Study regarding a theoretical model of the machining by grinding in the presence of the cutting fluid

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Abstract – In the paper is presented a theoretical model of the machining by grinding in the presence of the cutting fluid. First is presented the single grain model in the case of grinding in dry condition of work and after that is presented single grain model, in the presence of cutting fluid. It was established the role of the cutting fluid in the grinding process that quickly evacuate the heat from the cutting area and to quickly remove the formed chips and to form a separating layer between the abrasive grain and part, reducing friction and the amount of heat detached. The mathematical modeling of the roughness of the surfaces processed by grinding based on the spherical model it is considered a rather complex problem where we want to understand the action of the parameters with major influence on the quality of the workpieces. These parameters are: technological parameters, construction parameters and the cutting fluid.

Keywords –grinding process, mathematical model, surface finish, cutting fluid.

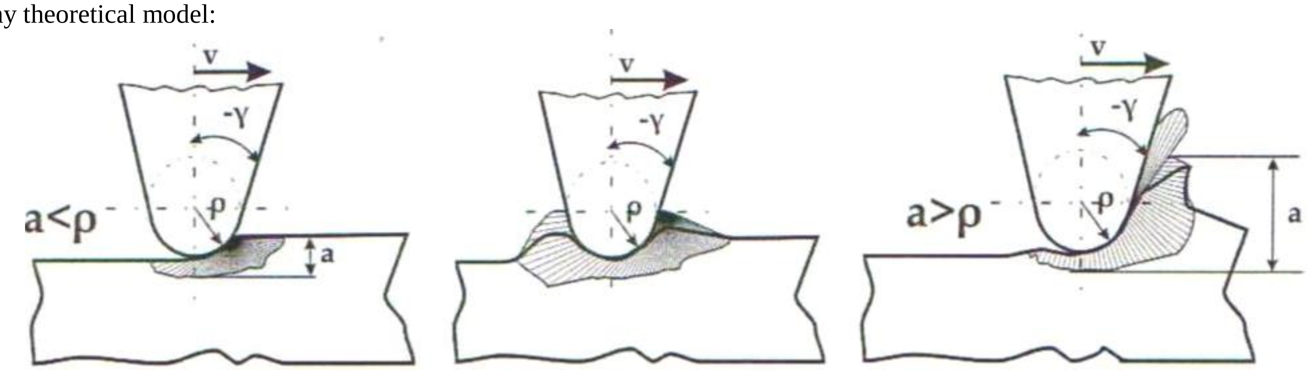
Received: June 8, 2021. Revised: March 15, 2022. Accepted: April 12, 2022. Published: July 4, 2022.

1. Introduction

The analysis of a cutting process involves the establishment of a physical model, an idealized approximation of reality, which reflects the development of principle and involves the admission of simplifying hypotheses. Based on the logical model, it must be possible to study the phenomena that accompany the technological process subject to research, right from its design phase.
This physical model must meet the essential conditions of any theoretical model:

- Be simple,
- To represent as accurately as possible the essence of the process being analyzed.

In order to be able to analyze more precisely the abrasion process, the sequence in which an abrasive grain is in full action of detaching a chip was considered.
It was considered that the processed surface is the result of the simultaneous action of the geometric factors characteristic of the abrasion process and of the plastic deformations that accompany it.



a) b) c)

Fig.1Phase of chip removal on grinding process

The edge of the abrasive grain is usually rounded; it reaches, after some wear, rounding radii of the order of ρ = 20-30μm and the grain begins to crawl on the cutting surface with a radial pressure and gradually increasing friction forces, producing a crushing (hardening) of the surface layer (Fig.1a). Then, as the cutting layer enlarges, the abrasive grain penetrates the material, initially producing only a scratch with a slight discharge of material in front and side (Fig.1b) and only a little later it detaches the chip (Fig.1c).

The crushing and scratching phenomena from the first phases are all the more intense, the smaller the thickness of the chip and the larger the rounding radius ρ (the ratio a / ρ is smaller).

From a micro geometric point of view, roughness is formed as a result of copying the marks left by the abrasive grains. Due to the fact that an abrasive grain raises the micro-chips with high specific forces, intense deformations take place that deform the micro relief obtained as a result of the action of the geometric parameters that characterize the abrasive grains.

The smoothness of the surface processed by abrasion is determined by the density of the scratches per unit area and to a lesser extent by their shape, respectively by the shape of the abrasive grains that produced them.

It is obvious that the improvement of the surface smoothness when grinding is obtained by increasing the number of passes, reducing the feed and reducing the grain size of the abrasive tool.

The correctness of the theoretical model presented above is supported by researchers in the field [3], [5], based on the following observations:

• All cutting edges of the abrasive grains have a certain blasting radius ρ whose value is amplified during the use of the cutting tool;

• The formation of the chip begins only after the abrasive grain has penetrated to a certain depth in the material of the part, depth depending on the size of the radius ρ, the geometric configuration of the trajectory described by the granule and the elastoplastic properties of the processed material;

• At too shallow depths of penetration, only elastic and plastic deformations occur, as well as strong heat releases due to friction;

• The thickness of the layer of effective material removed, t_A, is less than the theoretical value a, according to relation (1).

$$t_A = a - t_e - t_p, \qquad (1)$$

where t_A represents the thickness of the layer of effectively removed material, t_e - the thickness of the layer of elastically deformed material, tp - the thickness of the layer of plastic deformed material, a- the theoretical depth of cutting.

• The separation point (Fig.2), i.e. the point where the workpiece material breaks and begins to remove, is above the tip of the cutting edge.

The authors of the single grain model also notice certain limits of it, which they summarize as follows:

- The edges of the grains are randomly oriented and are located at different depths from a reference surface;
- The geometry of the cutting edges changes over time;
- Under the action of normal forces that appear between the part and the abrasive body, the grains at the periphery will yield elastically and will "sink" into the abrasive body, which results in an increase in the number of cutting edges in the work area;
- Not all cutting edges in the work area remove chips; there are negative rake angles, which do not allow cutting;
- The cutting edges were reduced to 1;
- The tip of the grain assimilated with a sphere allows to obtain a permanent orthogonal orientation on the piece, which does not correspond to reality.

On a simple analysis it can be seen that this model of the "single grain" that intervenes in the grinding process in the simplification effort of theorists completely neglects the active presence in the process of the cutting fluid. All explanations refer to dry friction, dry shear and dry detachment between the abrasive grain and the workpiece or the chip removed from it.

Comparative observations of grinding and superfinishing operations reveal a different "behavior" of the elements involved in the process, some of the differences arising from the interactions introduced by the cutting fluid as an active element of the machine technology system, tool-workpiece-cutting tool.

As a result, the "single grain" model in the case of grinding, should be improved as follows:

1. Both the cutting area comprising the chip with the separation point, the deformation area and the area which has been processed are "immersed" in a continuous medium of cutting fluid, specific to grinding.
2. If the cutting fluid is the emulsion, a dispersed system consisting of water and emulsifiable oil in a concentration of 3-5%, the dispersed oil droplets have the dimensions of 0.1-1μm and can be assimilated with some balls.
3. A first role in the process is played by oil droplets with active surface properties that adhere to solid metal and abrasive surfaces forming an adsorption layer with an active role in the balance of forces that are developed in cutting process. By means of this liquid layer, the dry friction between the grains and the part is replaced by the wet friction, which means a significant reduction of the friction coefficients, of the magnitude of the friction forces and implicitly of the developed heat. The layer formed by the surface agent (oil) has elastic properties, so that when the abrasive granule is pressed into the material to be processed, the cutting fluid behaves like an elastic cushion, which offers resistance to compression, reducing the depth of penetration of the abrasive grain in the workpiece; the surface thus obtained will have a lower roughness.
4. The oil particles are deposited to the same extent on the surface of the chip detached from the part, "embedding" and drawing the chip into the mass of the cutting liquid; this prevents the chip from entering the pores of the abrasive body, a situation found in the absence of cutting fluid. The rapid removal of chips from the processing area will be

done by water, a liquid present in the emulsion and which has a higher flow rate than oil.

5. Grinding is a process that takes place with the release of a large amount of heat and therefore a liquid with maximum cooling capacity - water is used as the cutting medium.

6. It should be noted that the reduction of friction by the presence of oil between the contact surfaces does not cancel the frictional forces.

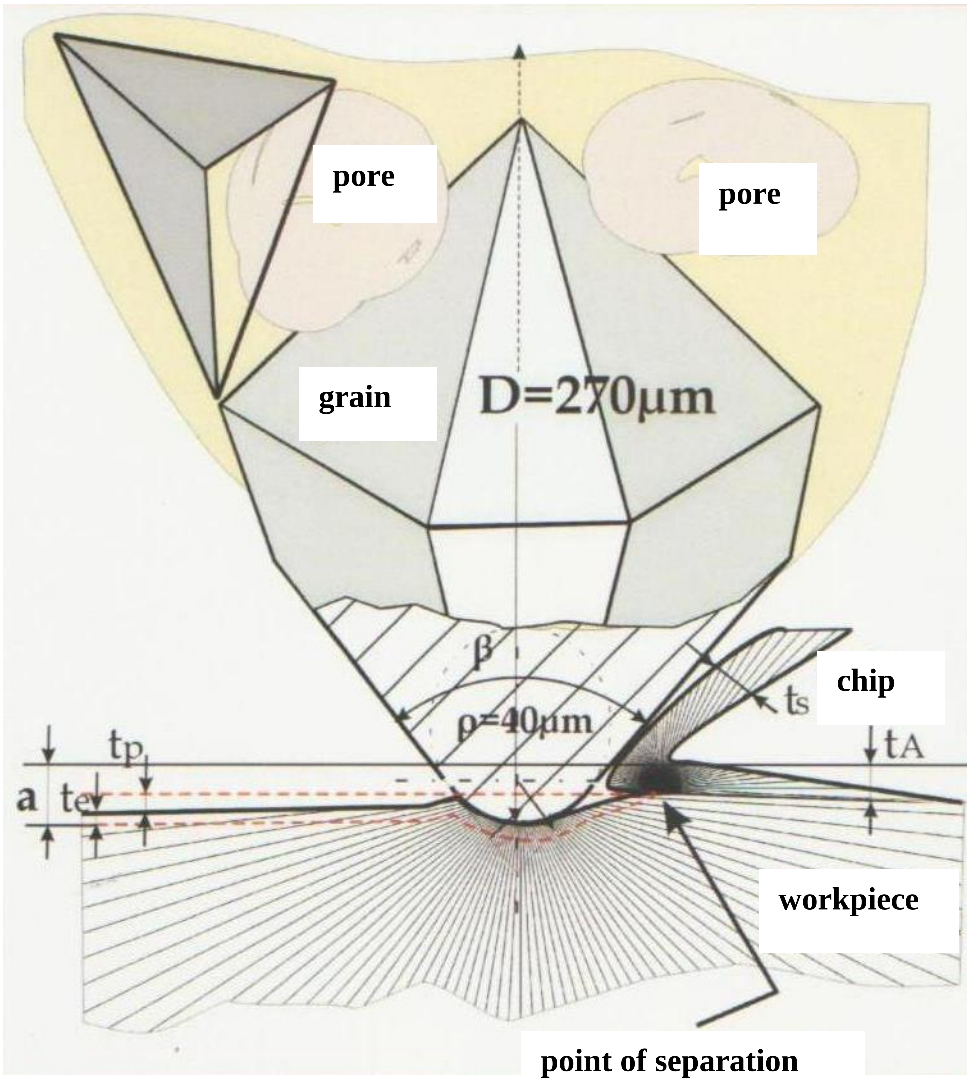


Fig.2 Single granule model, without the presence of liquid

2. Theoretical modeling of the roughness of grinded surfaces

For the mathematical modeling of the roughness obtained after grinding process, the model of the abrasive grain with spherical tip is considered Fig.3, [5] generally unanimously accepted and used mainly when approaching theoretical research on abrasive tool processing. The abrasive grain, with the cone angle β is considered to have the free height h_g, the embedding width b, the radius at the top r (obtained as a result of wear in the processing process). Let L_g be the distance between the grains, γ and α represent the rake and clearance angles of the abrasive grain.

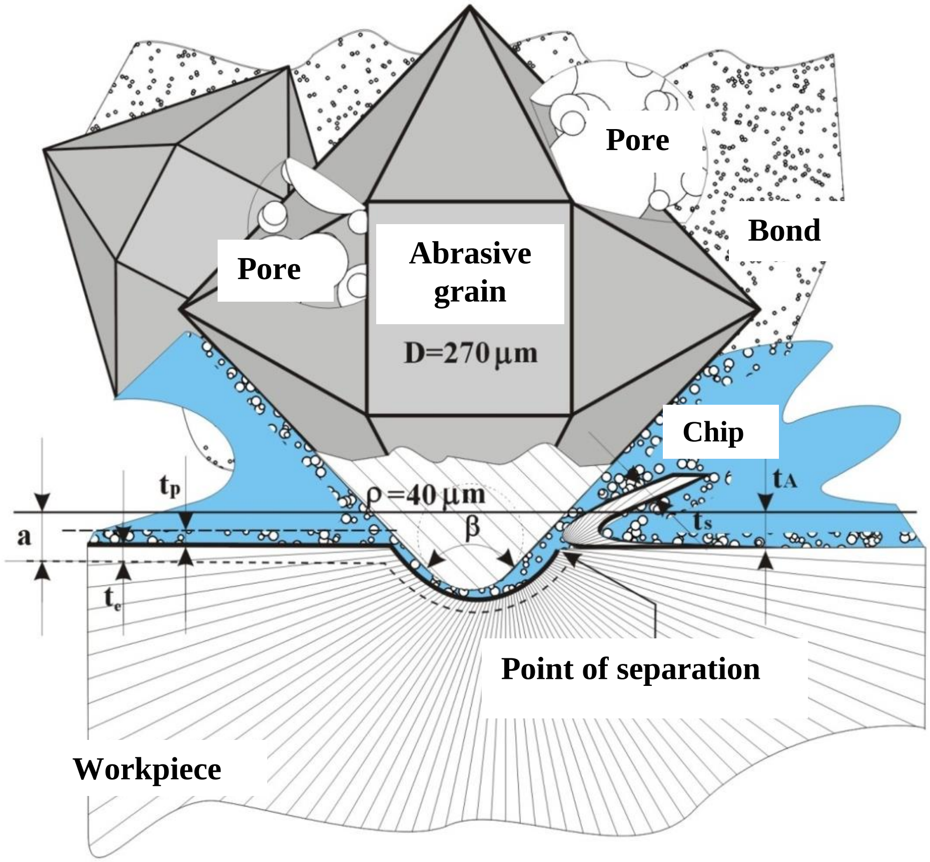


Fig.3 Single grain model, in the presence of cutting fluid

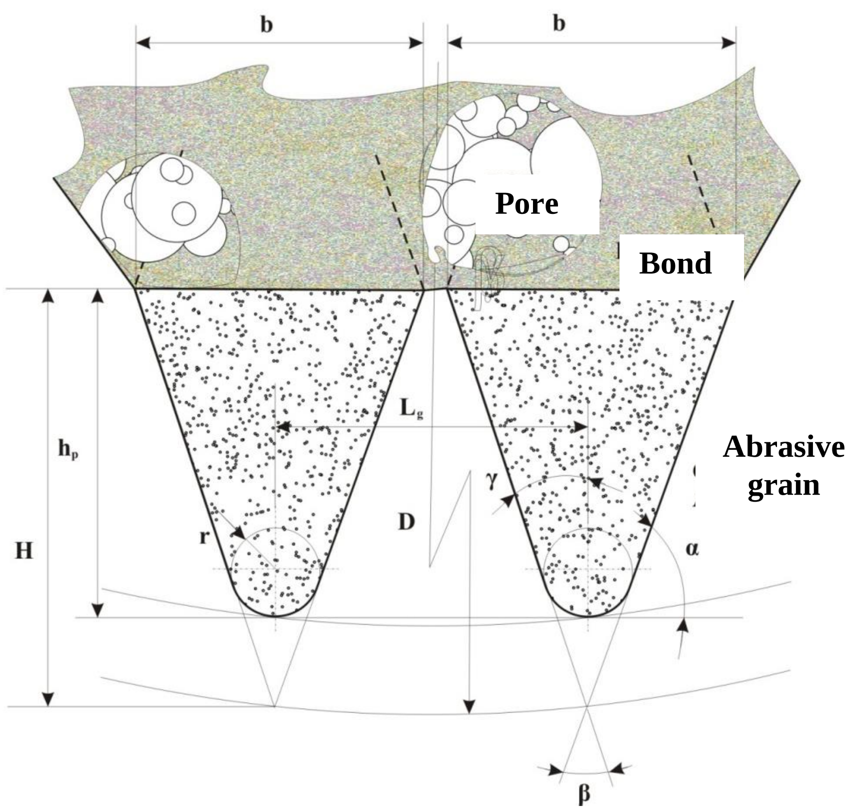


Fig.4 Spherical model of abrasive grain

According to the spherical model in Fig.4, by geometric calculations, considering the radius at the top of the grain r = 0, the following relation was reached:

$$b = 4 \cdot s_g \cdot tg\frac{\beta}{2}\sqrt{\frac{t}{D}} \quad (2)$$

where s_g is the feed on the abrasive grain, t - the depth of cut, D - the diameter of the abrasive wheel.

Considering that parameter b represents approximately the angular pitch of the abrasive grain cutting edges and assimilating the processing by grinding with that by cylindrical milling, it is proposed [7] an empirical relation to calculate the surface roughness:

$$h = \frac{s_l^2 \cdot \delta}{4 \cdot D \cdot v_s} \quad (3)$$

where$h$ is the height of the micronegularities, δ[radians] - the angular pitch of the cutting edges (in radians), s_l[mm / s] - the feed of the part, v_s[m / min] - the angular speed of the cutting tool.

Based on the notations presented in Fig.4, considering that b represents the angular pitch, the following relation of the height of the microneregularities at grinding process results:

$$h = \frac{t \cdot s_g \cdot tg\frac{\beta}{2}}{v_s \cdot D \cdot \sqrt{D}} \quad (4)$$

If the following grinding dependencies are considered [5]:

$$s_g = \frac{s_l}{N_g} \quad (5)$$

where$s_l$is the longitudinal feed,N_g- the number of abrasive grains working during a rotating feedrate, given by the relation:

$$N_g = \frac{\pi \cdot D}{L_g} \cdot k_1 \quad (6)$$

where$k_1$there is a coefficient that takes into account the fact that only a certain number of grains actually cut.

From the combination of relations (4) - (6), the following relation results (7):

$$h = \frac{t \cdot s_l \cdot L_g \cdot tg\frac{\beta}{2}}{\pi \cdot k_1 \cdot D^2 \cdot \sqrt{D} \cdot v_s} \quad (7)$$

The non-slip displacement condition of the abrasive grain on the processed surface is of the form [2]:

$$\propto \leq arctg\mu \quad (8)$$

where$\alpha$is the clearance angle of the abrasive grain, μ - the friction angle on the clearance surface.

Taking into account that based on Fig.4 it can be written that:

$$\gamma + \frac{\beta}{2} + 2 \cdot \alpha = \pi \quad (9)$$

After a series of trigonometric calculations it results that:

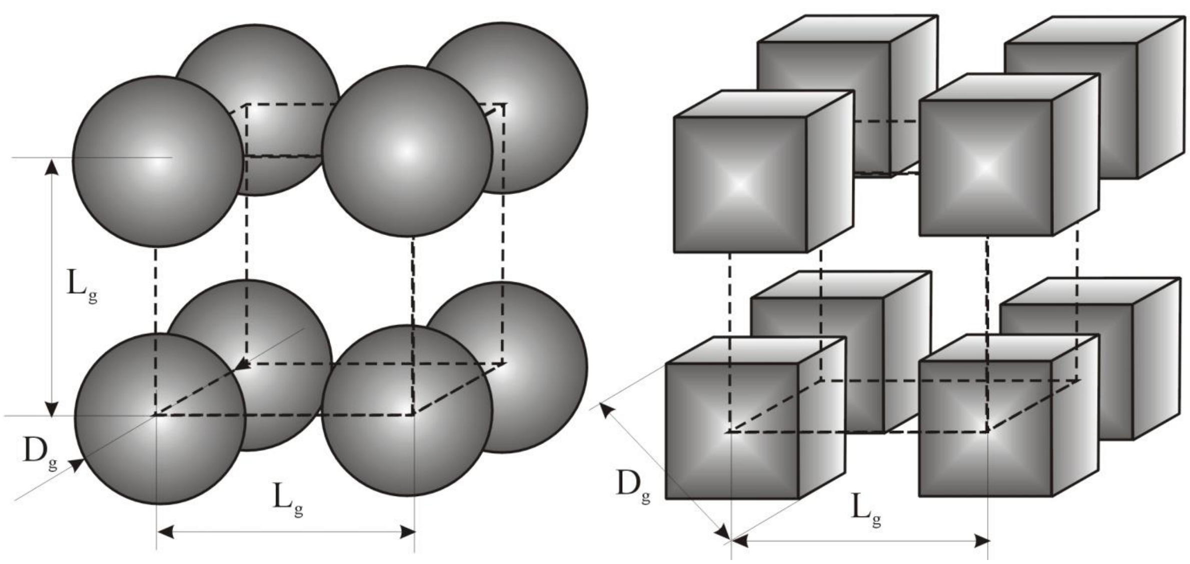
$$tg\frac{\beta}{2} = ctg(\gamma + 2 \cdot \alpha) \quad (10)$$

$$\mu = tg\alpha \quad (11)$$

Developing the relation (10) and imposing the boundary condition (11), the relation (7) turns into:

$$h = \frac{t \cdot s_l \cdot L_g}{\pi \cdot k_1 \cdot D^2 \sqrt{D} \cdot v_s} \cdot \frac{2 \cdot \mu \cdot [(1-\mu^2) \cdot ctg\gamma - 1]}{1-\mu^2 + 2 \cdot \mu \cdot ctg\gamma} \quad (12)$$

The distance$L_g$between the abrasive grains depends on the size of the abrasive grains that form the abrasive body and its structural index.



a) b)

Fig.5 The structure of an abrasive body

To evaluate the theoretical distance between the abrasive grains, the following are allowed:
1. The abrasive grains are of the same size, corresponding to the respective granulation characteristic according to DIN ISO 6344;
2. The abrasive grains have a regular spherical (Model 1, Fig.5a) or cubic (Model 2, Fig.5b) shape;
3. The percentage of the total volume of the abrasive body occupied by the abrasive grains is given by the structural characteristic of the abrasive body.
4. Consider an elementary volume of abrasive body consisting of an ordered network: 8 abrasive grains (spherical or cubic) arranged in the 8 corners of a cube.
Let L_g= the distance between the centers of two neighboring abrasive grains.
For the two models it results:
Model 1: the abrasive grains are spherical in shape.
The volume of the abrasive body is calculated with the formula:

$$V_{CA} = L^3 \tag{13}$$

The volume of abrasive grains (diameter D_g) contained in the elementary volume $V_{CA}$is calculated by the formula:

$$V_{GA} = 8 \cdot \frac{1}{8} \cdot \frac{4 \cdot \pi}{3} \cdot D_g^3 \tag{14}$$

The ratio between the volume of the abrasive grains and the volume of the abrasive body represents the structural index of the respective abrasive body.
Let *i*be the part of the volume of the abrasive body that is made up of abrasive grains.

$$i = \frac{V_{GA}}{V_{CA}} \tag{15}$$

Replacing in the expression (15) the relations (13) and (14) the following formula of the distance between the abrasive granules is obtained:

$$L = \sqrt[3]{\frac{\pi}{6 \cdot i}} \cdot D_g \tag{16}$$

Model 2: the abrasive granules are cubic in shape.
The volume of the abrasive body is calculated with the formula:

$$V_{CA} = L^3 \tag{17}$$

The volume of the abrasive grains (side “l”) contained in the elementary volume V_{CA} is calculated by the formula:

$$V_{GA} = 8 \cdot \frac{1}{8} \cdot l^3 = l^3 \tag{18}$$

It is considered that the side of the cube representing the theoretical grain is equal to the side of the sieve through which the grains were selected for the formation of abrasive bodies, see (19).

$$l = D_g \tag{19}$$

The ratio between the volume of the abrasive grains and the volume of the abrasive body represents the structural index of the respective abrasive body.
Let*i*be the part of the volume of the abrasive body that is made up of abrasive grains.

$$i = \frac{V_{GA}}{V_{CA}} \tag{20}$$

Replacing in the expression (20) the relations (17) and (18) the following formula of the distance between the abrasive granules is obtained:

$$L = \sqrt[3]{\frac{1}{i}} \cdot l \tag{21}$$

Substituting (19) into (21) we obtain:

$$L = \sqrt[3]{\frac{1}{i}} \cdot D_g \tag{22}$$

Replacing in the relation (12) the expression of the theoretical distance between the abrasive grains, the relations (23) and (24) are obtained for the model of the spherical granules respectively cubic:

$$h = \frac{t \cdot s_l \cdot \sqrt[3]{\frac{\pi}{6 \cdot i}} D_g \cdot}{\pi \cdot k_1 \cdot D^2 \cdot \sqrt{D} \cdot v_s} \cdot \frac{2 \cdot \mu \left[(1-\mu^2) \cdot ctg\gamma - 1 \right]}{1-\mu^2+2 \cdot \mu \cdot ctg\gamma} \tag{23}$$

$$h = \frac{t \cdot s_l \cdot \sqrt[3]{\frac{1}{i}} D_g \cdot}{\pi \cdot k_1 \cdot D^2 \cdot \sqrt{D} \cdot v_s} \cdot \frac{2 \cdot \mu \left[(1-\mu^2) \cdot ctg\gamma - 1 \right]}{1-\mu^2+2 \cdot \mu \cdot ctg\gamma} \tag{24}$$

If the influence of the peak radius of the grain on the angular pitch*b* is also taken into account, it results based on Fig.4 that:

$$b = 2 \cdot \left[h_g \cdot tg \frac{\beta}{2} + \frac{r \cdot \left(1 - sin\frac{\beta}{2}\right)}{cos\frac{\beta}{2}} \right] \tag{25}$$

The relation (3) finally becomes:

$$h = \frac{s_l}{2 \cdot D \cdot v_s} \cdot \left[h_g \cdot tg \frac{\beta}{2} + \frac{r \cdot \left(1 - sin\frac{\beta}{2}\right)}{cos\frac{\beta}{2}} \right] \tag{26}$$

The value of the optimal coefficient of friction, which ensures the minimum height of the microneregularities, is obtained by canceling the partial derivative of the relations (23) respectively (24) in relation to μ:

$$\frac{\partial h}{\partial \mu} = 0 \tag{27}$$

which leads after a series of calculations to solve the following equation:

$$\mu^4 \cdot ctg\gamma - \mu^3 \cdot (ctg\gamma - ctg\gamma^2) - \mu^2 (6 \cdot ctg\gamma^2 + 3 \cdot ctg\gamma - 2) - 3 \cdot \mu \cdot ctg\gamma + ctg\gamma = 0 \tag{28}$$

If we consider the very small values, of the order of hundreds, of μ, the terms of the equation of order 3 and 4 can be neglected and the equation becomes:

$$(6 \cdot ctg\gamma^2 + 3 \cdot ctg\gamma - 2) \cdot \mu^2 + 3 \cdot \mu \cdot ctg\gamma - ctg\gamma = 0 \quad (29)$$

The convenient solution of the equation is:

$$\mu_{optim} = \frac{-3 \cdot ctg\gamma + \sqrt{24 \cdot ctg\gamma^3 + 9 \cdot ctg\gamma^2 + 12 \cdot ctg\gamma - 8}}{2 \cdot (6 \cdot ctg\gamma^2 + 3 \cdot ctg\gamma - 2)} \quad (30)$$

3. Conclusions

1. Although there is unanimity of opinion among experts as to the important role that cutting fluid plays in grinding, the old theoretical model of grinding does not take it into account.
2. It was cooling liquid (homogeneous mixture of oil dispersed in water) and the surface active properties of the oil, it was considered that the oil droplets will form an adsorption layer on the surface of the intervening solids (abrasive granule, the workpiece and the detached chip) assimilable with a layer of small balls that prevents the realization of a direct contact between the granule and the part. Due to the binding of the oil particles to the detached chip, it is "drawn" into the liquid and removed with it from the cutting area to avoid clogging the abrasive body. For this, the cutting fluid must have very good flow properties.
3. The role of the cutting fluid in the grinding process is to quickly evacuate the heat from the cutting area (liquid with high cooling capacity), to quickly remove the formed chip (liquid with polar constituents) and to form a separating layer between the grain and part, reducing friction and the amount of heat detached.
4. The mathematical modeling of the roughness of the surfaces processed by grinding based on the spherical model is a rather complex problem when we want to understand the action of the parameters with major influence on the quality of the workpieces. These parameters are: technological parameters, construction parameters and the cutting fluid.
5. The calculation relations of the height of the microneregularities at grinding obtained as a result of this modeling (relations 23, 24, 26) largely confirm the conclusions expressed in the literature and the experimental results.
6. The influence of the cutting fluid on the quality of the surfaces through the prism of the friction coefficient μ is of parabolic type, which imposes the determination of the optimal value that minimizes the height of the geometric microasperities that form the real profile of the surface.
7. The relations of theoretical calculation of the distance between the abrasive grains were established, depending on the structure index of the abrasive body and the dimensions of the abrasive grains, assuming that all abrasive grains have the same size and are located at the same distance. Two models were considered: in one the abrasive grains were considered spheres and in the other cubes.

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Author Contributions:

Badea Lepadatescu carried out study regarding the mathematical model of grinding process that is in this field of manufacturing.

Flavia Fechete was responsible with theoretical modeling of the roughness of grinded surfaces