Methodology for designing optimal internal grinding cycles resistant to varying processing conditions

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Abstract. In this article the design methodology of optimal control cycles of radial and axial feeds by the example of internal grinding operations is considered. The methodology is based on the functional interrelation between main technological parameters of machining (cutting modes, cutting zone geometry, physical mechanical properties of machining material, wheel blunting and its characteristic) and cutting forces, processes occurring in the machining zone. Dynamic programming method was used as mathematical optimization method. Principal time (task of operating speed) was used as objective function. For stability augmentation of product-quality index the test of objective function limitations was made for two groups of machining conditions (favorable and unfavorable).

Legend

S_rad – radial feed, mm/double stroke;
V_soc – speed of axial feed, mm/min;
P – allowance, mm
M_Srad – quantity of machine radial feeds;
M_Vsoc – quantity of axial feeds speeds (according to the machine passport);
N – maximum number of allowance increment in which value of remaining allowance is equal to zero;
m_Vsoc – speed number of axial feed;
m_Srad – radial feed number;
n – allowance increment number;
z_Vsoc – stage number of axial feed speed switching;
z_Srad – stage number of radial feed speed switching.

1. Introduction

Growth of the digital economy sets Russian mechanical engineering quite complex and volume task-making up the production digitalization. It will let to significantly reduce preproduction expenses, ensure stability of product-quality index, etc. Technological preparation of digital production is led to the single information environment, which is hold at a virtual space, using technologies of digital
modeling and designing both – products, produces and production processes by creation of digital twins. Digital model or digital twin lets to realize virtual modeling of production process over the whole product life cycle which includes main technological aspects of production (equipment, tool, technological process, etc.) [1-3].

Production digitalization presupposes through preparation of all technological processes, among others the full automation of development control programs for CNC machines by converting the information about operation in digital form and using virtual modeling. As a result it becomes possible to find optimal cycles of cutting modes control, prediction of machining quality, possible problems detection and reliability testing of control programs for CNC machines in variable machining conditions of workpieces batch. It should be noted that for a moment that there are no virtual environment and digital designing technologies for optimal cycles of cutting modes control for internal grinding operations and other types of mechanical machining.

In the vast majority of САМ-systems the process of cutting modes’ control cycles designing for internal grinding operations is partially-automated, only for a tool withdrawal and supply, etc. Cutting modes are set by technologist manually on the basis of normative-reference or factory statistics, setting-up experience or by machining test billets (numerical method). Often to ensure target drawing objectives, cutting modes set by this way are significantly low, what affects the productivity of CNC machines (50..60% of technological capability are used [4]). Furthermore, cycles, designed by methods mentioned above, do not consider the affection of such variable technological factors as degree of wheel blunting, initial radial runout of the billet, allowance fluctuations, etc. Thus these cycles cannot guarantee the stability of accuracy and quality indexes during both workpiece machining cycle and machining of produces batch.

Questions of optimal cycles designing for different types of mechanical machining were studied at different times by many scientists in works of which [5-10] cycle optimization tasks were set, complex of main technological limitations on operation productivity were formulated, models of productivity limitations on power, roughness and etc. were developed. It should be noted that in the majority of researches the task for cycle’s optimization was a reduction of machining time to its minimum under the condition of drawing compliance for accuracy and quality. In spite of huge volume of researches, the most part of them have number of fundamental defects, making them unusable in conditions of modern automated production. Firstly, mathematical optimization methods are not used in many engineering techniques. It leads to the fact that cycles designed by these techniques are rational but not optimal. Secondly, these techniques have no one of the most important and mandatory models of operation productivity limitations on machining accuracy. Thirdly, the techniques do not consider variability of technological process during both workpiece machining cycle and machining of the billets batch.

2. Methodology for designing optimal internal grinding cycles resistant to varying processing conditions

Solution of the problem above is the development of designing methodology for the optimal cutting modes’ control cycles by the example of internal grinding with using of digital twin technologies [1-3]. The model of metal removal was developed as the digital twin for the internal grinding process [11]; this model:

– is based on the generalized force model of internal grinding process which considers kinematics features of internal grinding and sets functional relation of cutting forces with machining modes and other parameters;
– sets interrelation of actual and program feeds with cutting forces, elastic deformation of technological system, cutting modes, geometrical parameters of contact zone between the wheel and the billet, wheel characteristics and other technological parameters and machining conditions in a wide range of their variation;
– lets calculate the current values of actual radial feed, cutting force, section radii of the hole machined surface and etc. for the given cycles and different technological conditions of grinding.
As the mathematical optimization method the dynamic programming method (DPM) proposed by R. Bellman [12] was chosen; it is often used for technological processes’ optimization in many works. DPM does not limit neither number of optimized parameters (cutting modes, geometrical parameters and wheel characteristics, overtravel value, etc), nor number of imposed limitations (power, accuracy, technological capabilities of equipment, etc.). Thus DPM is a universal method which allows optimizing cycles of mechanical machining in multidimensional space of control parameters, covering all groups of control parameters (cutting modes, geometrical parameters and grinding wheel characteristics, overtravel value, etc). This article presents the partial optimization of internal grinding cycles where optimized parameters are the radial feed and speed of axial feed.

Let us consider the types of internal grinding cycles bringing under regulation the control of two regime parameters (fig. 1). Asynchronous cycles (fig. 1, a) in which the control parameters change by stages independently of one another. These cycles were not used in practice due to complexity of its tuning and realization. Synchronous type (fig. 1, b) is a cycle in which the switching of cycle control parameters is performed simultaneously in dependence on the allowance removal value. There can be also a mixed type in which one part of parameters switches independently of one another (asynchronous cycle part) and another part switches simultaneously in dependence on allowance removal value (synchronous cycle part).

To improve productivity of internal grinding operations performed on CNC machines the machining time was chosen as the optimality. As a result the objective function resolves the task of cycle optimization into finding a stable combination of optimal cutting modes’ control cycles at which guaranteed the drawing compliance for accuracy and quality at given technological machining conditions for the minimal machining time.

Due to DPM discreteness, after optimization it is possible to get an optimal «stageless cycle», which has many small stages bounded only by the number of grid nodes. For example, after optimization on the grid with increments 10*20 we can get 10-stage cycle, while as in production the real machining cycles have mostly 3-5 stages. Thus, to get the trajectory of optimal cycle with given number of stages let us impose the limitation of objective function in number of admissible cycle stages, i.e. in number of admissible switches made by ACE (automatic control equipment) or machine. Let us assume that each parameter of cycle control has a definite number of stages (for asynchronous and mixed cycle types). For example, on fig. 1, a the cycle of internal grinding with three stages of radial feed and three speed stages of axial feed is shown. Therefore, the total number of cycle stages is equal to six. If cycle is synchronous (fig. 1, b), the stage sequence number is counted at every simultaneous switch of cycle control parameters.

Figure 1. Types classification of internal grinding cycles: asynchronous (a), synchronous (b)
Optimization of internal grinding cycles in multidimensional space of control parameters is made in an optimization matrix containing informational cells (fig. 2). For description convenience of optimization sequence of internal grinding cycles the unit converts to informational cells (fig. 2) and the matrix – to grid fig.3.

Search of optimal cycles trajectory of radial and axial feeds control is performed in coordinates «Radial feed – Speed of axial feed – Allowance» (fig. 4). DPM applies for methods of discrete optimization. Thus scales are divided on into increments. Scale of radial feed is divided into \( S_{\text{рад}} \) over the range \([S_{\text{рад}}^{\min}, S_{\text{рад}}^{\max}]\), scale of axial feed speed into \( M_{\text{soc}} \) over the range \([V_{\text{soc}}^{\min}, V_{\text{soc}}^{\max}]\), scale of allowance into \( N \) increments.

On each grid intersection the informational cell is placed; it contains the data necessary for calculation: optimal time of state reaching, coordinates wherefrom the optimal stroke is made and etc.

According to DPM from the aggregate of competing strokes (possible variants of feeds switching in the cycle) made into informational cell with coordinates \([n, m_{\text{рад}}, z_{\text{рад}}, m_{\text{soc}}, z_{\text{soc}}]\) from the previous allowance increment \((n-1)\) at all program values of radial and axial feeds the strokes admissible by one or another limitation are chosen (fig. 3). Stroke is accepted admissible if in the reached state after this stroke all limitations of objective function are performed. Limitations, active in the cycle beginning (for example, power limitation), are checked on the considered allowance increment for each informational cell on the corresponding program feeds (fig. 3). Checking of limitations active during the whole cycle (for example, accuracy [13] and roughness limitations), is performed by modeling the removal of remaining allowance part at minimum possible (according to machine technical characteristics) radial and axial feeds.

To improve the indexes stability of accuracy and quality of the machined surface to effect of variable technological factors, the checking of objective function limitations is performed on two groups of ultimate value combinations of technological machining conditions (table 1): favorable (group 1) and unfavorable (group 2). The result of calculations in two groups of ultimate values of technological factors the tolerance zone of cycle parameters is got.

From the aggregate of admissible strokes the optimal stroke is chosen; it must have the optimal prime of state reaching and be admissible on all limitations (fig. 4). Then the number of radial and axial feeds, number of stage from which the optimal stroke was made (variables \( m_{\text{рад}}^{*} \) and \( m_{\text{soc}}^{**} \)) is...
written in the cell. After considering the last allowance increment from the range of optimal strokes, located in different numbers of radial and axial feeds, the one stroke which has a minimum time of final state reaching is chosen. For fixation of optimal trajectory of grinding cycle control the procedure of a return stroke is performed, which begins from the stroke having the minimum time of final state reaching. On fig. 4 the order of return stroke procedure is numbered by Roman numerals from I to IV.

### Table 1. Division of variable technological factors on groups of machining conditions

| Factors                  | Group 1          | Group 2          |
|--------------------------|------------------|------------------|
| grade of the wheel blunting | minimum          | maximum          |
| initial radial runout of the billet | minimum          | maximum          |
| allowance                | minimum          | maximum          |
| wheel diameter           | maximum          | minimum          |

In accordance with a huge volume of processed information, the calculation of optimal cycles of radial and axial feeds control on operations of internal grinding was set in the developed program environment (Official Registration Certificate For Computer Program № 2018613317). The checking of proposed designing methodology of radial and axial feeds’ control cycles is performed on enterprises of Russian engineering industry. Checking was performed by productivity comparison of factory and «calculated» cycles; it showed that the improvement of the designed cycle productivity against the factory is 33 %. Finished products ensure the accuracy and quality requirements with an allowance of machining time reduction.

**Figure 3.** Grid for cycles’ optimization of radial and axial feeds control on internal grinding operations DPM considering the limitations on admissible stage numbers of feeds’ cycles: 1 – informational cell; 2 – competing strokes; 3 – strokes admissible by one or another limitation; 4 – optimal stroke with minimum machining time; 5 – return stroke procedure; 6 – informational cell which is out of calculation;
3. Conclusions
The design methodology of optimal internal grinding cycles described in this article
– is based on the metal removal model which sets the functional interrelation with cutting modes, geometry of cutting zone (dimensions of grinded surface, wheel parameters, etc), physical mechanical properties of machined material, wheel blunting and wheel characteristic. Removal model allow to calculate actual radial feed, current radii values in different sections of machined hole, cutting forces, time of allowance increment removal, time of state reaching, etc.;
– considers any quantities of technological limitations for the objective function. Each step and calculation variant is checked with four capital limitations – accuracy, absence of burns, roughness and wear of abrasive tool – ensuring the needed quality and machining accuracy, and with the main limitations of technological system;
– considers changes of machining conditions (wheel grains’ blunting, fluctuation of allowance and initial accuracy of machined surface in a billets batch), which influences the fluctuations of resultant quality indexes of machined surface;
– allows to design optimal internal grinding cycles with mathematical accuracy, using DPM. Optimization results are the optimal values of radial feed and speed of axial feed in all cycle stages and optimal allowance distribution by all stages of control cycle for radial and axial feeds in which the minimum principal time is ensured.

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