Forecasting of operational indicators of grinding tools with the controlled form and orientation of abrasive grains

V A Korotkov[1, 2, a], E M Minkin[2, b]

[1]National Research Tomsk Polytechnic University,
Tomsk, 30 Lenin Avenue, 634050, Russia
[2]Kuzbass State Technical University named after T. F. Gorbachev,
Kemerovo, 28 Vesennjaja Street, 650000, Russia

[a]e-mail: korotkov-va@mail.ru, [b]e-mail: jonm1@mail.ru

Abstract. The interconnection of the abrasive grain front angle parameter with the form, orientation and wear out parameters is investigated. The form of the abrasive grains was estimated by means of form coefficient which represents the relation of diameters of the spheres described around contours of grains, to diameters of the spheres entered in them. The spatial orientation angle of the abrasive grains was defined between main (i.e. the biggest) axis of the grains and the cutting plane. It is established that, depending on an orientation angle at increase in a form coefficient of the abrasive grains can be either an increase or a decrease in the values of their front angles. In most cases, with an increase in a form coefficient of the oriented grinding grains (at orientation angles Θ=10°÷125°) the growth of their front angles is fixed. At tangential orientation of grains (Θ=0°) and at the close directions of orientation (Θ=135°÷180°) the return picture is observed. Also established that the longer the abrasive grain wears along the main axis and located in the tool body, the larger is its front angle. Besides that, the front angles of the abrasive grains reach the maximum positive values at orientation angles Θ=22.5°÷45°.Dependence of tension in grains during the work with parameters of their form, orientation and depth of embedment in the bundle is investigated. It was found that for all orientation angles of grains their tension significantly increases with an increase in their form coefficient. Besides that it is confirmed that the deeper the grain is in the bundle, the lower the tension is there. Also found that tension is minimal when the grains are tangential orientated. Further on increase the option of the grains in the direction of action of the cutting force follows. Such option of orientation is the most rational both from the point of view of minimization of tension, and for ensuring rational sizes of front angles of the abrasive grains. The rational angle of grain orientation for cutting disc are in range Θ=65°÷75°.
The joint analysis of dependences of front angles and tension in grains from factors of their form and orientation allows the prediction of operating characteristics of grinding tools at the design stage for specific tasks and processing conditions.

1. Introduction
The effectiveness of the grinding process is largely predetermined by the efficiency of the abrasive grains of which grinding tools are manufactured [1, 2, 3]. The most successful work of grains, with other things being equal (brand and granularity of an abrasive, type of the abrasive tool, hardness,

structure and bundle type of the tool, the grinding conditions), is possible when grains possess a favorable geometry for the chosen processing case. The geometry of the cutting part of grain is defined by two factors – a form and orientation in a body of the tool [4, 5, 6]. These factors in the process of production of abrasive tools are often remained uncontrolled and uninvolved.

So, bulk of grains from which manufacture the abrasive tools, has a form changing in the wide range from isometric to lamellar versions. Such dispersion of a form of grains is caused by specifics of standard technologies of their production which are based on crushing of abrasive ingots and the subsequent division of abrasive particles according to the sizes. At the same time, the grain form factor remains almost uncontrolled and uncontrollable. In world practice the attempts to streamline the form of grains in the abrasive tools by introduction of the special technologies directed on creation or allocation of fractions of grains with an identical form are known. Manufacturing techniques of spherical grains and grains of other special forms, technology of ovalization of grains in mills with pig-iron spheres, manufacturing techniques of abrasives in which thanks to the accelerated cooling of the abrasive melt and emergence on ingots a grid of micro cracks receive grains of needle and lamellar forms, etc. are known [1, 3, 7, 8, 9]. Along with the form parameter, other factor which actively influences geometry and overall performance of grains is their orientation in a body of the tool [3, 10, 11]. This is exemplified by the use of abrasive belts and skins produced using electrostatic field exposure. This effect makes it possible to orient the grain spikes perpendicular to the base tape [12]. Industrial and positive experience of creation of abrasive tools of other types with application of technologies on management of orientation of grains isn't known yet. Still more it belongs to production of abrasive tools at which the form and orientation of the abrasive grains would purposefully be regulated at the same time. The creation of such tools makes it possible to further improve the efficiency of grinding processes [13].

In this regard the problem of creation and application of new abrasive tools made of abrasive grains with controlled form and orientation is actual. Such tools allow to maximize the usage of cutting capabilities of each individual grain. The solution of this problem requires carrying out researches which would allow to predict the operational indicators of grinding tools depending on factors of a form and spatial orientation of abrasive grains.

2. Methodology of researches

For forecasting of operational characterizations of grinding tools at a design stage it is expedient to investigate the geometry of grains of which they are made, and to establish dependence of sizes of front angles of grains on factors of their form and orientation. After that it is necessary to analyze the scheme of operation of the grinding tool and to establish the value of the components of the cutting force acting on the grinding grains. Using the established sizes of components of the cutting force, it is necessary to establish dependence of the maximum tension in the abrasive grains on the factors of their form and orientation. The joint analysis of the received dependences of front angles and tension in grains from the factors of their form and orientation allows the design of grinding tools for specific tasks and processing conditions, based on the fact that values of front angles of grains have a direct impact on the cutting ability of tools, on sizes of deformations of the processed material, effective power and temperature of cutting, and the level of the maximum tension in the grains affect the wear of tools [14, 15].

3. Results and Discussion

Researches were conducted on the example of cutting discs with the characteristic Type 41 230×4×32 A 46 C BF 80 m/s, which performs cutting of workpieces (21.3×2.8 pipe steel 1010 (U.S. standard AISI)) at a speed of V=80 m/s and with constant workpiece clamping force to the disc F=32 N (P_y=32 N) [16, 17]. In the course of researches it was established dependences of the front angles of oriented abrasive grains A 46 on a variety of their form, taking into account a wear factor. Also the interrelation of a form and orientation of grains with sizes of tension arising in them during the work was established. The form of grinding grains was estimated by means of specially developed technique and the computer program [3, 18] by using the concept of the form coefficient (K_f) equal to the relation of diameters of the spheres described around contours of grains, to diameters of the spheres entered in them.

For an assessment of front angles of the oriented abrasive grains the special program complex allowing to turn images of abrasive grains (received by means of a microscope and the digital camera) under the demanded corner concerning the cutting plane and to define a front angle in all points of a contour is developed [19, 20].

The received results were tabulated with the subsequent construction of three-dimensional plots of dependence of front angles of abrasive grains on their form coefficient (K_f) and the spatial orientation angle (Θ), measured between main (i.e. the biggest) axis of the grains (L) and the cutting plane (figure 1).

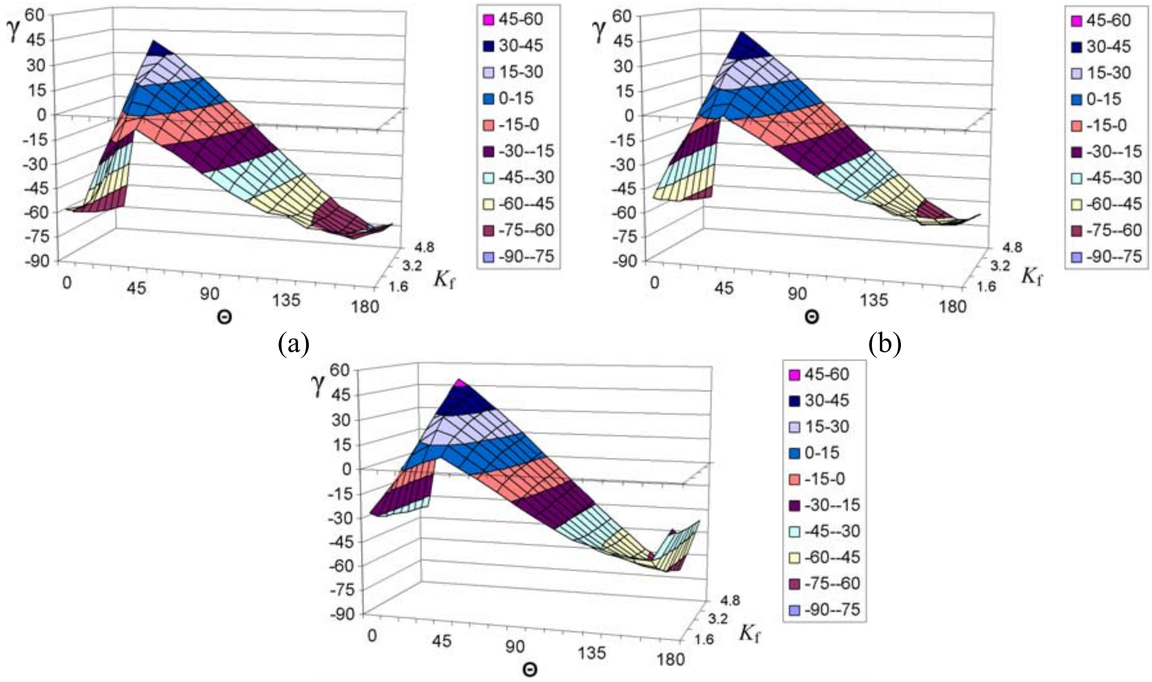


Figure 1. Dependences of front angles (γ) of the abrasive grains A 46 on their form coefficient (K_f) and the spatial orientation angle (Θ) at hypothetical wear to 1/3L (a), to 1/2L (b) and to 2/3L (c)

Results of researches allow to note that, regardless of the form coefficient, the more long the abrasive grain works, i.e. wears out along the main axis and is in a tool body, the more sharply (on average) there is its front angle. Thus the factor of orientation of grains concerning to the cutting plane very significantly influences sizes of front angles. So, for example, at K_f=1,6 front angles of abrasive grains can vary within -60° ÷ -6° (wear to 1/3L) and -44° ÷ +9° (wear to 2/3L).

Front angles of abrasive grains at K_f=4,8 depending on an orientation angle Θ change in the range of -77 ° ÷ +39 ° (wear to 1/3L) and -69 ° ÷ +49 ° (wear to 2/3L). Thus, the same grain which is differently oriented concerning the cutting plane is characterized by a considerable difference of sizes of front angles. It reaches 53° ÷ 54° at isometric abrasive grains (K_f=1,6) and 116° ÷ 118° at needle and lamellar grains (K_f=4,8) that essentially distinguishes geometry of grinding tools and for example cutters, drills and mills at which the cutting wedge has invariable geometry and is sharpened to within degree shares. The findings also show that the front angles of the abrasive grains reach the maximum positive values at orientation angles Θ=22.5° ÷ 45°.

Furthermore, depending on the angle of orientation with increasing grain form factor can be either an increase or a decrease in the values of their front angles. Thus, in most cases, with an increase in the form factor of the oriented abrasive grains (in the range of orientation angles Θ=10° ÷ 125°) their front angles increase. In tangentially oriented grains (Θ=0°) and grains with similar orientation direction (Θ=135° ÷ 180°) the opposite picture is observed.

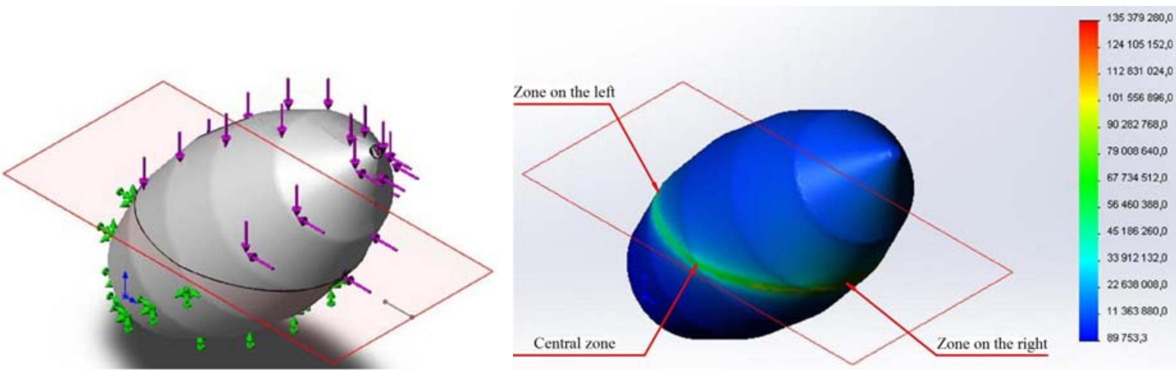
For research the values of tension in abrasive grains at various options of their orientation in a tool body the components of cutting force acting on the grains A 46 during the work of cutting discs were defined previously. For this purpose in processing of preparations, among other indicators, the effective power of cutting was defined. Proceeding from it the tangential component of cutting force was established (P_z=8.46 N) [3].

After that the sections of a working surface of cutting discs by the digital camera in the mode of macro shooting were photographed and calculation of amount of grains on surface unit of area in the graphic Paint editor was made. It is established that, on average, on a working surface of the researched discs the number of grains makes N_s=2.68 of grains/mm^2. Proceeding from this value, as well as the contact area of the cutting disc with the workpiece to be cut (S=22.4 mm^2), the amount of the abrasive grains which are at the same time participating in work (N_s=60 grains) and the sizes of forces operating on single abrasive grain is established (P_y=0.533 N; P_z=0.141 N). The obtained data allowed to make calculation of tension in models of abrasive grains of brand A 46 with various form coefficients and options of spatial orientation in a tool body by the program SolidWorks. Models of grains with various form coefficients are constructed on the basis of radially oriented grains given according to front angles received by means of special computer programs [19, 20].

Software settings for calculation of tension in grains: linear elastic isotropic model; material - corundum; strength at stretching $8.5 \cdot 10^7$ N/m^2; strength at compression of $7.6 \cdot 10^8$ N/m^2; module of elasticity of $3.74 \cdot 10^{11}$ N/m^2; Poisson's coefficient is 0.22; mass density is 4025 kg/m^3; module of shift of $1.5 \cdot 10^{11}$ N/m^2; coefficient of thermal expansion $8 \cdot 10^{-6}$ 1/K. Grid type: a grid on a solid body on the basis of curvature; 4 points of the Jacobian; the maximum element size 0.00968809 mm; the minimum element size 0.00322933 mm. Criterion of durability – the criterion of the maximum normal tension used for fragile materials.

The forces operating on real single abrasive grain (P_y=0.533 N; P_z=0.141 N) is applied to models of grains with different variants of their orientation and depth of setting in a bundle (figure 2 (a), (b)). It was found that depending on concrete option of orientation of models of grains, the maximum tension arises on their various locations along their boundary seal in a bundle.

For a more complete picture of the state of stress models of grinding grain at all variants of their orientation were recorded and analyzed the data in three specific areas on the border seal in the bunch: zone on the left, central zone and zone on the right (figure 2).



(a) (b)

Figure 2. The scheme of loading (a) and distribution of tension along the border in the bunch (b) in the model of grain A 46 with K_f=2.4 and the orientation angle Θ=45º, that is fixed in a bundle to 1/2L

The results of evaluation of tension in the model of abrasive grain with K_f=2.4 (average form coefficient of grains in the studied fraction) at various angles of orientation are presented in figure 3.

IOP Conf. Series: Materials Science and Engineering **91** (2015) 012041 doi:10.1088/1757-899X/91/1/012041

Given graphics (figure 3) indicate that the smallest tension arises at tangential orientation of grain. Further, in the range of grain orientation Θ=11º15′ to Θ=45º there is a significant increase in tension, with the maximum values achieved in the "zone on the right" under the console of the protruding portion of grain. In the following range from Θ=45º to Θ=67º30′ there is a decrease in the maximum tension to values, approximate to option of tangential orientation.

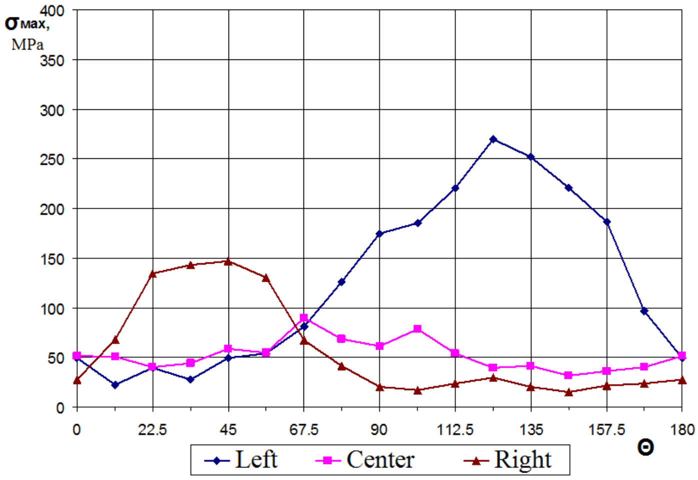


Figure 3. Tension in the model of abrasive grain A 46 with K_f=2.4 that is fixed in a bundle to 1/2*L* on border in a bundle at various corners of orientation

Thus, it is obvious that decrease in the maximum tension at Θ=67º30′ results from uniform distribution of tension in a grain body (at the left, on - to the center and on the right) along boundary seal in a bundle. Such distribution of tension is reached because the grain orientation angle Θ=67º30′ is close to the direction of the cutting force *P*.

In this case the components of the cutting force P_y=0.533 N, P_z=0,141 N, i.e. have a ratio 3,78:1 and the vector of cutting force *P* coincides with the maximal axis of grain at its orientation with Θ=75º12′. Calculation and the subsequent comparison of tension for orientation angles Θ=67º30′ and Θ=75º12′ show that more rational to reduce the maximum tension is the angle Θ=67º30′, which is explained by the peculiarities of termination of grain in the bundle.

With further increase in the orientation angle in the range of Θ=67º30′ to Θ=123º45′ there is a significant increase in tension to the largest observed values. The maximum loaded area here is "zone on the left" under the console of the acting part of grain. The obtained data also show that in all cases the more rational is the grain orientation by top towards to the direction of the component of the cutting force P_z. It finds an explanation that at orientation of grain towards to P_z the vector of cutting force *P* is near the main axis of grain. At a grain arrangement by its top from the P_z direction, the cutting force *P* works under big corners in relation to the main axis of grain, creating the maximum tension in "a zone at the left".

Further researches on establishment of rational angles of orientation of abrasive grains taking into account kinds of their form (K_f=1.6; K_f=2.4; K_f=3.2; K_f=4.0; K_f=4.8) and seal depths in a bundle revealed similar nature of tension distribution (figure 4 (a), (b), (c)).

The obtained data (figure 4) show that for all orientation angles of grains at increase in their form coefficient the maximum tension significantly increases. So, in the most rational angle of orientation of grains of an order Θ=67º30′ upon transition from K_f=1.6 to K_f =4.8 (seal in a bundle to 1/2*L*) the maximum tension increases by 4.2 times (from σ_{Max}=79,8 MPa to σ_{Max}=335,6 MPa). At the least rational orientation angle near Θ=123º75′ upon transition from K_f=1.6 to K_f =4.8 the maximum tension increases in the area by 7,7 times (from σ_{Max}=187,7 MPa to σ_{Max}=1443,9 MPa).

The revealed dependence correlates with results of tests according to wear and grinding coefficient of cutting discs with a controlled form of grains [16, 17] and allows to confirm them theoretically.

Besides, it is established that with reduction of depth of seal of grain in a bundle the maximum tension in grains also noticeably increases.

So, for various form coefficients of grains, upon transition from seal in a bundle to 2/3*L* to the sealing of up to 1/2*L* the maximum tension in grains (for various angles of orientation on average), increases in 1,03÷1,25 times, and upon transition from seal in a bundle to 1/2*L* to the sealing of up to 1/3*L* growth makes 1,24÷1,77 times. Thus, the effect of planting depth in the bundle increases with increasing of the grain form coefficient.

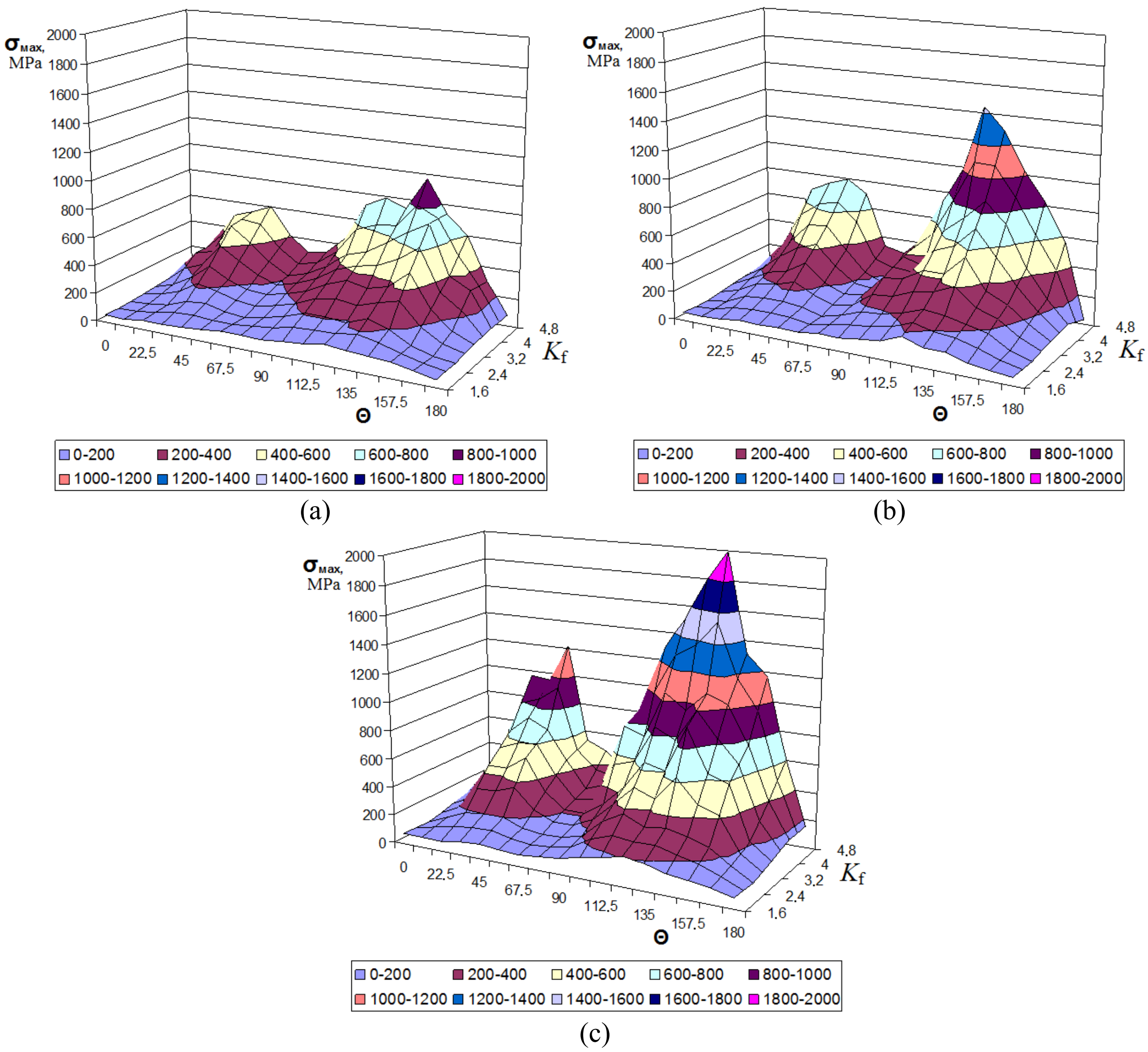


Figure 4. Dependence of the maximum tension in the models of the abrasive grains A 46 on seal border in a bundle on the orientation angle (Θ) and a form coefficient (K_f) while fixing in a bundle up to 2/3*L* (a) up to 1/2*L* (b) and up to 1/3*L* (c)

4. Conclusion

The joint analysis of the evaluation results of the front angles and tension in the oriented abrasive grains with a controlled form allowed to formulate the following conclusions:

- To achieve the maximum positive values of the front corners of the grains and the maximum work productivity of grinding tools should be used needle and lamellar grains (with high values of K_f) and orient them in the tools under orientation angles in the range Θ=22.5° ÷ 45°;

- To ensure maximum durability of grinding tools, with other things being equal, it is expedient to use abrasive grains of an isometric form (with the minimum K_f values), and also to focus grinding grains in the tangential direction (Θ=0°);
- Grinding tools with the increased work productivity and at the same time with a sufficiently high durability can be produced by orienting the abrasive grains under angles, close to the direction of the cutting force vector P;
- For the grinding wheels made of corundum abrasive grains and used for processing of structural steel at which operation the radial component of cutting force P_y in 3÷5 time bigger than the tangential component P_z, the rational angles of grain orientation are in range Θ=65°÷75°.

References

[1] Korotkov A N, Increase of operational opportunities of grinding tools, *Publishing House of Kuzbass State Technical University*, Kemerovo, 2005.
[2] Zaitsev A G, Influence of the diamond grains form on the wear resistance of grinding wheel for processing of firm alloys, *J. Sc. Bulletin of machine building*. 2 (1975) pp 76–77.
[3] Korotkov V A, Increase of operational opportunities of cutting discs, *Machine building*, Moscow, 2009.
[4] Korotkov A N, Operational properties of abrasive materials, *Publishing house of Krasnoyarsk University*, Krasnoyarsk, 1992.
[5] Granovsky G I, Granovsky V G, Cutting of metals, High School, Moscow, 1985.
[6] Vakser D B, Ways to increase productivity in grinding, *Publishing House of Moscow State Technical University named after N.E. Bauman*, Moscow, 2001.
[7] Tyrkov V N, Abrasive materials and instruments. Catalogue, All-Russian Research Institute of Information and Feasibility Studies in Mechanical Engineering and Robotics, Moscow, 1986.
[8] Pliss D A, Anakhin V A, Monakhov V N, Vibration separators, *Bowels of the earth*, Moscow, 1991.
[9] Korotkov V A, Technology and equipment for producing of the experimental cutting discs *Modern techniques and technologies (MTT – 2006) : Proceedings of the 12-th international scientific and practical conference of students, postgraduates and young scientists*, March 27–31, 2006. – Tomsk, Russia, 2006. pp 177–179.
[10] Lyukshin V S, Increase of operability of grinding tapes by use of grains with a controlled form and orientation, *Abstract of the thesis of Candidate of Technical Sciences*, Kemerovo, 2007.
[11] Korotkov V A, Russian Federation Patent 2,369,474. (2009).
[12] Kovalchuk A M, Fundamentals of design and manufacturing technology of abrasive and diamond tools, *Mechanical Engineering*, Moscow, 1984.
[13] Korotkov V A, Ways analysis operational characterization increase of the polishing wheels // Modern techniques and technologies (MTT 2003) : *Proceeding of the 9-th international scientific and practical conference of students, post-graduates and young scientists*, April 7–11, 2003. – Tomsk, Russia, 2003. pp 102–103.
[14] Korotkov V A, Minkin E M, Research of geometrical and strength characteristics of the oriented abrasive grains. , *J. Sc Processing of metals*. 3 (2012) pp 42-47.
[15] Petrushin S I, Proskokov A V, Theory of not free cutting of materials. Calculation of the intense deformed state in a cutting zone, J. Sc. *Bulletin of machine building*. 2 (2010) pp 34-40.
[16] Korotkov V A, Research of operational characterizations of cutting discs with oriented abrasive grains *Applied Mechanics and Materials* : Trans Tech Publications, doi : 10.4028/www.scientiffic.net/AMM.682.224 – Switzerland, 2014, Vol. 682(2014) pp 224–230.
[17] Korotkov V A, Research of the exploitation abilities of the cutting discs, which consist of the abrasive grains with controlled orientation *Modern Techniques and technologies* (MTT 2007) : Proceeding of the 13-th international scientific and practical conference of students,

post-graduates and young scientists, March 26–30, 2007. – Tomsk, Russia, 2007. pp 49–51.
[18] Korotkov V A, Rilov G M, Russian Federation Certificate on official registration of the computer program 2006,613,051 (2006).
[19] Korotkov V A, Minkin E M, Russian Federation Certificate on official registration of the computer program 2011,614,263 (2011).
[20] Korotkov V A, Minkin E M, Russian Federation Certificate on official registration of the computer program 2011,615,114 (2011).