Technological support of tool wear resistant qualities and cost saving of process of planetary grinding of flat parts

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Abstract. A lot of factors varied in time lead to instability of the grinding process. Besides, the method of grinding influences significantly the productivity and quality of processing. In this regard a creation of processes of intensive defect-free grinding on the basis of new constructive and technology solutions represents the scientific problem which is of great importance. One of such solutions is application of planetary face grinding which allows simultaneously changing the kinematics of movement, implementing discontinuous grinding. The distinctive features of such grinding are decreasing the heat release rate in a contact zone; ensuring intermittence of the process with a solid grinding wheel; reverse grinding; cutting by different edges of an abrasive grain; stabilization of working parameters of a grinding wheel; ensuring work of a grinding wheel in a self-sharpening mode. The design of the planetary grinding tool was developed for plane surface processing for implementation of the specified distinctive features of planetary grinding. The kinematics of shaping a surface by flat face diamond grinding has been investigated; manufacturing capabilities of planetary face grinding have been revealed, and ways of improvement of quality and productivity have been offered. The algorithm and the program to define the motion path of a grain depending on the given set of grinding factors were received. Optimization of the process of face diamond grinding using the planetary grinding device has been confirmed with the developed program and techniques to choose cutting conditions of planetary grinding and characteristics of grinding wheels for processing different materials. While studying the process of planetary grinding, special attention was paid to the research how processing conditions influence microgeometry of the processed surface made of steel 4X5M (Russian State Standard (GOST)). As a result of the executed research, it was established that surface roughness parameter Ra during the processing using the planetary grinding device is 35 - 40\% less than when using the tool with the solid cutting surface. This phenomenon can be accounted for more uniform work of the cutting grains of the planetary grinding tool as the number of meetings of diamond grains with the surface being processed increases. At the same time, it should be noted that during the planetary grinding more intensive smoothing of tops of microroughnesses is observed that provides the creation of steadier cutting shape. The given method of calculation of cost value of grinding operation...
allows solving various manufacturing problems: to compare cost value of grinding different materials, grinding wheels of different parameters; to define the optimum grinding conditions.

1. Introduction
Based on the tasks and requirements imposed on flat parts made of hard-to machine material, it is possible to consider that out of all finishing methods of processing the most efficient method is planetary grinding. Planetary grinding allows combining preprocessing and finishing processing of parts, receiving a processed surface with high surface roughness parameters, dimensional tool wear resistance, high efficiency. It differs by smaller temperature gradients that favorably affect heat stresses and quality of the processed surface. Planetary grinding allows one to make processing in one - two passages of the tool without preliminary edge cutting machining, to reduce tolerances, to reduce auxiliary and preparation and finishing-up time greatly, to simplify tool setup. Moreover, during planetary grinding, it is possible to apply the abrasive tool with higher cutting abilities and wear resistant qualities that, in turn, allows one to increase the number of cutting conditions and to shorten cutting time. Therefore, due to planetary grinding, the intensification of processing is provided and the labor productivity increases.

2. Materials and methods
Designing and improvement of the tool is one of the ways to expand considerably technological capabilities of the planetary grinding process. To provide rational conditions of the grinding process using a planetary tool means to choose processing parameters with which the quality of the processed surface corresponds to specifications and high productivity is provided at its minimum cost value.

When designing the planetary tool, the following tasks were set: to provide minimum weight and dimensions in order to use it in average-size grinders without their modernization; to use standard grinding wheel types 6A2 (Russian State Standard (GOST)); the maximum resultant cutting speeds should not exceed the speeds allowed by GOST 4785-84 for these grinding wheels; to provide grinding with alternating share strain in a surface layer of a part due to rotation of the adjacent grinding wheels in different directions.

To implement the specified distinctive features of planetary abrasive grinding, the design of the planetary device was developed for the processing of plane surfaces [1]. The device represents an external grinding cup wheel in which the planetary mechanism with the identical internal grinding wheels of 6A2 (Russian State Standard (GOST)) type is located. The rotation of the external and internal grinding tools in opposite directions and at different rotational frequency provides consecutive penetration of the cutting edges of abrasive grains into the processed surface; the intersection pattern increases (fig. 1). It promotes fuller use of cutting ability of diamond grains. As a result of the difficult abrasive grain movement, the vector of resultant cutting speed changes the direction concerning it, thereby providing the cutting process with different edges of a grain and grinding is conducted with alternating share strain in a surface layer of the processed part. At the same time, the tolerance between different grains is distributed more evenly; the trajectory of their intersection pattern increases so that it is possible to carry out the addition of movements.

When designing the planetary face device, the intermittence of contact of tools with the processed surface in a cutting zone was considered. At the same time the length of the cut-off chips decreases owing to the intersection of the paths left by the cutting edges of abrasive grains of wheels and the alternations of earlier cut scratches with peaks of the remained processed material. The path grid provides the intermittence of cutting and reduction of heat temperature of abrasive grains. The less the path pitch, the less the heating temperature which, finally, positively influences wear resistant qualities of the tool.
The quality of the processed surface is defined by the complex of microrelief parameters: sizes, form, and interposition of microroughnesses. One of the most important microrelief characteristics making significant effect on operating abilities of surfaces is the direction of traces of processing called “pattern”. Known nowadays machine-tools lappers with raster and cycloidal motion possess the greatest opportunities to change the “pattern” of roughnesses. All known designs of machine-tools for flat grinding have rotational movement drives, and rectilinear reciprocating motion of a table with a processed part. In some schemes, the additional oscillating motion is reported to a part or a tool. However, these machine-tools are used to process parts very small in size.

Modeling of kinematic schemes of grinding processes is carried out by combination of two elementary movements: rotary and progressive/rectilinear. Changing kinematic parameters in rather wide limits allows receiving the following trajectories of relative movement of a part and a tool:

1. The cycloid (normal, extended, shortened) is obtained at combination of rotation of a tool and reciprocating movement of a table in longitudinal direction (without oscillating movements in cross direction).
2. The cycloid imposed on a sinusoid is obtained during combination of passing direction of rotation of a tool and reciprocating movement in two mutual and perpendicular directions.
3. An ellipse and a circle is obtained during combination of rotation of a tool and reciprocating movement in the opposite direction at certain speed ratios of these movements and amplitudes of reciprocating movement.

Thus, flat planetary grinding with reverse rotation of tools allows changing the “pattern” of a trajectory and over a wide range changing one of the most important characteristics of a microrelief – the direction of roughnesses. It is established that the planetary device for plane surface processing due to chaotic and at different height arrangement of grinding grains on a working surface of grinding wheels will not remove layers in a certain geometrical sequence. Many grains get on the protruded sections of a microprofile of grinding surface; therefore after one turn of a wheel on the surface of a part there are roughnesses removed at new meetings of a wheel with a certain section of a part. These roughnesses during planetary grinding decrease in height due to the increase in the number of meetings of wheels with the processed sections. Whereas, during normal grinding, the reducing of roughness happens either due to additional passes, or due to table feed reduction.

Here is one of the ways of kinematic formation of motion path curves of abrasive grains. Let us suppose that the path of the grain located on the outer radius of a layer of the internal wheel rotates without sliding on the other path of the grain located on the inner radius of the external wheel. Any grain located in any place of the cutting layer of the internal wheel will describe a new path. As a result of the research, the motion path of an abrasive grain of the internal face grinding wheel during planetary grinding was received in a parametrical form:
\[
x = (r \cos \omega_{\text{internal}} t + R) \cos \omega_w t - r \sin \omega_{\text{internal}} t \cdot \sin \omega_w t \\
y = (r \cos \omega_{\text{internal}} t + R) \sin \omega_w t + r \sin \omega_{\text{internal}} t \cdot \cos \omega_w t
\]  

(1)

where \((x, s)\) – point coordinates in the time point of \(t\) in the motionless system of coordinates \(Oxy\); \(t \in \left[0, \frac{2\pi}{\omega_i}\right]\), \(R\) – center-to-center distance between external and internal grinding wheels; \(\omega_{\text{internal}}\) – angular speed of rotation of an internal grinding wheel.

If \(R = 57.5\) mm, \(r_{\text{inside}} = 31.5\) mm, \(\omega_{\text{inside}} = 99.46\) rad/s; \(\omega_w = 80\) rad/s, then the motion path of an abrasive grain will be:

\[
x = (31.5 \cos(99.46t) + 57.5 \cdot \cos(80t)) - 31.5 \sin(99.46t) \sin(80t) \\
y = -(31.5 \cos(99.46t) + 57.5) \cdot \sin(80t) - 31.5 \sin(99.46t) \cos(80t).
\]  

(2)

During rotation of the external grinding wheel and the internal grinding wheel in different directions and provided that \(R = 81.25\) mm, \(r_{\text{inside}} = 31.5\) mm, \(\omega_{\text{inside}} = -124.44\) rad/s; \(\omega_w = 80\) rad/s, expressions (1) will take a form:

\[
x = (31.5 \cos(124.44t) + 81.25) \cos(80t) + 31.5 \sin(124.44t) \sin(80t) \\
y = -(31.5 \cos(124.44t) + 81.25) \sin(80t) + 31.5 \sin(124.44t) \cos(80t).
\]  

(3)

The results of calculations are presented graphically in fig. 2.

The form of the external grinding wheel path is determined in the same way. Superimposing motion paths of abrasive grains of the external and internal grinding wheels and initiating the movement of the processed part at 1.5 m/min speed, one will receive the final paths presented in fig. 2.

**Figure 2.** The motion path of abrasive grains of external and internal grinding wheels: speed is 40 \(\pi\), \(V_w = 10\) m/s, \(V_p = 1.5\) m/min. 1 – rotation of the external wheel, 2 – movement with the external wheel in one direction, 3 – movement with the external wheel in opposite directions.

Thus, changing the direction of rotation of the internal grinding wheel relatively to the external grinding wheel leads to various forms of epicycloids which is the path of an abrasive grain located on
the internal grinding wheel. The increase of center-to-center distance between wheels and the high speed of rotation of the external grinding wheel leads to the increase of an angular velocity of the internal grinding wheel, therefore, the form of the abrasive grain path of the internal grinding wheel and the radius of curvature of paths change. Changing the direction of rotation of the internal grinding wheel leads to various path forms. It is explained, first, by various gearing of a planetary drive which forces to rotate internal wheels in opposite directions and, secondly, by their various angular velocities. The increase of an angular velocity of the external grinding wheel leads to the increase of angular velocities of the internal grinding wheels, as a result the radius of curvature of the motion path of the abrasive grain located on the internal grinding wheel increases independent of the direction of its rotation.

The form of a path of the external grinding wheel does not depend on the direction of rotation of internal grinding wheels, on the number of rotations of the external grinding wheel, and is constant for any parameters of the planetary gearing. It is established that the radius of a wheel has the most effect on the motion path of an abrasive grain of the external grinding wheel. With its increase, the motion path proportionally increases in a Cartesian coordinate system. The speed of rotation of the external wheel affects the number of revolutions of the cutting grain, and it has no significant effect on a path form.

One serious task of grinding is to ensure production characteristics of a surface with optimum microgeometrical characteristics of its roughness. So, the roughness of the surface of flat parts exerts great influence on their wear resistance, contact rigidity, rust resistance and many other performance criteria [1-13]. Therefore when studying the process of planetary grinding of plane surfaces, special attention was paid to the research of the influence of the processing conditions and tool master data on microgeometry of the processed surface.

Flat planetary grinding allows changing the "pattern" of a trajectory and over a wide range changing one of the most important characteristics of a microrelief, which is the direction of roughnesses. The planetary device for processing plane surface due to chaotic and at different height arrangement of grinding grains on a working surface of grinding wheels will not remove layers in a certain geometrical sequence. Many grains get on the protruded sections of a microprofile of grinding surface; therefore after one turn of a wheel on a surface of a part, there are roughnesses removed at new meetings of a wheel with a certain section of a part. The height of these roughnesses during planetary grinding decreases due to the increase in the number of meetings of wheels with processed sections. At the same time, during grinding, using a solid grinding tool, the reduction of roughness happens either due to additional passes or due to the reduction of table feed.

Therefore, studying the process of grinding using the planetary device, special attention was paid to the research of the influence of the processing conditions on microgeometry of the processed surface made of alloyed steel 4X5M (Russian State Standard (GOST)). For comparison, the experimental studies were conducted when grinding by using an ordinary (solid) tool with the part immersed into lubricating fluid. Researches were carried out using surface grinder 3E711B. The height of microroughnesses was determined by the profilogramma removed from the surface of the processed samples on the profilograph – the profilometer.

The results of the executed researches showing the dependence of roughness value from the table feed and depth of cuts are given in fig. 3. From graphic dependences (fig. 3, a), it is visible that with change of the table feed from 2 to 6.5 m/min, the value Ra increases; however, an absolute value of Ra, while working with a planetary device is 30 - 40% less than with a solid tool. This phenomenon can be explained, first, by more uniform work of the cutting grains of the planetary device; secondly, by more efficient impact on the cutting process of lubricating fluid INKAM-1 (Russian State Standard (GOST)) that promotes the creation of a steadier cutting profile and decreases frictional force.

With increase in the depth of cuts (fig. 3, b), value Ra increases as chip thickness increases; hence loading on each grain decreases that promotes the increase in the depth of grain penetration into the processed surface.
Figure 3. Dependence of height of microroughnesses Ra on a - traverse speed of a part, b - wheel speed, when grinding 4X5M steel (Russian State Standard (GOST)) planetary device: external grinding wheel made of 6A2 250х32х25 AC6 100/80 M1-01 4 (Russian State Standard (GOST)), internal grinding wheel made of 6A2 63х20х14 AC6 125/100 M2-01 4 (Russian State Standard (GOST)).

At the same time, it should be noted that during planetary grinding more intensive smoothing of tops of microroughnesses is observed. It is confirmed also by profilogramma of the processed surfaces (fig. 4).

Figure 4. Profilogramma of the processed surfaces: a - diamond planetary device Ra = 0.08; b – solid tool Ra = 0.2. Horizontal increase - x 50 times, vertical - x 800 times.

The analysis of profilogramma shows that geometrical height characteristics of roughness during planetary grinding with lubricating fluid supply into the cutting zone is much better than when grinding with a solid grinding wheel: radiuses of rounding of microroughness tops increase, slope angles of a profile decrease, roughnesses become more homogeneous. If speed increases more than 30 m/s, there is the considerable inhomogeneity of roughness height, glazing of the cutting surface of a wheel and occurrence of vibration.

While studying the process of planetary grinding, special attention was paid to the research of the influence of processing conditions on microgeometry of the processed surface made of steel 4X5M (Russian State Standard (GOST)). As a result of the executed research [2], it was established that parameter Ra while processing using a planetary grinding device is 35 - 40% less than with a solid tool. This phenomenon can be accounted for more uniform work of the cutting grains of a planetary grinding tool as the number of meetings of diamond grains with the surface being processed increases. At the same time, it should be noted that during the planetary grinding, more intensive smoothing of tops of microroughnesses is observed that provides the creation of a steadier cutting shape.

The working period of a grinding wheel between two dressings characterizes its wear resistance. Wear resistance is the ability of a grinding wheel to resist the processes of cutting edges dulling, metal pickup to its working surface and alteration of its exact geometrical form. Intensity of these processes and the efficient wheel life depend on its sizes and characteristic, material and configuration of the processed part, cutting conditions, rigidity and vibration resistance of a grinder and the composition of a lubricating fluid [1 - 30].

Wear resistant qualities and the processing conditions are the major factors defining the cost value of the grinding operation. The time spent by a worker for dressing and the consumption of an abrasive tool (about 80% of abrasive is spent for dressing of a wheel) depend on the wear resistant qualities of a wheel; the machine time necessary for stock removal depends on processing conditions. Thus, the dependence between wheel wear resistance and stock removal rate is the base for economic evaluation
of the grinding operation. The main criterion of such evaluation is the cost value of the grinding operation. To solve the problem of definition of economic conditions of grinding, i.e. the choice of the optimum characteristic of a wheel, its wear resistant qualities and purpose of the processing conditions, it is necessary to express cost value of the grinding operation as the function of wheel wear resistance and the material removal rate. For this purpose, let us present the cost value of operation as the sum of two types of expenses:

\[ C = C_{\text{oper}} + C_{\text{tool}}, \]  

where \( C_{\text{oper}} \) - the wage with shop overhead costs (rubles) per operation; \( C_{\text{tool}} \) - the costs for a cutting tool (rubles) per operation.

Equipment and fitment amortization costs, power consumption costs and suchlike costs are not considered here.

The wage cost (rubles) per operation is counted as:

\[ C_{\text{oper}} = C_b \left( \frac{t_{\text{mach}} + t_{\text{pr}}}{N} \right), \]  

where \( C_{\text{oper}} \) - a base wage rate taking into account overhead costs, rub.; \( t_{\text{mach}} \) - machine operating time, min.; \( t_{\text{pr}} \) - time spent for dressing of a wheel, min.; \( N \) - quantity of the parts processed between two dressings (piece), which \( T/t_{\text{mach}} \)

\[ t_{\text{mach}} = M/Q, \]  

where \( M \) - a machining stock in metal volume units in cubic cm.

The costs for the tool depending on the wheel consumption during grinding and dressing are determined by a formula:

\[ C_{\text{tool}} = k \left( q_{\text{mach}} + \frac{\pi DHh}{N} \right), \]  

where \( k \) - the cost of 1 cm\(^3\) of the cutting volume of the wheel in rub/cm\(^3\); \( q = C_q Q^n \) - dependence of wear \( q \) of a wheel on the metal-removal rate in cm\(^3\)/min.; \( D \) - the average diameter of a wheel equal to a half-sum of initial (before work) and final (after wear-out) diameters of a wheel in mm; \( N \) - wheel height in mm; \( h \) – dressing stock of a wheel in mm.

Substituting (7) and (5) in (3), and expressing wheel wear resistance \( T \) in terms of metal-removing rate \( T = C_r/Q^n \), one will receive:

\[ C = C_i M Q^{-1} + C_b M \frac{t}{C_r} Q^{n-1} + kMC_q Q^{n-1} + kM \frac{\pi DHhQ^{n-1}}{1000C_r}, \]  

where \( C_r \) – wheel wear resistance when \( Q = 1 \) cm\(^3\)/min.

Equation (8) shows the dependence of the cost value of operation on the metal removal rate. In equation (8), augend \( (C_i) \) expresses the wage of a machine operator for machine operating time. With the increase in \( Q \), it decreases hyperbolic. Addend \( (C_2) \) is the wage of a machine operator for the time spent for dressing of a wheel per one operation. Third summand \( (C_3) \) is the costs for the wheel consumption during the grinding. Fourth summand \( (C_4) \) expresses the costs for the wheel dressing per one operation. The last three summands express the overhead costs per one operation.

Dividing the both parts of the expression (8) by \( M \), one obtains the equation of the cost value per one volume unit of the removed metal:

\[ C = C_i Q^{-1} + C_b \frac{t}{C_r} Q^{n-1} + kC_q Q^{n-1} + k \frac{\pi DHhQ^{n-1}}{1000C_r} \]  

In expression (9), the costs for positioning and removal of a part, servicing time of a workbench, etc. are not included as these costs also do not change with the change of \( Q \).
The equation of the cost value can be represented in the form of the curve shown in fig. 5 as a solid line. With the increase in cutting conditions, i.e. with the increase in Q, the augend of the cost value decreases (the dashed line), but the share of the overhead (the shaded area on the schedule) increases. At some value Q, there is an equilibrium corresponding to the minimum cost value, then the cost value, despite the increase in cutting conditions, begins to grow (the ascending, the right branch of a curve) as in this area overheads prevail.

Figure 5. The curve of the cost value of the grinding operation as a function of the metal-removal rate

Figure 5 shows that the cost value of operation is greatly influenced by overheads; in intensive cutting conditions, these costs reach 70 - 90% of all cost value. The major part of overheads [the second and fourth summands of equation (9)] is defined by the wheel wear resistance in the considered range of cutting conditions. In the cost value equation, the wear resistance of a wheel is defined as coefficient \( C_T \) and an exponent of n. With the increase in coefficient \( C_T \), the second and the fourth summands of equation (9) decrease proportionally.

In equation (9), the value of constant \( C_T \) and n, and the dependence of wheel wear \( C_q \) on metal removal per unit of time m will be respectively the following: for carbon hardened steel - 11; 1.7; 0.072; 1.6; for alloyed structural steel - 3; 1.1; 0.1; 1.8; for high-speed steel – 2.0; 1.05; 0.2; 2.0.

If to accept the volume of removed material \( M = 9 \text{ cm}^3 \), \( t_p = 2 \text{ min} \), \( S_b = 8 \text{ rub/min} \), \( k = 1.5 \text{ rub/cm}^3 \), \( D_{av.} = 150 \text{ mm} \), \( h = 0.1 \text{ mm} \), one will receive the following equations:

For hardened steel 45 (Russian State Standard (GOST)):

\[
C = 72Q^{-1} + 13Q^{0.7} + 0.97Q^{0.6} + 2.89Q^{0.7} ;
\]

for alloyed steel 12XH3A (Russian State Standard (GOST)):

\[
C = 72Q^{-1} + 13Q^{0.7} + 48Q^{0.1} + 1.35Q^{0.8} + 10.6Q^{0.1} ;
\]

for high-speed steel:

\[
C = 72Q^{-1} + 72Q^{0.05} + 2.7Q^{1.0} + 15.89Q^{0.05} .
\]

The results of calculations are shown graphically in fig.6, where it is possible to see the influence of the metal removal on each summand of the cost value equation.

Figure 6. Dependence of the curve of cost value C on metal removal speed Q when grinding a) 45 hardened steel, b) alloyed steel 12XH3A, c) high-speed steel P18 (Russian State Standard (GOST))
Selecting cutting conditions, it is possible to regulate the cost value of grinding. At small values of cutting conditions (Q < 1), the share of overheads in the overall cost value is less than 10% for the easily ground steel 45 and it reaches 48% when grinding hard-to-machine steel P18. Thus, the grinding wheel wear resistance has significant effect on the cost value of the grinding operation.

3. Conclusion
The results of the executed complex theoretical and experimental studies of the process of grinding using a planetary device in comparison with solid wheels allow one to draw the following conclusions:
1. During the research of the mechanism of formation of a surface microprofile during planetary grinding, it is established that obtaining the required roughness can be received on more intensive conditions than during solid grinding.
2. During planetary grinding, the characteristic of the cutting process in time practically does not change, which demonstrates stable maintaining of the cutting properties.
3. The given method of calculation of the cost value of the grinding operation allows solving various problems of production: comparing the cost value of grinding various materials, wheels of various characteristics; defining the optimum conditions of grinding.

Thus, the executed researches allowed one to explain the advantages of applying the planetary tool when processing flat surfaces. The experience of using such tools showed that new technical solutions in the field of abrasive processing allow one to use rationally raw material and labor resources.

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