Final and element modeling of workpiece temperature at the combined grinding

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Abstract. The combined grinding is characterized by simultaneous preliminary and final machining of workpiece on one machine tool without replacement a coarse-grained on a fine-grained grinding wheel, that allows to reduce the main and auxiliary time for performance of technological operation, and, therefore, to increase grinding process productivity. Entry and boundary conditions of computer modeling of the maximum temperature of the processed surface at the combined and traditional grinding are defined. Modeling of surface temperature is carried out in the modern Solid Works software product for simultaneous grinding by wheels with various characteristic of abrasive material, what in scientific-technical literature was not considered earlier. Models of the maximum temperature of the processed surface in a function of removed overmeasure, longitudinal and cross-feed of workpiece, on the basis of which the cutting regime of the combined flat peripheral grinding, providing elimination of thermal damage of the processed blanket, is appointed are established.

1. Introduction
The grinding processes are widely used for final machining and are continuously improved in direction of discretization of the cutting surface [1, 2], modeling of the processed surfaces [3, 4], creation of high-porous [5], single-component [6] and textured grinding wheels [7, 8]. Along with it the grinding processes by standard wheels are improved too [9]. The grinding processes, existing for today, in the conditions of single and small-serial production (at the small program of release) are carried out for one technological operation. A preliminary processing is carried out by a coarse-grained grinding wheel, further this wheel is removed from a spindle. On its place establish a fine-grained wheel and carry out final processing with observance of the physic-mechanical properties, a micro and macro-geometry of a processed surface. Such grinding technology leads to expenses of a large number of main and auxiliary time for performance of technological operation (breaking-out of a coarse-grained wheel, its removal from a spindle of machine tool, installation, fixing of a fine-grained wheel on a spindle, its editing, balancing, control for given size, etc.). In the conditions of medium serial, large-serial and mass production preliminary and final grinding are carried out for two technological operations by separate carrying out preliminary processing by a coarse-grained and a final processing - by a fine-grained wheel. Such processing is carried out at least on two grinding machine tools, which service requires twice more workers-grinders, to floor space, and also
transportation of workpieces from the machine tool for preliminary to the machine tool for final grinding. Both options of traditional technology of grinding (at the small and big program of release) lead to reduction of processing productivity and to increasing of technological prime cost of a product. In this regard a creation of the new ways of grinding, allowing to increase a processing productivity with observance of requirements to quality of details, is an important scientific task.

2. Simultaneous grinding of workpieces by wheels with various characteristics of abrasive material

It is possible to eliminate the shortcomings of grinding traditional technology on the basis of a so-called combined method, at which on one machine tool at the same time preliminary and final processing of workpiece is performed [10]. Fine-grained and coarse-grained grinding wheels fix on one spindle of the grinding machine tool so, that the fine-grained wheel was located closer to the operator, serving the machine tool. A coarse-grained wheel is situated between a front support of a spindle and a fine-grained wheel. Between coarse-grained and fine-grained grinding wheels there is a ring for an exception of contact of abrasive material of both wheels. Include rotation of a spindle with the grinding wheels and move a coarse-grained grinding wheel to workpiece for emergence of a small spark.

Include longitudinal feed of workpiece, then move a coarse-grained wheel on a size of the overmeasure, which has to be removed at preliminary grinding. After control of a coarse-grained wheel for given size, include cross-feed in the direction to the operator, serving the machine tool. The main fraction of abrasive grains of a grinding wheel for preliminary processing has granularity, for example, of F30-F36 GOST P52381-2005, and of a grinding wheel for final processing – F(90-120). The coarse-grained wheel removes the main overmeasure, and a fine-grained wheel - a small overmeasure for providing required geometry of the processed surface.

In an initial stage of grinding process the coarse-grained wheel contacts with a workpiece on the small area, and eventually it begins to interact with workpiece on all the height. After that a fine-grained wheel begins to work, and both grinding wheels are in work at the same time. At movement of workpiece in the direction of cross-feed the coarse-grained grinding wheel finishes a cutting process, in work remains a fine-grained wheel, which removes the roughness, remaining after processing by a coarse-grained wheel. Eventually the fine-grained wheel also finishes a workpiece processing. On this the main cycle of the combined grinding (preliminary and final processing) comes to an end.

At high requirements to roughness and waviness of processed surfaces perform additional pass only by a fine-grained wheel. Diameter of the cutting surface of a coarse-grained wheel on (4-6) micrometers less, than diameter of a fine-grained wheel, therefore a coarse-grained wheel does not concern the processed surface, what does not worsen the small roughness, created by a fine-grained wheel. Thus, the process of combined grinding provides the required geometry of processed surfaces at exception of auxiliary time, connected with replacement of a coarse-grained on a fine-grained grinding wheel and with setup of the machine tool for performance of final processing. Besides, a simultaneous performance of preliminary and final grinding on one machine tool allows to reduce also main time, i.e. time, connected directly with cutting process. At the combined grinding in contact with workpiece at the same time there are coarse-grained and fine-grained wheel, what leads to forming of the heat fluxes, different from streams at traditional grinding. Earlier the temperature research of workpieces in the grinding process were not carried out at the same time by several wheels, differing in characteristics of abrasive material. Modeling of temperature of the processed surface of workpiece at the combined grinding is directed to development of thermal model, on the basis of which the cutting regimes, which are not causing thermal damage to a processed blanket, are defined.

3. Solid-state model of workpiece and preparation of basic data for temperature modeling

The sizes of solid-state model of workpiece were defined by the area of contact of a grinding wheel with the processed surface and also by the sizes of the cutting surface of wheels for preliminary and final grinding. Length of solid-state model was broken into sites 1 mm long, at the same time it
includes 98794 knots and 552812 elements of a grid, that allowed to analyse results of a research most precisely.

Final and element modeling of temperature was carried out with use of modern CAD - the Solid Works complex, it consisted in the solution of a non-stationary task of heat conductivity in three-dimensional performance Final and element modeling of temperature was carried out with use of modern CAD - the Solid Works complex, it consisted in the solution of a non-stationary task of heat conductivity in three-dimensional statement. For splitting of solid-state model of workpiece on the separate elements-tetrahedrons and for creation of a grid, was used a method of final and element modeling (DEM). During grinding a workpiece moves in the direction of longitudinal feed and after of each longitudinal pass discretely moves in the direction of cross-feed (fig. 1, a).

![Figure 1. Solid-state model of workpiece (a), to which the heat flux is brought, and the scheme for calculation of time of heating and cooling of workpiece (b).](image)

In the cross direction the solid-state model was divided into sites 1-3, to which serially put the heat flux of \( q \), generated in the course of grinding. Other workpiece surfaces were cooled as a result of the convective heat exchange, determined by coefficient of a convective thermolysis \( \alpha \). Values of the temperature field, formed as a result of contact of a wheel with workpiece on sites 1 and 3, were used as entry conditions for the subsequent stage of modeling, at which the heat flux of \( q \) was put to a site 2, the temperature field of which was by the end result of modeling.

For rational use of a resource of the program Solid Works complex a length \( A \) of solid-state model of a workpiece was determined by summation of wheels heights for preliminary and final grinding, and a width \( B \) of a solid-state model - by summation of 3 lengths of arches of contact of a grinding wheel with workpiece. The arch of contact of a grinding wheel with workpiece is curvilinear, its radius of curvature can be accepted equal to the radius of the cutting surface of a grinding wheel. Calculation accuracy of temperature at modeling depends on a correct task of boundary conditions of heat exchange between the processed workpiece and the environment. Boundary conditions of the second sort, at which the heat flux of \( q \) is set, are characteristic of a contact zone of the grinding tool with workpiece, and outside this zone the cooling function of the environment and boundary conditions of the third sort, which are set by conditions of convective heat exchange, are fair. Amount of heat, going to workpiece, depends on the grinding regime, heat-physical characteristics of abrasive material of the grinding tool, workpiece and is (60-90) % of total number of heat, generated in a cutting zone. The cutting power, spent for grinding process, is determined by formula:

\[
N_{rez} = C_n D_{spr}^x t^y D_{sp}^y ,
\]

where \( C_n, r, x, y \) – respectively constant coefficient and exponents at longitudinal feed \( D_{spr} \) (m/min); at depth \( t \) of grinding (mm) and at cross-feed \( D_{sp} \) (mm/pass of table with workpiece).

Density of the heat flux, going to workpiece, was determined by formula:
\[ q = (0.6 - 0.9) \frac{N_{rec}}{N_k}, \quad (2) \]

where \( S_k \) - the area of contact of the tool and workpiece.

The maximum areas of contact of course-grained and a fine-grained grinding wheel with workpiece arise at cutting by all wheel height and are determined by formulas:

\[
S_{k1} = B_1 L_1 = B_1 \left( 1 \pm \frac{D_{spr}}{v} \right) \sqrt{t_1 D_1},
\]

\[
S_{k2} = B_2 L_2 = B_2 \left( 1 \pm \frac{D_{spr}}{v} \right) \sqrt{t_2 D_2},
\]

(3)

(4)

where \( B_1, L_1, t_1, D_1 \); \( B_2, L_2, t_2, D_2 \) - respectively height, contact arch length, grinding depth, diameter of the cutting surface of a peripheral course-grained and fine-grained grinding wheel; \( v \) - cutting speed.

For determination of the contact area of course-grained and of fine-grained grinding wheel with workpiece in expressions (3) and (4) it is necessary to change height \( B_1 \) and \( B_2 \) by the actual contact height, measured on the cylindrical cutting surface of the tool. The air cooling environment has a heat exchange coefficient \( \alpha = 50 \) W / m\(^2\) K. Material of workpiece - steel with density \( \rho = 7830 \) kg/m\(^3\), heat conductivity coefficient \( \lambda = 27 \) W/m-K, the specific heat \( c = 640 \) J/kg-K. For modeling of temperature of the ground surface it is necessary to know also time of heating and cooling of the considered zone, the settlement scheme is for this purpose made. In processing grinding wheel 1 (fig. 1, b) contacts to the workpiece 2, established on a table 3, the studied zone 4 heats up. Time of heating of zone 4 is determined by a formula:

\[
\tau_h = \frac{60L_4}{D_{spr}},
\]

(5)

where \( L_4 \) - projection of length of contact arch of grinding wheel with workpiece to the horizontal plane.

A cooling time of zone 4 depends on value of longitudinal feed \( D_{spr} \), width \( B_z \) of workpiece, diameter of the cutting surface of grinding wheel and is determined by formula:

\[
\tau_c = \frac{60(B_z - L_4 + L_{srec} + L_{per})}{D_{spr}},
\]

(6)

where \( L_{srec}, L_{per} \) - respectively a length of incision and rerun of a grinding wheel.

Modeling is carried out for various values of cutting depth, longitudinal and cross-feed at the following geometrical characteristics of the tool for the combined grinding: height of the cutting surface of wheel for preliminary grinding \( B_1 = 20 \) mm, height of the cutting surface of wheel for final grinding \( B_2 = 10 \) mm, a width of ring, which is situated between two grinding wheels, \( \delta = 2 \) mm, diameter of the cutting surface of wheel for preliminary grinding \( D_1 = 250 \) mm, diameter of the
cutting surface of wheel for final grinding $D_2 = 250.01$ mm. The sizes of the processed workpiece: length - 100 mm, width - 100 mm, height - 10 mm. The starting temperature of workpiece was equal to an ambient temperature 20 °C.

4. Results of temperature modeling at the traditional and combined grinding of workpiece

For longitudinal feed $D_{spr} = 15$ m/min, cross-feed $D_{sp} = 3$ mm/pass of a table, cutting speed $v = 35$ m/s; for overmeasure, removed by preliminary grinding, $z_{pr} = 60$ micrometers, by wheel for final grinding $z_o = 5$ micrometers, the temperature maximum on the site, which is in contact with a coarse-grained wheel, was 309.1 °C, and in contact with fine-grained wheel – 102.2 °C (fig. 2).

![Figure 2](image)

**Figure 2.** The sites, processed by a coarse-grained and fine-grained grinding wheel (a) and the temperature field (b) of the site, contacting to a coarse-grained wheel.

At the combined grinding by two wheels a temperature of the site of a surface, contacting to a coarse-grained wheel was 309.1 °C (fig. 2), that exceeds for 6.5% temperature 289.1 °C (fig. 3), arising at traditional processing by a similar wheel. At the combined grinding by two wheels a temperature of the surface, which contacts with a coarse-grained wheel, was 309.1 °C (fig. 2), what exceeds a temperature 289.1 °C (fig. 3), arising at traditional processing by a similar wheel. Increasing of temperature at the combined grinding in comparison with traditional is explained by the fact, that the fine-grained wheel, being in work with a coarse-grained wheel, also generates heat fluxes, which interfere, though in insignificant degree, with heat removal from a cutting zone by a coarse-grained wheel. At traditional grinding by a fine-grained wheel temperature of a surface was 90.2 °C (fig. 4), at combined grinding of the site, contacting with a fine-grained wheel – 102.2 °C (fig. 2). At traditional processing by a coarse-grained wheel a temperature was 289 °C (fig. 3).

![Figure 3](image)

**Figure 3.** The sites of a surface, processed by a coarse-grained wheel (a) according to the traditional scheme of grinding and the temperature field of a surface (b).
Removal by a fine-grained wheel according to the traditional scheme of an overmeasure more than 6 micrometers, causes increase in temperature of the processed surface in comparison with processing by the same wheel on the combined scheme.

5. Influence of regime elements of the combined and traditional grinding on temperature of the processed surface

From a practical position an information about an influence of the dominating factors of the traditional and combined grinding on the maximum temperature of the processed surface is very important, in this regard thermal fields at various values of a longitudinal, cross-feed and thickness of the removed overmeasure were studied.

Experimental models are received and schedules of temperature dependence in function of cutting regime elements are constructed (fig. 5, b and c). The equations, characterizing dependence of the maximum temperature of the processed surface in the function of the removed overmeasure, at grinding by a coarse-grained wheel for the offered and traditional way respectively have an appearance (fig. 5, a, straight line 1 and 2):

\[ T_k = 2300 z_{pr} + 165 \]  \hspace{1cm} (7)

\[ T_t = 2300 z_{pr} + 135. \]  \hspace{1cm} (8)

At the combined grinding a changing of overmeasure from 0.04 to 0.10 mm leads an increase in temperature of the surface, contacting to a coarse-grained wheel, from 257 to 395 °C, and when processing on a traditional way – from 227 to 365 °C. At the combined grinding a temperature of the site, processed by a fine-grained wheel, does not depend from value of the overmeasure, removed by a coarse-grained wheel, as the overmeasure for final processing is defined by the semi-difference of diameters of fine-grained and coarse-grained grinding wheel.

The semi-difference of diameters is set at editing of grinding wheels and is a constant. In these conditions temperature of the surface, processed by a fine-grained wheel at the combined scheme, also is a constant \( T_f = 105 \) °C. Processing by a fine-grained wheel according to the traditional scheme is forced to carry out with removal of the overmeasure on the each pass of a table, equal or more error of workpiece installation in a device of machine tool. In machine tool 3M71 a workpiece is established on a magnetic plate, for which the installation error is not less, than 12 micrometers, what leads at processing workpiece to increasing of a temperature up to 118 °C.
Figure 5. Dependence of surface temperature from thickness of the removed overmeasure (a), longitudinal feed (b); cross-feed of workpiece (c) at the combined and traditional grinding.

In other words, what we would not appoint a overmeasure at the combined preliminary grinding, temperature of the surface, processed by a fine-grained wheel, changes slightly, what is explained by removal of overmeasure, constant and small in size. The received result of modeling leads to a conclusion, that during combined grinding it is possible to appoint a necessary overmeasure for preliminary grinding without deterioration in a physic-mechanical properties of the processed blanket, as further processing by a fine-grained wheel causes significant decrease in temperature, at the same time replacement course-grained on a fine-grained wheel is not required. Increase in longitudinal feed of workpiece causes increase of surface temperature, but its influence rather is less in comparison with the size of the removed overmeasure. The equations, connecting the maximum surface temperature with longitudinal feed respectively at the combined and traditional grinding by a course-grained wheel, have an appearance:

\[ T_k = 8.2 \ D_{spr} + 185 \]  
\[ T_r = 8.2 \ D_{spr} + 165. \]  

Change of longitudinal feed from 12 to 21 m/min at the combined grinding by a coarse-grained wheel leads to increase in surface temperature from 283.4 to 357.2 °C, and at traditional grinding - from 263.4 to 337.2 °C. In all cases of grinding by a fine-grained wheel a temperature of the processed surface much less, and is in interval (105–118) °C. Straight lines 1 and 2 (fig. 5, b) are received at a contact of workpiece on all height of wheel, when in a cutting zone the maximum quantity of heat is formed. Cross-feed of workpiece influences on the surface temperature more, than other factors of grinding process. Equations, which connect the maximum temperature of a surface with cross-feed of workpiece at the combined and traditional grinding by coarse-grained wheel, are described:

\[ T_k = 64.3 \ D_{sp} + 120 \]  
\[ T_r = 64.3 \ D_{sp} + 102. \]  

Change of cross-feed from 2 to 6 mm on each pass of a table at the combined grinding by a coarse-grained wheel causes increase in the maximum temperature of a surface from 248.5 to 505.9 °C (fig. 5, c, a straight line 1). When grinding by the same wheel on a traditional way, temperature changes from 240.5 up to 497.9 °C (straight lines 2). However, as it was noted earlier, temperature of the surface, processed by a fine-grained wheel at the combined scheme, is less, than at traditional scheme. The equations (7)–(12) are necessary for design of grinding processes and definition of the cutting regime, providing lack of thermal damage to a blanket.

Thus, results of modeling showed, that surface temperature at the combined grinding is less, than at traditional, what is connected with need of reinstallation of workpiece and removal of a bigger
overmeasure by fine-grained wheel at traditional grinding. Along with it the combined grinding allows to reduce the main and auxiliary time on a performance of technological operation, what leads to increasing of grinding productivity.

Conclusion
1. As a result of modeling in the program Solid Works complex of the maximum temperature of surfaces, subjected to the combined and traditional grinding, the formulas, which connect a temperature with removed overmeasure, longitudinal and cross-feed of workpiece, and allow to appoint the cutting regime, providing temperature, at which there is no thermal damage of the processed blanket, are determined.

2. The maximum temperature of the surface, processed by the coarse-grained wheel at a traditional grinding, is 6.5% lower, than temperature, arising at the combined grinding at the same time by coarse- and fine-grained wheels. However, the combined grinding also allows to carry out a final pass only by a fine-grained wheel and to remove a small overmeasure, what leads to reduction on 11% of surface temperature, arising at traditional final grinding.

3. Realization on one machine tool at the same time of preliminary and final processing of surfaces at the combined grinding allows to reduce the main and to exclude auxiliary time for replacement of coarse-grained on a fine-grained wheel, its balancing and editing, and also for control of the required size, what leads to increasing of grinding processes productivity.

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