Numerical analysis of the influence of abrasive grain geometry and cutting angle on states of strain and stress in the surface layer of object

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Abstract

Grinding is a very complicated technological process. To increase the quality of the product and minimize the cost of abrasive machining, we should know the physical phenomena which exist during the process. The first step to the solution of this problem is an analysis of a machining process with a single abrasive grain. In the papers [Kukielka and Kustra, *Surface Treatment VI Computation Methods and Experimental Measurements for Surface Treatment Effects*. WIT Press, 2003, pp.109–118; Kukielka et al, *Computer Methods and Experimental Measurements for Surface Effects and Contact Mechanics VII*. WIT Press, 2005, pp. 57–66.] the thermo-mechanical models of this process are presented, but in this work attention is drawn to the chip formation and its separation from the object. The influence of the tool geometry and the cutting angle on the states of strain and stress in the surface layer during machining is explained. The phenomena on a typical incremental step were described using a step-by-step incremental procedure, with an updated Lagrangian formulation. Then, the finite elements methods (FEM) and the dynamic explicit method (DEM) were used to obtain the solution. The application was developed in the ANSYS system, which makes possible a complex time analysis of the physical phenomena: states of displacements, strains and stresses. Numerical computations of the strain have been conducted with the use of two methodologies. The first one requires an introduction of boundary conditions for displacements in the contact area determined in the modeling investigation, while the second – a proper definition of the contact zone through the introduction of finite elements of TARGET and CONTACT types, without the necessity to introduce boundary conditions. Examples of calculations for the strain and stress field in the surface layer zones of object were presented.
Keywords: abrasive grain, single-grain machining, chip creation, yield stress, FEM, numerical analysis, state of strain, state of stress.

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1 Introduction

Grinding is considered to be a particularly complex and hard to execute way of machining, in which there occur many not yet fully investigated phenomena. This results from a large number of factors which have an influence on the course of the machining process. This requires the development of different varieties of the process and conducting of comprehensive cognitive research.

Grinding is characterised by many specific features, which make this process basically different from the ways of machining [4, 7]:

- an irregular arrangement of a very large number of abrasive grains on the working surface of the grinding wheel,
- diversified shapes of abrasive grains and negative working rakes of the cutting edges of grain apexes,
- different heights of the cutting edges of grain apexes on the active surface of the grinding wheel,
- an unspecified dependency between the thickness and the width of the chip removed with individual abrasive grains,
- non-isolation of the main and auxiliary machining edges,
- peculiar properties of abrasive grains: high hardness, resistance to the action of heat, sharpness, brittleness, and an ability to crack in the cleat plane, etc.,
- small penetration depths of abrasive grains into the material machined in comparison with their average sizes,
- large tangential velocities of micro-machining, which ensure the removal of a large quantity of chips in a unit of time.

The shape of a single abrasive grain shows a significant influence on the course of the machining process [9]. As it was found, the grains of abrasive materials, once their size has been reduced, are usually characterised by an irregular shape and a differentiated degree of the sharpness of machining corners and edges. While considering the work of such grains, their sizes, shape and geometry are subject to experiential investigation, and they are replaced with grains with a regular shape, which can be mathematically described. Most often, as a replacement model of the abrasive grain [1], the cone or the pyramid (with rounding or without rounding of its vertex) is accepted with the apex angle equal 2θ [2] and a sphere with radius ρ_k [10], while the spheroid with a constant semi-axis [8] is accepted less often.

A creation of abrasive wheels with abrasive grains geometrically correct and located properly in the binding material would substantially contribute to the change of the course of the work. The first stage is the recognition of the process of machining with a single abrasive grain. Learning about the topology of the abrasive grain and the mutual relations between its individual sizes should have a significant influence on the creation of its correct geometrical model. This model in combination with the suitable manner of giving specified shapes to grains in the process of their production would lead to the creation of a grinding wheel whose abrasive grains would perform e.g. the processes of the initial and finishing machining at the same time.

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The process of the chip creation proves to have a substantial influence on the grinding process, together with the geometrical and kinematic dependencies in the contact zone of the grinding wheel-the object machined. It has a significant impact on the wear of the grinding wheel, the value of the components of the machining force, the temperature and the quality of the surface machined.

During the machining process, there occur large and fast plastic strains, which occur only in the part of the object machined. Under the influence of these strains in the material, its physical properties are subject to change: the hardness and strength increase. There occurs the so-called consolidation phenomenon of the material. The geometry of the zone of the chip creation during machining allows one to accept an assumption that in the area in question there is a plate state of strains.

For the correct modelling and analysis of the grinding process, the knowledge of the course of the physical phenomena occurring in the machining zone in real conditions proves to be necessary. For this purpose, an analysis of the process of machining with a single abrasive grain was conducted. This process was considered as a problem of a displacement of the model abrasive grain (Fig. 1) specified in paper [21] on the elastic/visco-plastic body.

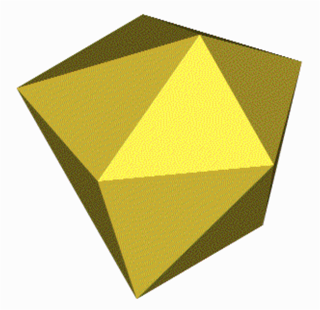


Figure 1: Geometry of the most probable abrasive grain [21].

An abrasive grain with the apex angle of $2\theta = 80 \div 120^0$ and the corner rounding $r = 0{,}001$ μm is tilted in relation to the foundation by angle $\alpha = 45 \div 65^0$ (Fig. 2). The allowance was $h = 0{,}01$ μm. The value of the real layer thickness of the material removed as a result of elastic strains was smaller and was ca. $h_r = 0{,}009$ μm.

It was assumed that the grain movement was kinematically forced and it slides horizontally on the surface of the elastic/adhesive-plastic body. The value of α angle determines whether there will occur a machining phenomenon (chip creation) or the strengthening process of the surface layer through burnishing (no chip).

In papers [21, 22], a thermal and mechanic model of the process of the grain displacement on the elastic/visco-plastic body was developed and the distributions of temperatures were determined together with the intensities of strain in the material machined in the initial chip creation phase.

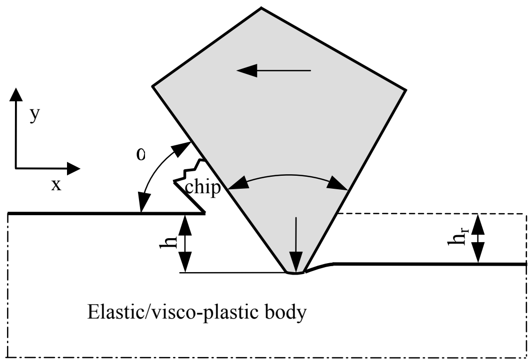


Figure 2: Diagram of the considered issue of the displacement of the abrasive grain on the elastic/visco-plastic body.

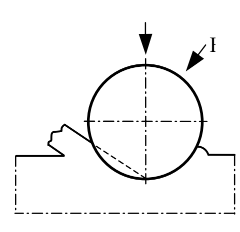
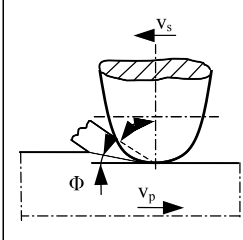
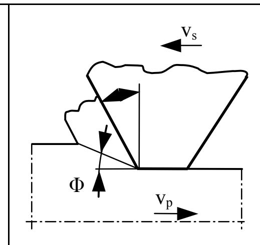
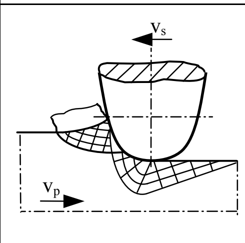
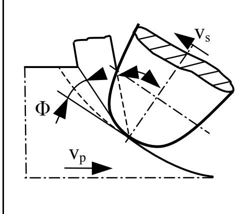
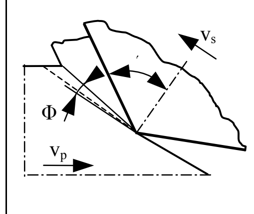
This study concerns the issues of the creation of the properties of the surface layer of a product, the chip formation and separation from the material of the part. The influence of the apex angle of the abrasive grain 2θ was determined together with the angle of its tool cutting edge angle α on the states of strains and tensions in the surface layer of the object at any time of the process. For the purpose of a description of phenomena at individual moments with the step-by-step method, an upgraded Lagrange's description was applied. In order to solve the problem, the finite elements method (FEM) and the dynamic explicit method (DEM) was used. Examples of solutions were presented in ANSYS programme for tensions and strains in the surface layer of the object.

2 Models of chip creation

Investigations concerning the chip creation process most often used the machining theory, which considers its creation as a result of the displacement of the material machined along the cutting plane. A modification of views in this area took into account machining with a grain with a spherical cutting blade (Table 1).

Models of chip creation during grinding with a conical cutting edge are an analogy to turning and milling – processes, which have been so far much better investigated than grinding. In many publications, these have been used in the description of the chip creation during grinding, while considering the features characteristic of this process [2, 6, 10, 20]. However, such an approach to the solution of the problem discussed was questioned as a result of numerous research studies. There are studies which treat the process of the chip creation during grinding as an extrusion of the material with a spherical cutting edge. These include the papers by Shaw [15, 23], which constitute an analogy to the hardness measurement with Brinell and Lortz's methods [3, 11], who based them on the theory described by Tomlenov [19] concerning the field of the path of shear for the perpendicular penetration into the material of a rounded punch with the consideration of friction. A detailed theoretical description supplied by Lortz of the chip creation by the extrusion of the material with a spherical cutting edge constituted the basis for further studies in this area [13, 14, 16-18]. Owing to the consideration of the so-called dead zone, the determination of the conditions in which the chip is created and the possibility to determine strains in the surface layer of the object machined, it can be stated that this description constitutes the most representative model of the chip creation process.

Table 1: Models of chip creation with single-grain machining [5].

Movement \ Shape		Grain with a spherical cutting blade		Grain with a conical cutting blade
		Chip creation by extrusion of material	Chip creation along cutting plane	
Grain movement in relation to the object	Rectilinear			
	Curvilinear			

Legend: F – machining force, v_s – tangential speed of grinding wheel, v_p – tangential speed of the object machined, γ – tool rake angle, Φ – shear angle.

3 Data for computer simulation

It was accepted in the simulations that the abrasive grain is a non-deformable body, while the object is an elastic/visco-plastic body described with the aid of Cowper–Symonds' model. In the model, Huber–Mises–Hencky's plasticity model is used together with the associated flow right. The model takes into consideration the line-isotropic $(\beta = 1)$, kinematic $(\beta = 0)$ or mixed $(0 < \beta < 1)$ plastic strengthening as well as the influence of the intensity of the plastic strain speed, according to the involution dependence:

$$\sigma_Y = (R_e + \beta E_{tan}\varphi_i^{(p)})[1 + (\dot{\varphi}_i^{(p)}/C)]^m \text{, [MPa]} \tag{1}$$

where σ_Y – yield stress, R_e [MPa] – initial yield stress point, $\varphi_i^{(p)}\ [-]$, $\dot{\varphi}_i^{(p)}\ [s^{-1}]$ – intensity of strain and plastic strain rate respectively, $C\ [s^{-1}]$ – material parameter to determine the influence of the intensity of the plastic strain rate, $m = 1/P$ – material constant determining the sensitiveness of material on the plastic strain rate, $E_{tan} = E_T E/(E - E_T)$ – material parameter dependent of the module of plastic hardening $E_T = \partial\sigma_p/\partial\varphi_i^{(p)}$ and of Young's elasticity module E.

The following parameter values were accepted: density of body material $\rho = 7865$ kg/m^3, Poisson's number $\nu = 0{,}27$, limiting damaging strain $\varepsilon_f = 2{,}5$ and $E = 200$ GPa, $R_e = 310$ MPa, $E_{tan} = 763$ MPa, $C = 40$ s^{-1} and $P = 5$.

Also, constant values were accepted of static $\mu_s = 0{,}1$ and dynamic $\mu_d = 0{,}05$ friction coefficients. The apex angle of the grain changes in the range of $2\theta = 80 \div 120^0$, while the tool cutting edge angle $\alpha = 45 \div 65^0$. The rounding radius of the grain apex was $r = 0{,}001$ μm.

4 Method of solution

For the purpose of the solution of the problem, the dynamic explicit method, also known as the method of central differences, was used. In this method, the equation which describes the movement and deformation of the object investigated has the following form:

$$[\boldsymbol{M}]\{\ddot{\boldsymbol{r}}(\tau)\} + [\boldsymbol{C}]\{\dot{\boldsymbol{r}}(\tau)\} + [\boldsymbol{K}]\{\boldsymbol{r}(\tau)\} = \{\boldsymbol{R}(\tau)\}, \quad \tau \in [t_0, t_s] \tag{2}$$

where *[M]*, *[C]* and *[K]* are matrices constant in time of: mass, damping and rigidity of the system respectively, *{R}* is the external load vector, and $\{\boldsymbol{r}\}, \{\dot{\boldsymbol{r}}\}, \{\ddot{\boldsymbol{r}}\}$ are vectors of the displacement, speed and acceleration of the nods of the system. This equation is integrated in relation to time with the step-by-step method and, additionally, is not rearranged during this operation. If it is assumed that the displacements, speeds and accelerations of the system are known at the beginning, at moment $\tau = t_0$ and equal $\{\boldsymbol{r}_0\}, \{\dot{\boldsymbol{r}}_0\}, \{\ddot{\boldsymbol{r}}_0\}$ respectively, than the whole interval is divided into parts with lengths Δt and on each step, a solution is sought for the abovementioned equation. This means that this equation is to be satisfied only in the selected times and not in the whole interval investigated. This means that for every moment, one can search the positions of the equilibrium of a system subject to external forces, force of inertia and forces of damping, while applying algorithms from a static analysis. The end of every moment of time is at the same time the beginning of another.

5 Results of numerical calculations

Numerical simulation in the ANSYS system was conducted for different apex angles 2θ and the tool cutting edge angle α of the grain. The object machined and the abrasive grain were digitised by elements of PLANE 162 type with a non-linear function of shape. The contact grain with body was modeling by element TARGE 169 and CONTA 171. The net of finished elements was concentrated in the contact area (Fig. 3). Sample simulation results are presented in Figs. 4 and 5.

While analysing the results obtained it was found that together with the change of the tool cutting edge angle α and the change of apex angle of the cutting edge 2θ, the values of strains and stresses are subject to change. Abrupt increases of stresses are the result of the chip creation phenomenon. Together with the increase of the tool cutting edge angle, the shear angle Φ of the material separated from the foundation increases, as well. It was found that both angles have a significant influence on the chip shape.

For the tool cutting edge angle $\alpha = 45^0$, we observe fast disturbances of the cohesion of the material between the neighbouring chip elements. This results in the fact that the chip drops off from the cutting edge in the form of separate elements – a segmental chip (Fig. 4(a), (b)).

(a) (b)

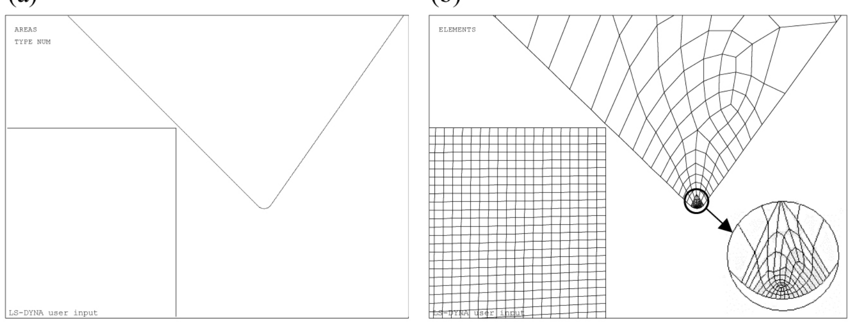


Figure 3: View of abrasive grain apex and object's fragment: (a) before digitising, (b) after digitising.

(a) (b)

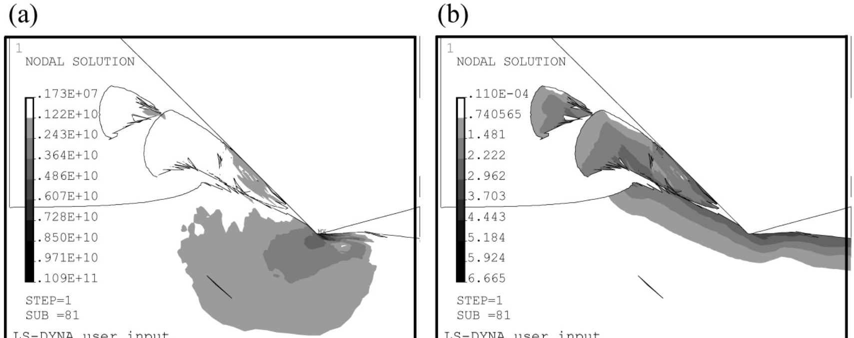


Figure 4: Maps of stress intensities (a) and strain intensities (b) in the chip creation phase for $2\theta = 120^0$, $\alpha = 45^0$, $r = 0{,}001$ μm.

For angle $\alpha = 65^0$, there occurs the phenomenon of chip curling (Fig. 5(a), (b)) in the direction of the foundation machined – a stepped chip. This is the result of the fact that the chip line from the side of the cutting edge action surface is longer than the chip line on its opposite side. For angle $\alpha = 55^0$, the chips created are segment chips. Fast cracking of the chip elements is observed.

a) b)

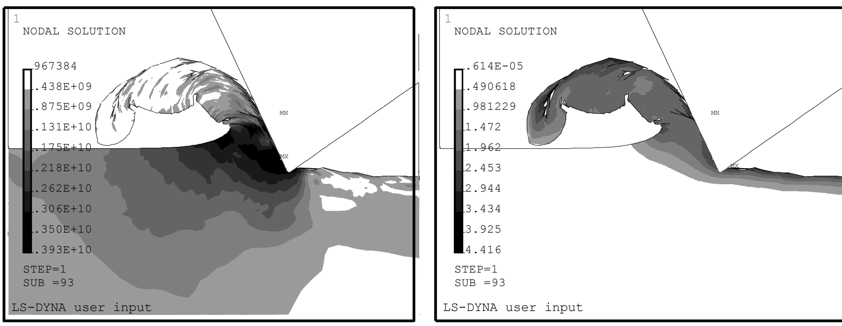


Figure 5: Maps of stress intensities (a) and strain intensities (b) in the chip creation phase for $2\theta = 80^0$, $\alpha = 65^0$, $r = 0{,}001$ μm.

During the grain movement on the surface, without a clear stage of the chip formation, the maximum intensity of stresses occurred in the contact place of the grain apex with the foundation of the material. It was ca. $\sigma_i = 9250$ MPa for $2\theta = 80^0$, $\alpha = 65^0$, $\sigma_i = 7100$ MPa for $2\theta = 80^0$, $\alpha = 55^0$, and $\sigma_i = 3700$ MPa for $2\theta = 80^0$, $\alpha = 45^0$ and it propagated in the direction of machining, and not deep into the material. The maximum intensity of stresses for the same values of angles and the same time steps of the simulation were: $\varepsilon_i = 17{,}87$, 4.85 and 2.22 respectively. Maximum stresses in the material at the moment of a distinct stage of chip creation for $2\theta = 80^0$, $\alpha = 65^0$ occurred in the cutting plane. At the moment of its formation, an increase of stresses was observed in this region from the value of ca. $\sigma_i = 6370$ MPa to the value of $\sigma_i = 8210$ MPa at the moment of the material cracking of separation from the foundation. For $2\theta = 80^0$, $\alpha = 55^0$, the values of maximum stresses $\sigma_i = 4190$ MPa were concentrated also in the cutting plane. For $2\theta = 80^0$, $\alpha = 45^0$, the maximum intensity of strains was ca. $\sigma_i = 4130$ MPa. At the moment of the chip being separated from the foundation, there occurred a distinct drop of stresses in the material. Stresses in the chip were also on a low level. Strains in the material after the grain had passed concentrated in the surface layer of the material of the foundation. Strains occurring in the material located before the cutting edge of the grain propagated not only in compliance with the machining direction but also inside the material. This was the result of the phenomenon of the creation of flashes in the initial phase and on further stages of the chip creation.

A characteristic zone in the material machined is the so-called dead zone. It plays the role of an additional cutting edge with a smaller angle of action than in the case of the proper cutting edge. The ratio of h_r/h decreased together with the increase of the apex angle, and in certain cases this resulted in the occurrence of a wave of the material under the grain without any creation of the chip (noticeable for $\alpha = 65^0$).

6 Conclusions

An application of modern numerical methods and computing systems allows an analysis of complex physical phenomena occurring in the process under investigation. The application developed in the ANSYS system enables a time analysis of the process of machining with a single abrasive grain, with the consideration of the changeability of the grain's apex angle and the angle of its action.

Investigations into the shape of the chips obtained after machining with a single abrasive grain lead to the conclusion that the temperature of the material machined, and strictly speaking, the thermal conditions in which plastic strains occur, have a significant influence on the creation process and the shape of the chip. Machining with a single abrasive grain thus gives one or two chips, shorter and thicker ones, and the groove cut is with large flashes. In a similar machining process with a single abrasive grain, but concerning material heated up to 700^0C, flashes are much smaller, while chips are in the number and shape similar to those obtained by machining with a grain tied up in the grinding wheel [21].

The obtained results of the computer simulation of the process of machining with a single abrasive grain with a geometry of $2\theta = 120^0$ and action angle $\alpha = 45^0$ coincide with the results obtained by Kita and Ido [12]. They made an investigation into the influence of the cutting edge apex angle 2θ on the course of the creation of a chip and its shape with dry machining and with the use of a cooling and lubricating liquid. They obtained various chip shapes. For example, for angles $2\theta = 100^0$, $\alpha = 40^0$, they obtained a stepped chip with shallow gaps, which is similar to the one obtained here with the aid of a numerical simulation (Fig. 4(a), (b)). The material flashes obtained before the grain cutting edge and its shapes similar to the results of experiential investigations confirm the justifiability of the use of computer simulations and their reliability.

The distributions of stresses and strains obtained for different grain geometries and action angles, on particular phases of the deformation process, can be made use of while designing machining: making a selection of the machining conditions and its optimising in the aspect of the technological quality of the product.

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