Namely, it has not been determined in wide-ranging mathematical models for processing conditions in the normative space of all combinations of steel grades, wheel performance indicators, parameters of accuracy and quality of the treated surface, the diameters and geometry of the contact zone of the wheel and the workpiece, parameters of machine tools, cutting modes, engineering setup, etc.

Therefore, in automated engineering, there are no methods for automatic designing of the optimal cycles of cutting modes considering the parameters of the wheel with different characteristics. To solve this problem, it is necessary to experimentally confirm the mathematical model of cutting force which contains a parameter that considers the wheel performance indicators as a whole.

2 Review of Existing Methods for Developing Models of the Cutting Force Occurring During Internal Grinding

Radial cutting force P_y is the main integral parameter which determines the elastic movements of metal-cutting machines and, accordingly, through the actual radial feed, stock removal rate, and current values of the radii of the treated surface [1–4]. It can be said that the radial component has the strongest influence on the accuracy parameters of the workpiece and the quality of the treated surface. Grinding is often the final stage of the technological process, after which the finished product is delivered to the consumer. Therefore, grinding operations are held to strict requirements for the quality and accuracy of the treated surface. For example, the requirements for internal grinding are as follows: diameter dimensions—5–6 accuracy grade; deviation from roundness and deviation of the longitudinal section profile by 5–7 accuracy grade; fine finish of the surface—Ra 0.06–2.5; there must be no burnt places, cracks, abrasive scratches, and other defects.

The development of force models of the grinding process and experimental confirmation thereof has been the focus of papers by researchers from around the world [5–12]. Most of these are devoted to modeling cutting force in the form of empirical dependencies in a narrow range of variable factors (for one wheel performance indicator and several steel grades) without considering the dulling of the wheel grains. In addition, there are no power models of internal grinding that take into account fluctuations in technological conditions over a wide range as well as the kinematics of hole grinding.

It is worth noting the work of Korchak [5], which describes a cutting force model, realized on the basis of equality of cutting forces and resistance force of the processed metal to plastic deformation during grinding with a single abrasive grain. Also of note is the work of Pereverzev [13], who determined the balance of power of cutting forces using a model with a single abrasive grain. At the same time, the functional correlation between the intensity of stock removal during surface grinding and the deformable volume of metal in the shear zone is used as the foundation of their research. The power balance of the cutting forces makes it possible to sum the cutting forces of single grains in the cutting zone of the wheel and the workpiece. As a result, the researchers obtained a force model of external grinding with radial feed [13]. The power balance of the cutting forces makes it possible to sum the cutting forces that occur on each abrasive grain in the zone of allowance. The model sets the interrelation between the cutting force, cutting modes, geometrical parameters, and the performance indicators of the grinding wheel.

3 Analytical Model of the Cutting Force that Occurs During Internal Grinding

Using the model of the interaction between abrasive grains and the workpiece developed in work [5], and summing up the cutting forces from each abrasive grain [13], we obtained a mathematical model of the cutting force for internal grinding. This model was more thoroughly described in a previous publication [14]. In this article, we will only need the radial element of the cutting force:

$$P_Y = M_1 S_f + M_2 \sqrt{S_f} \tag{1}$$

Coefficients M_1 and M_2 can be found by formulas:

$$M_1 = \frac{1.86 \sigma_i \pi d V_{Soc}}{\sqrt{(V_{GW} + V_W)^2 + V_{Soc}^2}} \tag{2}$$

$$M_2 = \frac{\sigma_i \eta T}{3} \sqrt{\frac{dD}{d - D}} \tag{3}$$

To account for cutting force fluctuations during processing, we must consider the dulling of the abrasive grains on the wheel during grinding. Therefore, we will take a parameter called the degree of wheel dulling as a measure of the dulling of the abrasive grains and denote it using the variable η. Degree of wheel dulling η is equal to the relation of the total area of grain dulling to the area of the wheel working surface, i.e., η determines the relative base surface of the wheel on areas of the wheel grains dulling.

It should be noted that the obtained force model [14] considers the kinematics of grinding holes and the features of the process internal grinding and defines the relationship between all the main technological parameters affecting the process of stock removal (cutting modes, grinding wheel performance indicators, contact area of the wheel with the workpiece, properties of the processed material).

Many parameters in the cutting force model of internal grinding (1) maintain the values of their constants: workpiece diameter and width, physical and mechanical properties of the processed material, circumferential speed of wheel rotation, etc. Three parameters are exceptions: the radial component of the cutting force, actual radial feed, and the degree of wheel dulling. Therefore, for our experimental tests of the cutting force model, it is sufficient to control only two parameters if the constant value of the third parameter is ensured.

4 Experimental Studies of the Cutting Force in Internal Grinding with Wheels with Various Performance Indicators

Through analysis of experimental methods, we have determined that if grinding is performed with a constant value of the radial element of the cutting force $P_y = \text{const}$, then we can measure the experimental values of the actual radial feed S_f and ratio of the wheel dulling η. With these data, it is possible to plot the graph $S_f = f(\eta)$ and complete an adequacy assessment of the force model.

To obtain the analytical model $S_f = f(\eta)$, we solve Eq. (1) in relation to the actual radial feed S_f and obtain an expression (4) showing the interrelation between the actual radial feed, the degree of wheel dulling, and the radial component of the cutting force:

$$S_f = \left[\frac{-(\eta M_2) + \sqrt{(\eta M_2)^2 + 4M_1 P_Y}}{2M_1} \right]^2 \tag{4}$$

Experimental studies were conducted to assess the adequacy of the cutting force model. The experiments were conducted on a special stand that ensures constant pressure at the wheel–workpiece interface. During the experiment, we measured actual radial feed S_f and the degree of wheel dulling η.

The change in actual radial feed S_f was measured through the stock removal rate Q by periodically measuring the volume of stock removed from the sample at specified time intervals. The productivity of the stock removal rate Q can be calculated using the following formula (for internal grinding) [15]:

$$Q = \pi d V_{Soc} S_f. \tag{5}$$

Express the formula (4) through the parameter Q after the joint solution of the Eqs. (4) and (5):

$$Q = \pi d V_{Soc} \left[\frac{-(\eta M_2) + \sqrt{(\eta M_2)^2 + 4M_1 P_Y}}{2M_1} \right]^2. \tag{6}$$

Samples from different steel grades were ground during the experiment. The radial component of the cutting force ($P_y = \text{const}$) was selected in a way that allows to carry on grinding in a guaranteed dulling mode with the formation of dulling areas on the back surface of cutting grains. Grinding was carried out from 0.5 to 2 min in dependence on the force $P_y = \text{const}$ and wheel characteristic. In the intervals between grinding the sample, the stock removal rate Q and the ratio of the wheel dulling η were measured.

The experimental value of η was determined by measuring the dimensions of the grain dulling areas [16–18]. The value of the parameter η was calculated as the relation of the total area of the grain dulling areas on the measured working surface to the working surface of the wheel. The abrasive grain dulling areas were measured using a binocular microscope installed on the grinding tool above the grinding wheel.

When installing the microscope, the axis of its lens is directed along the axis of the grinding wheel (Fig. 1) such that the working surface of the wheel and grain dulling areas are perpendicular to the axis of the microscope lens. A point light source was directed into one eyepiece of the microscope. The other eyepiece has a built-in grid, by which the grain dulling areas were measured at 105x magnification.

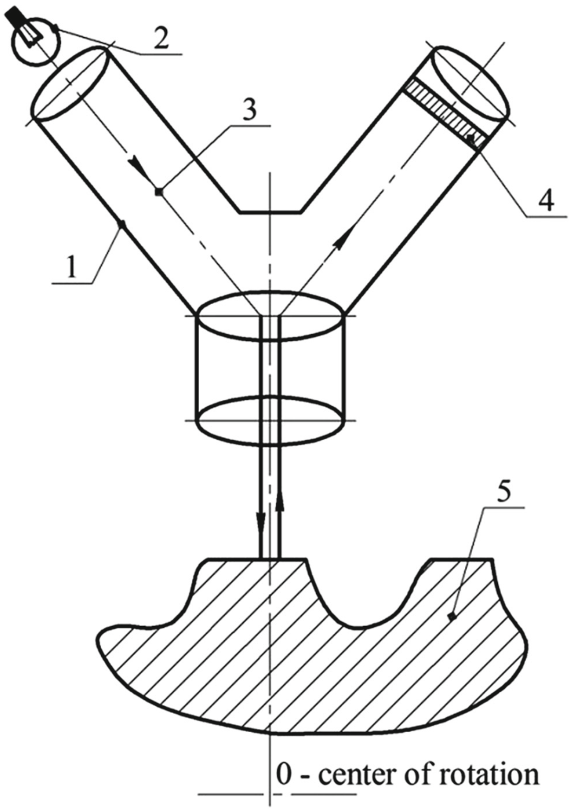

Fig. 1. Scheme of the measurement of dulling areas: 1—Microscope; 2—Point source of light; 3—Ray; 4—Measuring grid; 5—Section of the grinding wheel profile.

All grain dulling areas involved in the metal cutting and friction on the back surface are located perpendicular to the ray of light coming from the microscope lens; they are clearly visible (Fig. 2). Grinding was carried out using wheels 5 50x40x63 25AF60M7V35A1 (40 mm wheel diameter), at 35 m/sec wheel speed, with the revolution speeds of the wheel and the workpiece equal to 2600 min^{-1} and 180 min^{-1}, respectively. The diameter of the sample before processing was 60 mm. The width of the processed surface of the sample is equal to 100 mm. During the experiment, the diameter of the sample was measured using a micrometer. The wheel was dressed with a C-1 diamond dresser. An aqueous solution of soda (1%) and sodium nitrite (0.4%) was used as the coolant.

Samples of the S600 steel grade were polished on the stand. The chemical composition of steel in % according to standard 19265-73 is as follows: carbon C 0.85–0.95%;

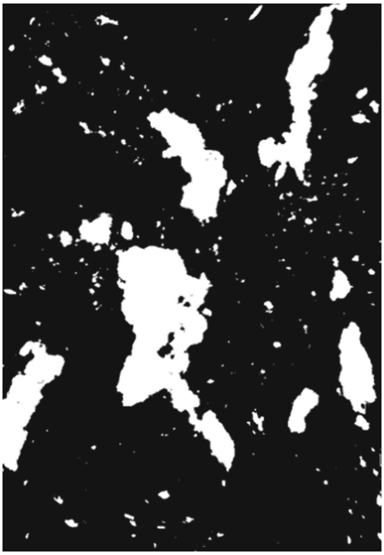

Fig. 2. Dulling areas of grains in reflected light (250X).

magnesium Mg $\leq 0.5\%$; nickel Ni $\leq 0.4\%$; sulfur S $\leq 0.03\%$; phosphorus P $\leq 0.03\%$; chromium Cr 3.8– 4.4%; molybdenum Mo $\leq 1\%$; tungsten W 8.5–9.5%; vanadium V 2.3–2.7%; cobalt Co $\leq 0.5\%$; silicon Si $\leq 0.5\%$; the remainder is iron Fe. Stress intensity $\sigma_i = 3198$ MPa [5]. Grinding time was 60 s.

Figure 3 displays our obtained graphs of the experimental dependencies of changes in the stock removal rate Q and ratio of the wheel dulling η when grinding a sample of P9 steel with constant pressure at the wheel–workpiece interface.

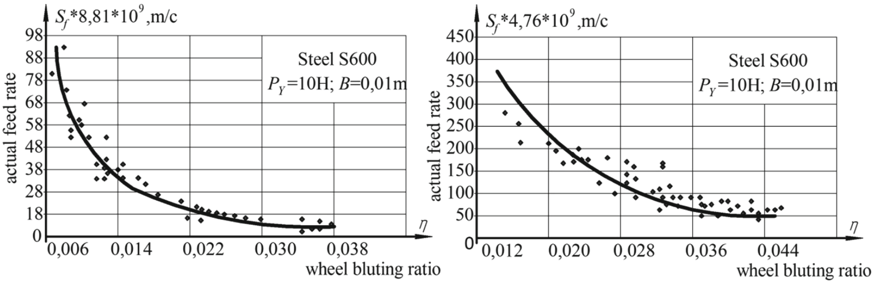

Fig. 3. Experimental points and theoretical dependence between stock removal rate and degree of dulling.

Analysis of our experimental data shows that the stock removal rate decreases as the abrasive grains of the wheel dull during grinding with constant pressure at the wheel–workpiece interface. That is, our experiment confirmed the correctness of the theoretical model of cutting force.

In Fig. 3, we show an approximation of the experimental data of the theoretical curve according to formula (14). Statistical manipulation of the results of the experiments showed that the calculation error does not exceed 15% with a confidence interval of 0.95. Therefore, our mathematical model (2) can be applied to the model of surface formation during grinding.

5 Conclusions

The existing model of cutting force for internal grinding [14] takes into account the kinematics of hole grinding and the features of stock removal process. Our model also lays out the relationships between cutting force, cutting modes, and other technological factors which have a significant impact on its value, including the introduced concept of "degree of wheel dulling."

This article presents an experimental confirmation of the mathematical model proposed in [14] for the relationship of cutting force with the parameters of a wheel's performance indicators. This relationship was found through a complex parameter of the degree of wheel dullness. Analysis of our obtained experimental data confirms the theoretical model of cutting force which posited that the stock removal rate decreases as the abrasive grains of the wheel become dull during grinding with constant pressure at the wheel–workpiece interface.

In the future, the developed cutting force model will serve as the foundation for a stock removal model for internal grinding [19], which in turn will allow for the optimization of internal grinding cycles [20]. Doing so will support the precise accuracy and quality of processed surfaces under varying technological conditions.

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