Optimization of conditions for small-rigid prismatic workpieces flat grinding by elastic deformations controlling

V N Tyshkevich*, V A Nosenko and A V Sarazov
Volzhsky Polytechnical Institute (Branch), Volgogradsky State Technical University, 42a, Engels St., Bldg. Volzhsky 404121, Russia

*tubem@mail.ru

Abstract. The authors propose the technique of optimization the conditions for small-rigid prismatic workpieces side surfaces flat grinding that guarantees obtaining the predefined quality requirements of the machined surface while ensuring the maximum process efficiency. The input factors (grinding wheel hardness, depth of grinding, table feed speed and run, etc.) are considered as the grinding process optimization parameters. Mathematical models of the output factors (surface roughness parameter $Ra$, absence of grinding burns, required flatness tolerance of surface) are used to limit the range of optimization parameters allowable values. The resulted efficiency is an objective function. The optimization of parameters in the range of allowable values is carried out with the view of ensuring the maximum process efficiency. The required flatness admission is provided at the second optimization stage of the workpieces by controlling the elastic deformation extent. The varied parameters at controlling the maximum elastic deformation are cutting forces, the attraction of the magnetic field of the machine table and rigidity of workpiece at a bend. The terms for providing of the required side surface flatness tolerance are determined for workpieces taking into account elastic deformation of the small-rigid workpieces under the magnetic field effect on the machine table and the radial component of the grinding force. Keywords: elastic deformations; small-rigid prismatic workpieces; flat grinding; quality of machined surface; process optimization.

1. Introduction
Ensuring required quality of the side surfaces of small-rigid prismatic workpieces, that have an initial deviation from flatness of the base side surface due to heat treatment or previous machining operations, is a challenging task while grinding. Being attached by the magnetic field of a table and then grinded, a small-rigid workpiece receives the elastic deformation normal to the surface of the machine table. After terminating the cutting forces and unfastening the workpiece, certain deviations from flatness of the end surfaces are returned in the result of elastic deformation. Technological ways of fixing the occurring defects of form significantly increase the processing time and the cost of the operation [1-2].

Experience in manufacturing small-rigid prismatic guiding rails (figure 1) shows that modern technology of grinding processing cannot be developed without regard to the hardness of parts and elastic deformation during the machining process [3-11].

Objective of the research: developing an algorithm and methodology of optimizing the process of flat grinding of the side surfaces of small-rigid prismatic billets, providing the specified tolerance...
flatness of surfaces and other mandatory requirements to the finished surface quality with a maximum efficiency of the process of flat grinding.

Figure 1. Examples of small-rigid prismatic guiding rails of the bearings.

2. Algorithm and methodology of optimizing the process

The proposed algorithm involves a two-step optimization process. In the first stage (figure 2), when choosing the optimal conditions for grinding (mode 1), the workpiece is considered as absolutely rigid and optimization modes are carried out with a view of implementing requirements for such parameters as roughness, waviness, absence of grinding burn marks, cracks etc., excepting the flatness tolerance [7-11].

Using mathematical models of radial and tangential components of cutting force, roughness parameter etc. \( P_y = P_y (x_1, x_2, ..., x_k); P_z = P_z (x_1, x_2, ..., x_k); Ra = Ra (x_1, x_2, ..., x_k); K_g = K_g (x_1, x_2, ..., x_k); \) etc. (see figure 2) we can determine tolerance range for the parameters of abrasive tools characteristics and modes \( x_1, x_2, ..., x_k \), ensuring that the surface complies with predetermined quality requirements.

Further optimization of the parameters in the tolerance range is performed according to the criterion of the maximal productivity of the process, \( Q_{\text{max}} (x_1, x_2, ..., x_k) \). These optimal parameters determine the first grinding mode (mode 1) [7-11].

Figure 2. Algorithm for optimizing modes of grinding side surfaces of small-rigid prismatic guiding rails of the bearings (first stage).
In the above examples of realization of the first stage we used mathematical models [7, 8, 11, 12], obtained by grinding of bearing steel ShH15 and steel 20Kh. The input model parameters are the given characteristics of the abrasive tool (grit of grinding powder and hardness of the wheel), performance factors (speed table feed, depth of grinding) and groundwork (volume of removed metal).

The elastic deformation of a workpiece during grinding occurs under the action of radial component of cutting force. As other quality indicators in the present example we selected machined surface roughness (parameter $Ra$) and the absence of grinding burn marks. The main reason for the formation of grinding burn marks is grinding temperature-dependent tangent component of the cutting force; therefore, to optimize the grinding process it is necessary to create a mathematical model of the components of the cutting force and machined surface roughness.

According to the optimal parameters of the mode 1 we can determine the optimal value of the radial and tangential components of cutting force.

Required flatness tolerance is provided at the second stage of optimizing control of elastic deformation value (figure 3).

The varied parameters at controlling the maximum elastic deformation are cutting forces, the attraction of the magnetic field of the machine table and rigidity of workpiece at a bend.

As showed researches, the major factor defining initial deviations from flatness of the side surfaces of small-rigid prismatic workpieces is deformation of preparation in the course of its heat treatment or previous machining operations. In this regard workpiece receives curvature of a surface with the expressed regular waves of macrodeviations (figure 4).

The macrodeviation of a surface of the workpiece adjoining to a smooth surface of a table is modelled by a cylindrical surface from directing in the form of a sinusoid with the characteristic wavelength of $l$ (figure 5).

Characteristic wavelength depends on design features of workpiece, its flexural rigidity and preceding grinding of mechanical and heat treatment. With big lengths of workpieces in its length several regular waves of a sinusoid can keep within. The doubled amplitude of a sinusoid of $y$ is accepted to the equal maximum height of macrodeviations (see figure 5).

The developed solution of removing the bent of ends of the rings by grinding is patented [13]. Workpiece is modelled by not cutting beam with the number of flights of $n$ equal to number of waves of a sinusoid on workpiece length. When fixing workpiece with magnetic field of a table workpiece is affected by evenly distributed loading with intensity: $q = q_c + q_m$, where $q_c$ are the intensity of evenly distributed loading from action of an attraction of magnetic field of a table of the machine; $q_m$ are the intensity of evenly distributed loading from action of a body weight of workpiece (see figure 5).

The maximum deformation when fixing workpiece with magnetic field of a table of $w_{pmaxnc}$ is defined taking into account maximum elastic deformations of workpiece at a bend, respectively under the influence of a lot of workpiece and effort of an attraction of magnetic field of a table of the $w_{qn}$ machine (see figure 5) and contact deformations [14].

The maximum elastic deformation of the workpiece during bending under the action respectively of the cutting force and contact deformation of $w_{pmaxnc}$ are added at grinding of side surface of workpiece [14]. For increase in rigidity of workpiece at a bend when fixing with magnetic field of table of the machine it is recommended to use compensator bars (figure 6) [14].

The sufficient number of compensator bars from condition of ensuring the required flatness tolerances is determined by control algorithms of the size of elastic deformation (see figure 3) with specification of blocks in [14].

The maximum number of pairs of compensator bars on the characteristic length is limited to five of reasons of cutting-down of auxiliary time for grinding operations.

When using more than two pairs of compensator bars closing of spacing between the surfaces of workpiece and table of the machine (contact of surfaces at deformation of bend) will consistently come from the first flight of beam to average. If the size of the maximum deflection in the first flight of beam is more or is equal to spacing between the surfaces (contact points) of workpiece and table:
\[ w_{q_{n2}} \geq y_{n2}; \quad w_{q_{n3}} \geq y_{n3}; \quad w_{q_{n4}} \geq y_{n4}; \quad w_{q_{n5}} \geq y_{n5}, \] and amount of clearance will be less or is equal to the allowed maximum elastic deformation of the workpiece \([\Delta]\): \[ y_{n2} \leq [\Delta]; \quad y_{n3} \leq [\Delta]; \quad y_{n4} \leq [\Delta]; \quad y_{n5} \leq [\Delta], \] that further calculations of size of the maximum deflection needs to be continued on average flight of beam [14].

**Figure 3.** Algorithm for optimizing modes of grinding side surfaces of small-rigid prismatic guiding rails of the bearings by controlling elastic deformations (second stage). 2 - Check of a possibility of grinding without sparkout with workpiece fastening by a magnetic field of a table and with compensators (mode 1). 3 - Check of a possibility of grinding without sparkout and without fastening by the magnetic field of a table and with compensators, the workpiece is fixed via stops (mode 1). 4 - Check of a possibility of grinding without sparkout with workpiece fastening by a magnetic field of a table and with compensators, when reducing the value of \(P_y\) due to the corresponding reduction factors (mode 2). 5 - Check of a possibility of sparkout grinding (mode 3). 6 - Check of a possibility of sparkout grinding without sparkout with workpiece fastening by a magnetic field of a table.
Figure 4. 3D model of guiding rail with increase by 100 times of macrodeviations from flatness.

Figure 5. Analytical model of workpiece fastening by a magnetic field of a table.

Figure 6. Installation of compensator bars.

Value $[\Delta]$ considering coefficient precision $\lambda$ is found by the following formula (1) [7, 11, 14]:

$$[\Delta] = \lambda \Delta - \Delta_h,$$  \hspace{1cm} (1)

where $\Delta$ - flatness tolerances of the end surface during grinding process; $\Delta_h$ – flatness tolerances when grinding hard workpieces.

The maximum deformations $w_{q_{\text{max}_n}}$, $w'_{q_{\text{max}_n}}$ and distance between points of contact of surfaces of $y_{nc}$, $y'_{nc}$ are defined on [14].

Using the magnetic field of the machine table for fastening the workpiece is possible when the following inequalities are satisfied [7, 14]:

$$y_{nc} \leq [\Delta]; w_{q_{\text{max}_n}} \leq [\Delta]; y'_{nc} \leq [\Delta]; w'_{q_{\text{max}_n}} \leq [\Delta]; c = 0...5,$$  \hspace{1cm} (2)

where $w_{q_{\text{max}_n}}$, $w'_{q_{\text{max}_n}}$ are determined in the first and on average flight of a beam, respectively, by an algorithm [14] at action only of effort of an attraction of magnetic field of a table and a body weight of the workpiece; $y_{nc}$, $y'_{nc}$ - distance between points of contact of surfaces of the workpiece and the table in the first and on average flight of a beam, respectively; $n$ – number of flights in workpiece length; $c$ – number of pairs of compensators.

The workpiece is fixed via stops on a table of the machine when the following inequality is satisfied [7, 14]:

$$w_{q_{\text{max}_n}5} > [\Delta].$$  \hspace{1cm} (3)
To ensure optimal grinding mode with maximum performance when the workpiece is fastened by the magnetic field of a table, the condition (3) is supplemented by the following equality [7, 14]:

\[ p = [p_1], \]  

(4)

where \( p \) is the specific attraction of the machine table magnetic field; \([p_1]\) - minimum allowable intensity of attraction with the absence of shear of the workpiece [5].

Conditions ensuring a specified flatness tolerance for the surfaces of the workpiece without sparkout when fastening the workpiece by the magnetic field of a table is determined by the following inequalities [7, 14]:

\[ y_{nc} \leq \Delta; \; w_{maxnc} \leq \Delta; \; y'_{nc} \leq \Delta; \; w'_{maxnc} \leq \Delta, \]

(5)

where \( w_{maxnc} \), \( w'_{maxnc} \) are determined by an algorithm of block 2 of the integrated algorithm (see figure 3).

As practice shows, achieving the required roughness of the workpiece surfaces is possible without the use of sparkout. Sparkout is used to ensure the flatness tolerance. The basic processing time with sparkout increases in average by 40% [3-7]. Non-sparkout grinding of a workpiece fastened by the magnetic field of the table with \( p = [p_1] \) is possible when reducing the value of \( P \) due to the corresponding reduction factors in the previously defined range and search in the same range of the allowed values for process parameters, under which the following conditions are met [7, 14]:

\[ y_{nt5} \leq \Delta; \; y'_{nt5} \leq \Delta; \; w_{maxnt5} \leq \Delta; \; w'_{maxnt5} \leq \Delta; \; T_o < 1.4T_{omin}, \]

(6)

where \( T_o \) is the basic time of grinding, \( T_{omin} \) – the basic time of non-sparkout grinding, with a maximum processing performance, the parameters of which were predetermined (mode 1).

With the existence in the tolerance range of process parameters that satisfy the conditions (6), further optimization is carried out with criterion of maximum productivity (mode 2).

When conditions (6) are not met, mode 3 (sparkout grinding) is implemented. The parameters of the grinding process correspond to mode 1, but the grinding time increases by an average of 40%.

If the condition (2) is not met, grinding the first side of the workpiece is performed without fastening by the magnetic field of a table, the workpiece is fixed via stops.

The condition for ensuring the specified flatness tolerance of the mechanical surface of the workpiece without sparkout and without fastening the workpiece to a table by its magnetic field is determined by the inequalities:

\[ y_{nc} \leq \Delta; \; w_{pmaxnc} \leq \Delta; \; y'_{nc} \leq \Delta; \; w'_{pmaxnc} \leq \Delta, \]

(7)

where \( w_{pmaxnc} \), \( w'_{pmaxnc} \) are determined by an algorithm of block 3 of the integrated algorithm (see figure 3) [7, 14].

If the condition (7) is met, grinding the first side surfaces of the workpiece is performed with the parameters of mode 1.

The implementation of mode 2 without fastening the workpiece by the magnetic field of a table, is possible when the following conditions are met:

\[ w_{pmaxnt5} \leq \Delta; \; w_{pmaxnt5}' \leq \Delta; \; T_o < 1.4T_{omin}; \; y_{nt5} \leq \Delta; \; y'_{nt5} \leq \Delta; \; w'_{pmaxnt5} \leq \Delta, \]

(8)

where \( w_{pn} \), \( w_{mn} \) are the maximum elastic deformation of the workpiece during bending under the action respectively of the cutting force and the mass of the workpiece.

If the conditions (8) are not met, the grinding of the first side surfaces of the workpiece is performed without fastening by the magnetic field of a table with sparkout (mode 3).

Technique and recommendations developed based on this algorithm has improved the efficiency of the technological process of grinding the ends of small-rigid prismatic guiding rails of the bearing LRH 6/350 (see figure 1) [15].
3. Conclusions
We have developed the algorithm and methodology for optimization of flat grinding at the periphery of the wheel on the machines with a magnetic table of small-rigid prismatic workpieces with an initial deviation of side surfaces from flatness. We also developed the conditions that ensure the specified flatness tolerance of the mechanical surface of the small-rigid prismatic workpiece.

Optimal modes provide the specified quality requirements of the machined surface with a maximum efficiency of the process of flat grinding.

The required flatness tolerances of the mechanical surface of small-rigid prismatic workpieces is provided by controlling the value of elastic deformation of the workpiece.

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