Unified approach to developing analytical models of different grinding processes based on basic cutting process model

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Abstract. The appearance of modern CNC grinding machines allowed concentrating multipass and multistage processing of different workpiece surfaces by means of using different grinding types and different tool types. Meanwhile, the processing of different surfaces is carried out with different allowances and accuracy requirements and performed according to the specified stepwise cycles of the feeds control. As a result, there is a difficult task of quick and reliable calculation of the optimal feed cycles and other cutting modes for different types of processing of different surfaces with various grinding conditions. The solution to this problem is developing of mathematical models that link processing accuracy with cutting modes and other technological conditions of the processing. The development of such models should begin with the creation of a complex of the cutting forces’ models for each grinding type. This article describes a method for deriving generalized analytical model of the cutting force for the different grinding types which is based on the functional interrelation between the intensity of the metal removal performed by the wheel and elementary volumes of metal deformable in the shear zone. The complex of the cutting forces models for different grinding types, obtained by means of using this technique, establishes functional interrelation of the cutting force with cutting modes, strength properties of the treated material, kinematics of the grinding process, geometry of the cutting zone, characteristics and geometric parameters of the grinding wheel, etc. It should also be noted that the developed models cover the majority of production conditions and they are wide-range in terms of the main technological parameters (dimensions of the treated surfaces, allowances, tolerance grades, etc.).

1. Introduction
Due to the constantly increasing requirements for improving the productivity and accuracy of the parts processing – in conditions when more than 80% of machine-building products are manufactured in small batches, as well as the mass digital transformation of enterprises [1] – there is a constant increase of the CNC machines fleet. The main advantage of CNC machines is that the machine changeover takes ten times less preparation time due to their high versatility and the ability of quickly changing the program for the parts processing.

As a result of the growth of production dynamism due to the constant improvement of the machines design, there is an increase in the need to process tens of thousands parts of different nomenclature per year, which leads to a sharp increase in the volume of work on technical preparation of production (TPP). Mandatory stage of TPP in serial production is the monthly development of several thousand control programs (CP) for CNC machines. Considering the high complexity of CP designing, with the growing of automation level, the share of expenditure on TPP in the total cost structure for the
products manufacture increases, respectively the productivity of TPP affects the productivity of the whole automated production [2].

Therefore, there is an increase of TPP requirements on automation of design works, but today they are almost impracticable due to the lack of regulatory, scientific, methodological, mathematical and algorithmic support of CAD TP and CAD/CAM-systems for designing CP.

As a result, modern CAD/CAM-systems allow designing for CP only tool spatial movements trajectories and a sequence of discrete commands for integration of feeds control. The technological part of CP, related to the assignment of cutting modes, cycles of feed changes, number of strokes, etc. are assigned subjectively by the technologist on the basis of the experience of processing similar parts, the use of trial-end-error method, the use of standard or group technical processes-analogues. All these methods are «starter», because they give averaged and understated processing productivity modes in order to increase the reliability of the quality assurance and require further experimental (test) adjustment. Therefore, in modern automated machine-building production, equipped with a fleet of CNC machines, the mandatory stage at conducting TPP is still the test adjustment of the CP technological part for each part, what takes more than half of the total downtime of CNC machines. It is obvious that the presence of the test adjustment stage of the CP technological part reduces not only flexibility, versatility and productivity of expensive CNC machines, but also makes it impossible to fully automate TPP and all the digitalization of metalworking production.

The task of ensuring high productivity of the processing on CNC machines can be solved by applying mathematical modeling of technological processes of surfaces forming, operation control systems and prediction calculations of expected processing errors to calculate the optimal cutting modes in CP that reliably ensure the quality of parts processing. The use of modern CNC machines allow increasing productivity and accuracy of processing not only due to high versatility and flexibility in changeovers by quickly changing the program of processing, but also due to the following types of high concentration of working strokes, tools and different operations of mechanical processing, performed per single installation of the workpiece (considered on the example of the circular grinding CNC machine):

- concentration of tools: spindle for circular external grinding, spindle for internal grinding, magazine of grinding wheels;
- concentration of multipass processing, when a single tool is used to remove the allowance sequentially through the stages of rough, semi-finishing and finishing processing by automatic stepwise change of the feed in the process of allowance removal;
- concentration of feeds – joint program control of radial and axial feeds by their automatic stepwise change during processing time of the initial workpiece to the finished part;
- concentration of the treated surfaces, when different surfaces are treated sequentially with different tools;
- concentration of different grinding types, when different surfaces are treated by different grinding types.

Therefore, one multipass and multitool concentrated CNC operation replaces technological process performed on several traditional machines. As an example of different concentration types figures 1 and 2 shows possible schemes for processing external and internal surfaces of a conditional complex part installed on the CNC grinding machine. On the complex part it is possible to select the following types of surfaces by location – internal, external and end, by shape – cylindrical, conical (including chamfers). Treatment of external and internal cylindrical surfaces in dependence on its length is performed by applying circular (external/internal) grinding with longitudinal feed (fig. 1, a) or plunge circular (external/internal) grinding with only radial feed (fig. 1, b). Treatment of conical surfaces, including chamfers, is performed by turning the grinding spindle or chuck with a workpiece to the needed angle in dependence of the technological capabilities of the equipment (fig. 1, c и d). The above types of grinding are used.
Figure 1. Processing schemes for the circular (external/internal) grinding with longitudinal feed (a) and for the circular plunge grinding (b), treatment schemes for conical surfaces by turning the chuck with a workpiece (c) and turning the spindle with the wheel (d)

There are a lot of possibilities for treatment by grinding internal and external end surfaces. External ends can be processed by the end of the straight profile wheel with undercut with axial or radial feed (fig. 2, pos. 1 and 4), internal grinding wheel of the straight profile with radial feed (fig. 2, pos. 3), cup wheel with radial feed (fig. 2, pos. 6), recessed straight wheel with axial feed (fig. 2, pos. 7). Internal ends – by the recessed straight wheel with longitudinal feed at point-blank (fig. 2, pos. 2) or if it is impossible to damage the treated end surface by the fixing screw by internal grinding wheel of the straight profile with longitudinal feed at point-blank. In case of internal grinding it is also allowed to jointly process a hole and its end by recessed straight wheel with longitudinal feed at point-blank (fig. 2, pos. 5).

Thus, modern CNC circular grinding machines allow combining multistage processing of several different surfaces at a single setting of a workpiece (external and internal cylindrical, conical and profile surfaces, and also external and internal end surfaces) by using various types of grinding (circular, end and others) and different tools. Treatment of different surfaces with different allowances and accuracy requirements is performed according to different stepwise feed control cycles. As a result, there is a difficult task to quickly and calculate optimal feed cycles and other cutting modes for
different types of various surfaces treatment with different grinding conditions. As it was mentioned above, the solution of this problem is not yet possible due to the absence of mathematical models that link the processing accuracy with cutting modes and technological processing conditions. The development of such models is a complex scientific and technical task, which despite the 30-year existence of CNC machines has not yet been solved.

Many scientists have been working on improving cycle’s productivity and stabilizing quality parameters at different times [3-7, etc.]. At the same time, the matter of optimizing more than 2 parameters was practically not considered. Most commonly only one parameter is optimized – the radial feed, and then for the finished cycle of the radial feed another cutting mode was selected by full enumeration method [8-9]. It should be noted that the designed cycles were rational, because the method of mathematical optimization was not used, and they did not guarantee stability of processing accuracy figure, because accuracy restrictions were not used. Summing up, it could be said that no one dealt with a complex optimization of cutting modes’ cycles and other control cycle parameters (geometric parameters and wheel characteristics, number of wheel dressings per cycle, etc) and especially for different types of the various surfaces treatment with different grinding conditions considering variable technological factors (blunting ratio of the wheel, initial radial runout of the workpiece, etc.).

Solving the complex task of designing optimal feed cycles and other cutting modes for different types of various surfaces treatment with different grinding conditions must begin with creating a complex of cutting force models for each grinding type. The main purpose of the complex of the cutting force models under development should be establishing interrelation of the cutting force with cutting modes, strength properties of the treated material, kinematics of the grinding process, geometry of the cutting zone and parameters of the grinding wheel.
2. Method for derivation of generalized analytical models of cutting force for various grinding types

Basis of any grinding process is the same process of mass stochastic metal cut off by the grains set, which differs in different types of circular grinding by the kinematics of grains movement on the surface of the part, depth and width of cutting, length of the contact arc, contact area of the wheel grains with the part surface in the process of metal cutting. The set of grains that cut off the metal layer consists of unit grains which perform the same process of the metal cut off by means of plastic deformation of the metal micro volumes in the shear zone and converting it into chips with companion processes of friction and heat buildup in the contact area [10].

For all types of circular grinding the following general interrelations between unit grains and the wheel as a whole can be distinguished:

– sum of the cutting forces of all unit cutting grains is equal to the cutting force of the grinding wheel \( P_u \) as a whole;

– cutting speed is the same for all unit grains. Therefore, the speed of metal removal \( (Q, \text{mm}^3/\text{min}) \) is also the same for all unit cutting grains and equal to ratio of the metal volume in the shear zone to the time of plastic deformation of this metal volume after which the metal converts to chips. Consequently, the sum of the metal removal speeds by all unit cutting grains is equal to the metal removal speed by the wheel as a whole;

– all single cutting grains of the wheel have the area of blunting on the back surface which is in contact with the surface of the metal layer being cut off. Areas of blunting have a negative impact in the process of the metal cut off because they prevent deeper deepening grains into the metal and increase the cutting force. Aggregate of all blunting areas of the unit grains forms the base surface of the wheel as a whole, which contacts the part along the back surface of the wheel grains. Therefore, the area of blunting areas of all unit cutting grains is equal to the base surface area of the wheel as a whole. The relative proportion of the base surface area of the wheel from the geometric working area of the wheel characterizes the ratio of the wheel grains bluntness along the back surface. Therefore this relative base surface of the wheel will be called further the blunting ratio of the wheel \( \eta \);

– metal is cut off by the unit cutting grains of the wheel in the contact area of the wheel with the part. Geometric contact area \( F_g \) depends on the length and width of the contact area. Actual area \( F \) of the contact on blunting areas (base surface of the wheel) is equal to \( F = F_g \times \eta \).

In accordance with this representation of the general properties of the metal removal process, for all types of circular grinding it is possible to create a unified model of the cutting force with kinematic parameters \( Q, F \) and \( \eta \), independent of the grinding type, i.e.

\[
P_u = f(Q, F, \eta, ....)
\]  

(1)

Model of the cutting force (1) is the unified generalized model for all grinding types and it is the basis for obtaining the models of the cutting force for all grinding types by disclosing parameters \( Q \) and \( F \).

Besides, to cover the majority of production processing conditions the model of cutting force must be adequate in the normative general machine-building range of technological parameters and conditions of the parts processing. In other words, the model must include ranges of the treated surfaces dimensions, ranges of allowances, tolerance grades of the treated dimensions of the part and workpiece, ranges of machinability groups of materials, feed range of regime parameters, ranges of roughness and hardness of the treated surface, characteristics of the cutting tool, power ranges of machines actuator, ranges of attainable accuracy of machines. At the same time the scope of application of the cutting force model should cover all grinding types considering their kinematics and features of the metal removal process.

Proceeding from the unified understanding of the physics of cutting by a unit abrasive grain, the force model [10] will be the basis of the process model for any grinding type; the force model should establish interrelation between the cutting force and main process parameters that directly affect this force (wheel characteristics, cutting modes, etc.). Besides, the force model of the grinding process
must be wide-range, i.e. consider the process parameters in all ranges of variation, and not only for experimental values.

Analysis of literature sources showed that the available developments [11-16] mainly considered the modeling of micro-cutting with a unit abrasive grain and the occurrence of the cutting force on its top. In work [11] the physical interrelation between the force of cutting by unit abrasive grain with the main parameters of the grinding process, in particular with stresses of shear and compression, which depend on the strength of the workpiece material at real speeds of deformation and temperatures in the grinding zone, was established for the first time. In later works [12-16] the chip inertia force, shape and geometry of the grain top were additionally taken into consideration.

Undoubtedly, the cutting force models from the works above are adequate, experimentally confirmed and applicable in practice, but the large amount of data that requires complex calculation and large algorithms makes them inapplicable for digital models in the process of grinding cycles optimization and prediction of quality parameters stability, etc. In addition, most models do not establish a direct relation between the cutting force and cutting modes, and not all models take into consideration the process of grain blunting. Therefore, it was decided to develop a method for derivation the generalized analytical model of the cutting force for different grinding types.

The basis of this method is the model of interaction of abrasive grains with the workpiece [11], which establishes the fundamental regularities of mechanics of the metal plastic deformation by wheel grains in the cutting zone, kinematic features of the cutting process by abrasive grains under conditions of temperature and speed parameters during the grinding process, which established in work [11]. Summing up the cutting forces of unit grains in the cutting zone of the wheel with the workpiece with use of power balance of the cutting forces [17], it is possible to obtain the model of the cutting force for different grinding types:

\[
P_y = \frac{Q \sigma \epsilon \eta F_g}{V_p} + \frac{\sigma \eta F_g \beta}{3} \quad \text{(2)}
\]

\[
P_z = \frac{Q \sigma \epsilon \cos \varphi}{V_p} + \frac{\sigma \eta \mu F_g}{3} \quad \text{(3)}
\]

\[
P_x = \frac{Q \sigma \epsilon \sin \varphi}{V_p} + \frac{\sigma \eta \mu F_g}{3} \quad \text{(4)}
\]

where \(\sigma\) – average value of stresses intensity, N/mm\(^2\); \(\eta\) – blunting ratio of the wheel; \(\mu\) – coefficient of the abrasive grain friction on the treated material; \(V_p\) – cutting speed, m/min; \(Q\) – intensity of metal removal, m\(^3\)/s; \(F_g\) – geometric area of the contact area of wheel and workpiece, mm\(^2\); \(\beta\) – angle between the grain speed vector and the resultant of forces \(P_{yp}\) and \(P_{zp}\), acting in the chip formation zone when cutting a unit sharp grain [11]; \(\epsilon_i\) – average value of the deformation degree intensity; \(\varphi\) – angle between the axial speed of workpiece movement and cutting speed, deg.

The last three parameters (cutting speed, intensity of metal removal, area of the contact area of wheel and workpiece) depend on the grinding type. For example, the cutting speed vector of a unit grain of the wheel consists of three vectors: rotational speed of the grinding wheel, rotational speed of the workpiece and speed of the wheel axial feed. As a result, the cutting speed of the abrasive grain of the grinding wheel can be found by the following formulas: (5) – for grinding with axial feed and (6) – for grinding with radial feed.

\[
V_p = \sqrt{(V_1 + V_2)^2 + V_{soc}^2} \quad \text{(5)}
\]

\[
V_p = V_1 + V_2 \quad \text{(6)}
\]

where \(V_1\) – rotational speed of the wheel, m/s; \(V_2\) – rotational speed of the workpiece, m/min; \(V_{soc}\) – speed of the axial feed, m/min.
Intensity of removal is the volume of metal removed by grinding wheel per unit of time; it can be calculated by the following formulas [17]:

for circular (external/internal) grinding with axial feed:
\[ Q = \pi d V_{Soc} S_{rad} \]  
(7)

for circular (external/internal) grinding with radial feed:
\[ Q = \pi d T V_{rad} \]  
(8)

for flat grinding (processing of end surfaces)
\[ Q = V T S_{rad} \]  
(9)

where
- \( d \) – workpiece diameter, mm;
- \( T \) – wheel height, mm;
- \( S_{rad} \) – radial feed on stroke, mm/stroke;
- \( V_{rad} \) – speed of plunge radial feed, mm/min.

Geometric area of the contact area of wheel and workpiece during external (plus sign) and internal (minus sign) grinding in the plane of action radial (Y axis) and tangential (Z axis) cutting force is determined by the formula:
\[ F_{g}^{Y,Z} = T \sqrt{\frac{d S_{rad}}{d \pm D}} \]  
(10)

For flat grinding the geometric area of the contact area of wheel and workpiece will be found by formula:
\[ F_{g}^{Y,Z} = 2T \sqrt{DS_{rad}} \]  
(11)

where \( D \) – wheel diameter, mm.

Substituting all three parameters, depending on the grinding type, in formula (2) it is possible to obtain, for example, the radial component of the cutting force for the internal grinding (12) – with axial feed and (13) – with radial feed):
\[ P_{r} = \frac{\epsilon_{tg} \beta \sigma \pi d V_{Soc} S_{rad}}{\sqrt{[V_{1} + V_{2}]^{2} + V_{Soc}^{2}}} + \frac{\eta T \sigma}{3} \sqrt{\frac{d S_{rad}}{d - D}} \]  
(12)
\[ P_{r} = \frac{\epsilon_{tg} \beta \sigma V_{rad} T_{rad}}{V_{1}} + \frac{\eta T \sigma}{3} \sqrt{\frac{d T_{rad}}{d - D}} \]  
(13)

where \( t_{rad} \) – plunge radial feed, mm/rev.

It should be noted that values of parameters \( \beta, \epsilon_{i} \) and \( \varphi \) can be found in work [17]. Proposed method for derivation the generalized analytical model of the cutting force for the grinding process establishes functional interrelation of the cutting force with cutting modes, geometric parameters of the contact area of the wheel with the part, strength properties of the treated material, blunting of the wheel grains. More detailed description of the cutting force model, as well as an experimental test for internal grinding can be found in article [18], for external grinding – [19], for flat grinding – [20]. In the future, the cutting force models for different grinding types obtained by this method find their practical application in the development of the digital model of the grinding process, in particular when optimizing grinding cycles, checking the stability of quality indicators in the designed active cycles, etc.

3. Conclusions

1. Appearance of modern CNC grinding machines, which allow to perform complex treatment of all surfaces per single installation of the workpiece at high cutting speeds and according to specified cycles, revealed the problem of absence of an effective tool in mechanical engineering, which allow
quickly design optimal feed cycles and other cutting modes for different types of various surfaces treatment with different grinding conditions in a unified digital space. The solution to this problem should be started with creating a complex of the cutting forces models for each grinding type, which will establish interrelation of the cutting force with cutting modes, strength properties of the treated material, kinematics of the grinding process, geometry of the cutting area and grinding wheel parameters.

2. Proposed method of derivation of the generalized analytical models of the cutting force for different grinding types (external, internal and flat) is based firstly, on the equality work of acting cutting forces and resistance forces of the processed metal to plastic deformation during grinding by a unit abrasive grain, and secondly, on the functional relation of the intensity of the metal removal by the wheel with the elementary metal volumes deformable in the shear zone.

3. Complex of cutting forces models for different grinding types, obtained by means of this method, establishes the functional relation of the cutting force with the cutting modes, strength properties of the treated material, kinematics of the grinding process, geometry of the cutting zone, characteristics and geometric parameters of the grinding wheel, etc. It should also be noted that the obtained models of the cutting forces for different grinding types cover the majority of production conditions and they are wide-range in terms of the main technological parameters (dimensions of the treated surfaces, allowances, tolerance grades, etc.).

References
[1] Vasja RV, Meško M and Krapež A 2016 J. SAGE Open 1 11
[2] Schumacher A, Schumacher C and Sihn W 2020 ICPRI 2019 104 301
[3] Le XH, Le HK, Tran TH, Nguyen VC, Do DT, Nguyen HP, Luu AT and Ngoc PV 2020 ICERA 2019, LNNS 104 557
[4] Jiajian Gu and Haolin Li November 2019 International Journal of Advanced Manufacturing Technology 105 7
[5] Gupta R, Shishodia KS and Sekhon GS 2001 J. Mater. Process. Technol. 112 63
[6] Gao S, Yang C, Xu J, Fu Y, Su H and Ding W 2017 Journal of Advanced Manufacturing Technology 92 1105
[7] Tung L, Hong T, Cuong N and Vu N 2019 ICERA 2019: Advances in Engineering Research and Application, Proceedings of the International Conference on Engineering Research and Applications 104 121
[8] Guzeev V and Nurkenov A 2016 J. Procedia Engineering 150 815
[9] Shipulin LV and Ardashev DV 2019 J. Procedia Manufacturing 1 1
[10]. Malkin S and Guo C Grinding Technology: Theory and Applications of Machining with Abrasives (Industrial Press, New York, USA, 2008)
[11] Korchak SN The Productivity of the Grinding of Steel Parts (Maschinostroenie, Moscow, Russia, 1974)
[12] Oliveira JFG, Silva EJ, Guo C and Hashimoto F 2009 J. CIRP Annals Technology 58 663
[13] Kim SH and Ahn JH 1999 J. of Materials Processing Technology 88 190
[14] Shavva MA and Grubiš SV 2015 J. Applied Mechanics and Materials 770 163
[15] Liu YM, Yang TY, He Z and Li JY 2018 J. Archives of Civil and Mechanical Engineering 18 17
[16] Rowe WB and Ebbrell S 2004 J. CIRP Ann 53 255
[17] Pereverzev PP and Pimenov DY 2016 Journal of Friction and Wear 37 60-65
[18] Pereverzev PP and Akintseva AV 2016 J. Procedia Engineering 150 1113
[19] Alsigar MK 2018 Journal of Advanced Research in Technical Science 9 26
[20] Yudin S, Smolyanoy K and Pereverzev P IOP Conference Series Materials Science and Engineering 709 033005