Generalized cutting force model for grinding

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Abstract. In CNC grinding operations different surfaces are processed with various types of grinding. Model of cutting force is necessarily used in cutting modes calculating. However, it’s impossible to use partial empirical dependences of cutting force for automating of cutting modes calculation because they do not cover all normative space of grinding conditions and are not intended for use in the calculation of automatic CNC grinding cycles. Therefore analytical wide-range models of cutting forces for different types of grinding are needed, but these models should be designed on the basis of common idea of kinematics and physics of metal removal processes. The article proposes the method of obtaining cutting force models for different grinding types, obtained from a generalized analytical wide-range cutting force model, as particular cases for a given grinding type. Generalized model of cutting force is obtained on the basis of fundamental regularities of mechanics of metal plastic deformation by wheel grains in a cutting zone, kinematic of cutting process by abrasive grains under conditions of temperature and speed parameters during grinding, functionally related with cutting modes, geometrical parameters of a contact zone between a wheel and a workpiece, structural behaviors of processed material, wheel grains blunting.

1. Problem
The main and the most common method of high-productive final machining of the hardened workpieces of high accuracy are circular and plane grinding. Prevalence of CNC grinding operations requires a high level of automation in the design of control programs for CNC because for CNC operations different types of grinding (infeed, with axial feed, etc.) are used for surface-by-surface machining (cylindrical and face surfaces during circular grinding) with different quality requirements. Requirements for a high level of automation of control programs for CNC are intensified in accordance with a program of digital economy development, introduction of Industry 4.0 concept, cyber-physical systems, etc.

High machining productivity on CNC machines is ensured by the joint program control of automatic step cycles of all operation parameters. For example, in plane grinding on CNC joint cycles of two feeds (transverse and axial) controlling and table speed are used.

However in the practice of automated mechanical engineering the design and optimization of automatic control parameter cycles for CNC machines are still conducted manually due to the lack of CAM-systems that allow to design optimal cycles of control parameters for various grinding types in sequential machining of different surfaces in the whole regulatory space of grinding conditions (ranges: diameters and sizes of machined surface, requirements for the processing quality, steel grades,
grinding types, grinding wheels characteristics, variable technological factors, etc). Existing CAM-systems, designed for developing of control programs (CP) for CNC machines, allow designing only the input and output of grinding wheel and its rapid motion. Manual designing of automatic cycles of control parameters for CNC machines has led to low productivity of CNC grinding operations.

Thus, there is a problem in modern automated mechanical engineering – low productivity mechanical machining operations on CNC grinding machines due to the lack of blocks of automated designing of control parameters’ optimal cycles for CNC grinding operations in CAM-systems of CP.

2. Analysis
Problem of improving CNC grinding operations can be solved by developing the methodology of automatic designing of optimal cycles for control parameters. Researches solve this task by different ways: using formed empirical dependences of metal removal speed for the grinding time until complete allowance removal [1]; construction of cycles in tolerance zone of actual feed speed in dependence of burn and dimensional wheel deterioration without considering requirements for accuracy and roughness of machining [2, 3]; methodology of the grinding cycle designing based on the optimal grinding controlling, normal component of cutting force is taken as the control parameter [4, 5, 6]; methodology of the grinding cycle designing based on the imitation designing [7 - 11]; methodology of optimal grinding cycle designing [12 - 13].

The model of cutting force is a basis of all given methodologies of grinding cycles designing for control parameters. Cutting force is a special technological factor that changes under action of all other technological factors of grinding. In addition, the cutting force directly affects the machining accuracy and other quality parameters, forcing to lower intensity of grinding and productivity of CNC grinding operations to provide the required quality of machined surface.

Considering the feature of CNC grinding operations – from the one hand, one wheel grinds different surfaces using different grinding types, and from the other, physics of grinding is the same for all types of it and the difference is in different contact area, kinematics and dynamics of surface formation during cutting – it is necessary to derive the generalized model of cutting force for grinding from which cutting force models for different grinding types can be obtained. These obtained models are special cases of generalized model solution, based on a single idea of cutting physics. Obtaining generalized model will allow predicting and generating models for other, still unexplored, grinding types.

3. Purpose and tasks of work
The purpose of work is obtaining the generalized model of cutting force for grinding. Tasks needed to be solved to achieve the goal:
1. Obtain a methodology of deriving generalized analytical model of cutting force for grinding which constitutes its functional relation with cutting modes, geometrical parameters of contact area between a wheel and a workpiece, structural behaviors of machined material, blunting wheel grains on the basis of fundamental mechanics regularities of metal plastic deformation by wheel grains in the cutting zone, kinematics regularities of cutting by abrasive grains in conditions of temperature and speed parameters during grinding.
2. Develop a methodology of obtaining analytical wide-range cutting force models for concrete grinding types from the generalized cutting force model.

4. Main part
To develop the model of cutting force during grinding it is necessary to consider the work of all cutting force components, acting in the direction of cutting speed vector on a unity grain of the grinding wheel. In work [14] S.N. Korchak developed a model of interaction of abrasive grain and workpiece – we will take it as the basis for a new model. Korchak model is derived from the equality of resistant forces of machined metal to plastic deformation and works of operating cutting forces.

Man-made assumptions [7]:
1. As a rule, a width of cut is in many times larger than a thickness; that is why wheel grains work according to free cutting scheme. Grains have a blunting platform.

2. Due to a fixed voltage along the length of cutting edge, the scheme of tensions in the metal in the shift zone can be considered as a plane scheme.

3. Area of shift zone is characterized by the finite value of its thickness \( m \) and thickness of shear \( a_s \).

4. The process of metal cutting by the unity wheel grain is accompanied by certain energy expenditures (usually evaluated by work \( A \) and power \( N \)), depending on physical mechanical properties of plastically deformable metal, speed and temperature, at which plastic deformation is made, and characteristics of deformable metal bulk.

In work [12] the generalized model of cutting force at the grinding by wheel in general (1) was obtained. This model is obtained on the basis of S.N. Korchak model by summing of metal removal speeds of the wheel cutting grains.

As the final result, for generalized model of cutting force tangential and radial forces are found by formulas:

\[
P_Y = \frac{\sigma_i \cdot \varepsilon_i \cdot tg_\beta}{V_W} \cdot Q + \frac{\sigma_i}{3} \cdot \eta \cdot B \cdot L,
\]

\[
P_Z = \frac{\sigma_i \cdot \varepsilon_i}{V_W} \cdot Q + \mu \cdot \frac{\sigma_i}{3} \cdot \eta \cdot B \cdot L,
\]

\( P_Y \) – radial component of cutting force;
\( P_Z \) – tangential component of cutting force;
\( \sigma_i \) – tension intensity in the moving metal bulk, characterizing the metal resistance to plastic deformation at degree, deformation speed and temperature inherent grinding;
\( \varepsilon_i \) – intensity of deformation speed of metal bulk in the shift zone;
\( tg_\beta \) – tangent of an angle between resultant and cutting direction;
\( \eta \) - degree of grinding wheel blunting, which is equal to ratio of total area of blunting platforms of all wheel grains (on its entire surface) to geometrical area of all wheel working surface;
\( \mu \) – friction coefficient;
\( V_W \) – wheel speed;
\( B \) – width of contact zone;
\( Q \) – speed of metal removal during grinding by the wheel in whole;
\( L \) – length of contact arc between grinding wheel and billet.

Thus, using the generalized model of cutting force, on the basis of a unified understanding of thermophysical cutting process during grinding, and knowing components \( Q \) and \( L \), particular cases of the cutting model can be derived.

For example, for circular external grinding [12]:

\[
Q = \pi \cdot d \cdot B \cdot S_F,
\]

\[
L = \frac{d \cdot D \cdot \Delta t_F}{D + d} = \frac{d \cdot D \cdot \Delta S_F}{n \cdot (D + d)},
\]

substituting it in the generalized model (1) and (2) we derive the following expression:

\[
P_Y = \frac{\sigma_i \cdot \varepsilon_i \cdot tg_\beta}{V_W} \cdot \pi \cdot d \cdot B \cdot S_F + \frac{\sigma_i}{3} \cdot \eta \cdot B \cdot \sqrt{\frac{d \cdot D \cdot \Delta S_F}{n \cdot (D + d)}},
\]
For circular internal grinding $Q$ is equal to its value for circular external, i.e. correspond to expression (3), and $L$ will be derived the following way [13]:

$$L = \sqrt{\frac{d \cdot D \cdot \Delta t_F}{D - d}} = \sqrt{\frac{d \cdot D \cdot \Delta S_F}{n \cdot (D - d)}}.$$  
(7)

After substituting (1) and (2) in expressions the following formulas will be derived:

$$P_Y = \frac{\sigma_i \cdot \varepsilon_i \cdot \frac{t g_B}{V_W} \cdot \pi \cdot d \cdot B \cdot S_F + \frac{\sigma_i}{3} \cdot \eta \cdot B \cdot \sqrt{\frac{d \cdot D \cdot \Delta S_F}{n \cdot (D - d)}}}{V_W},$$  
(8)

$$P_Z = \frac{\sigma_i \cdot \varepsilon_i \cdot \pi \cdot d \cdot B \cdot S_F + \mu \cdot \frac{\sigma_i}{3} \cdot \eta \cdot B \cdot \sqrt{\frac{d \cdot D \cdot \Delta S_F}{n \cdot (D - d)}}}{V_W}.$$  
(9)

By the same principle $Q$ (for plane grinding by wheel peripheral) will match the expression (3), $L$ will be given by [11]:

$$L = \sqrt{D \cdot t_F}.$$  
(10)

After putting (1) and (2) in expressions the following formulas will be obtained:

$$P_Y = \Delta t_F \cdot V_P \cdot B \frac{\sigma_i \cdot \varepsilon_i \cdot \frac{t g_B}{V_W}}{V_W} + \eta \cdot B \cdot \frac{\sigma_i}{3} \cdot \sqrt{D \cdot t_F};$$  
(11)

$$P_Z = \Delta t_F \cdot V_A \cdot B \frac{\sigma_i \cdot \varepsilon_i}{V_W} + \eta \cdot B \cdot \frac{\sigma_i}{3} \cdot \sqrt{D \cdot t_F}.$$  
(12)

Usually grinding is considered as two-axis process, in which the cutting forces act in two axes and causes corresponding deformations. On faceroundgrinding operations with an angle feed more complex three-dimensional system of forces and deformations. The axial force, causing deformation, emerges; this force acts on the grinding wheel foremost [8-9].

It is taken that during the grinding of diametrical surface with adopted angle $\theta$ by one wheel cone, the force interaction is considered mainly by transverse component of the feed speed; during the grinding of face surface of workpiece by the second cone the component is longitudinal.

Considering elementary area having a width:

$$\Delta B = \frac{\Delta R}{\sin \theta}.$$  
(13)

With current wheel radius $R_j$ and elementary radius increment $\Delta R$, component $P_y$ after integration can be found the following way:
\[ P_{yj} = \frac{\sigma_j \cdot \varepsilon_j \cdot Q_j \cdot \tan \theta}{V_{wj}} + \frac{\sigma_j \cdot \eta \cdot B_j \cdot L_j}{C}, \] (14)

\( B_j \) – width of elementary wheel area;
\( L_j \) – length of contact arc;
\( Q_j \) – metal removal speed;
\( C \) – coefficient, bringing proportion between tension intensity and contact pressure.

We get the formula:
\[ P_{y1} = \frac{\sigma_i \cdot \varepsilon_i \cdot \tan \theta \cdot d \cdot S_{\text{cross feed}} \cdot \cot \theta}{2 \cdot n_{w}} \cdot \ln \frac{R_{\text{max}}}{R_{\text{min}}} + \frac{\sigma_j \cdot \eta \cdot B_j \cdot L_j}{C \cdot \sin \theta} \cdot \sqrt{\frac{2 \cdot d \cdot S_{\text{cross feed}} \cdot \cos^2 \theta}{n}}, \] (15)

\( R_{\text{max}} \) and \( R_{\text{min}} \) – maximum and minimum wheel radii;
\( \theta \) – angle between wheel axis and \( y \) axis between the axis of the circle and the axis of the part.

Since at grinding the cone profile of the workpiece face by wheel, the contact area is an intersection between cone and surface; length of the contact arc will be variable. Using analogical fragmentation of the whole contact area between the wheel and the workpiece and applying an approach, described by V.A. Iogolevich [9], which is based on similarity of considering scheme for the elementary area to the scheme of plane grinding, converting formulas:
\[ L_j = \frac{S \cdot \sin \theta}{n \cdot \sqrt{1 + \left(\frac{S \cdot \tan \theta}{2 \pi \cdot n \cdot R_j}\right)^2}}, \] (18)
\[ Q = V_S \cdot B_j \cdot t_j, \] (17)

\( V_S \) – resultant point speed on the workpiece surface, obtained by summing circumferential speed and speed of table motion;
\( B_j \) – grinding width;
\( R_j \) – wheel radius, working with \( j \)-th workpiece radius.

Then we will get the following formulas:
\[ L_j = \sin \theta \cdot \frac{2 \cdot R_j \cdot S}{n \cdot \sqrt{1 + \left(\frac{S \cdot \tan \theta}{2 \pi \cdot n \cdot R_j}\right)^2}}, \] (18)
\[ L_j = \frac{\Delta R \cdot S^2 \cdot \sin^2 \theta + (2 \cdot \pi \cdot n \cdot R_j \cos \theta)^2 \cdot S \cdot \tan \theta}{n \cdot \sqrt{1 + \left(\frac{S \cdot \tan \theta}{2 \pi \cdot n \cdot R_j}\right)^2}}. \] (19)

Summary expression for the component \( P_y \) of this shear part:
\[
P_{y2} = \int_{R_{min}}^{R_{max}} \left( \frac{\sigma_i \cdot e_i \cdot t g \beta \cdot S \cdot t g \theta \cdot \sqrt{S^2 \cdot \sin^2 \theta + (2 \cdot \pi \cdot n \cdot R_j \cdot \cos \theta)^2}}{R_j \cdot n \cdot n_w \cdot \left(1 + \left(\frac{S \cdot t g \theta}{2 \cdot \pi \cdot n \cdot R_j}\right)^2\right)^2} \right) dR_j 
\]

General expression of the force component for the whole wheel will be obtained after summing expressions \( P_{y1} \) and \( P_{y2} \). The same approach is used for obtaining the formulas for other cutting forces components.

Given concept of the generalized model of the cutting force is confirmed for the particular cases of the circular external grinding [9,12,15], circular internal grinding [13], plane grinding by the wheel peripheral [11], angle grinding [8,9].

5. Conclusions by given research and prospects of the further line development

1. The derivation methodology of the generalized analytical model of the cutting force is developed; it establishes its functional interconnection with cutting modes, geometrical parameters of the contact zone between the wheel and the workpiece, structural behaviors of the machined material by wheel grains blunting, on the basis of fundamental regularities of plastic deformation mechanics of metal by wheel grains in the cutting zone, kinematic regularities of the cutting by abrasive grains in conditions of temperature and speed parameters during grinding.

2. Methodology of obtaining analytical wide-range models of cutting forces for the concrete grinding types (as particular cases of the generalized model), in which the metal removal process matches physical regularities of the grinding in the generalized model of the cutting force, is developed.

3. Models of forces for the circular external and internal grinding (with radial and axial feed), for angle grinding and plane grinding by the wheel peripheral are obtained from the generalized model of the cutting forces. Adequacy of all obtained models is confirmed experimentally.

4. Adequacy of the generalized model of the cutting force is confirmed by presence of the adequate models of cutting forces for other grinding types.

5. Obtaining methodology of the generalized cutting force and its particular cases can be used in other types of metal machining by cutting.

6. Properties conformity of obtained models of the cutting forces to real processes for different grinding types in a wide range of technological parameters variation allows recommending these force models for using at building model of technological restrictions for the processing accuracy in the optimization systems of grinding cycles on CNC machines.

References

[1] Lurie, G.B. Theory of working cycle in circular grinding and its automation / G.B. Lurie // Main questions of highly productive grinding / under the editorship of E.N. Maslov. – M.: Mashgiz, 1960. – P.87-108.

[2] Ostrovsky, V.I. Theoretical basics of grinding process / V.I. Ostrovsky. – L.: Publishing house of the Leningrad University, 1981. – 144 p.

[3] Mikhelkevich, V.N. Automatic grinding control / V.N. Mikhelkevich. – M.: Mecchanical Engineering, 1975. – 304 p.

[4] Kalennik, D.V. Research of internal infeed grinding process with automatic control of the radial effort :dissertation.... Candidate of Engineering Sciences : 05.02.08 / Kalennik Dmitry Vladimirovich. – Chelyabinsk, 1974. – 237 p.
[5] Manokhin, Y.I. Improving the efficiency if internal infeed grinding on the basis of optimal process control: dissertation. ... Candidate of Engineering Sciences / Manokhin Yuri Ivanovich.– Chelyabinsk, 1977. – 223 p.

[6] Levin, A.I. Optimization of infeed circular grinding cycle / A.I. Levin, V.M. Mshinistov // Machines and tools. –1992. – № 12. –P.27-29.

[7] Shipulin, L.V. Development of design methodology of plane grinding operations by wheel peripheral on the basis of the complex imitational process modelling: dissertation. ... Candidate of Engineering Sciences. Chelyabinsk, 2013. 187 p.

[8] Zhuchenko, A.V. Development of highly productive automatic cycles for the complex of restrictions for joint grinding of cylindrical and face surfaces: dissertation. ... Candidate of Engineering Sciences: 05.02.08 / Zhuchenko Alexander Viktorovich.– Chelyabinsk, 1988. – 230 p.

[9] Iogolevich, V.A. Improvement of productivity and accuracy fo processing on circular grinder with CNC considering dynamic properties of grinding: dissertation. ... Candidate of Engineering Sciences: 05.02.08 / Iogolevich Vladimir Aleksandrovich. – Chelyabinsk, 1992. – 175 p.

[10] Kulygin, V.L. Development of theory and calculating methodology of automatic cycles with the highest productivity with a given processing accuracy for circular external longitudinal grinding : dissertation. Candidate of Engineering Sciences. - Chelyabinsk, 1987. – 170 p.

[11] Nikolaenko, A.A. Modeling and calculating of highly productive automatic cycles of plane deep profile grinding for CNC machines: dissertation. ... Doctor of Engineering : 05.02.08 / Nikolaenko Aleksandr Alekseevich. – Chelyabinsk, 1998. – 349 p.

[12] Pereverzev, P.P. Theory and calculation methodology of optimal processing cycles of workpieces on circular grinds with program control: dissertation. ... Doctor of Engineering : 05.02.08 / Pereverzev Pavel Petrovich. – Chelyabinsk, 1999. – 295 p.

[13] Akintseva, A.V. Productivity improvement of internal grinding by cycles optimization of feeds control: dissertation. ... Candidate of Engineering Sciences: 05.02.08 / Akintseva Aleksandra Viktorovna. – Chelyabinsk, 1992. – 175 p.

[14] Korchak, S. N. Theoretical basics of technological factors impact on productivity improvement of grinding steel workpieces: dissertation. Doctor of Engineering. Chelyabinsk, 1973. 372 p.

[15] Alsigar, M.K. Modeling the interconnection of the cutting force with main technological factors during circular grinding with longitudinal feed/ M.K. Alsigar, P.P. Pereverzev // International Scientific Edition Modern Basis and Applied Researches. 2017. № 4-1 (27). P. 38-44.