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CONTENTS

EXPERIMENTAL SIMULATION OF HEAT AND STRESS FORMATION FOR SURFACE GRINDING

BILEK, O. & LUKOVICS, I.

Abstract: *The article describes an application of a FEM simulation for grinding process. The further experimental computer simulation solves the influence of abrasive grain wear on the output parameters such as heat generation, chip temperature and stress formation; a grinding grain was substituted by an approximate sharp and worn model.*

Key words: *FEM, Grinding, Simulation, Heat, Grinding Grain*

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1. Introduction

A technological and economic situation in branch of production engineering brings about a quest for the existing processes optimization. A Finite Element Method (FEM) of analysis is suitable for their understanding. The desired results of every single production process can be reached only if fundamental physical processes are clearly understood. The quantitative results can be also gained from a numerical analysis. However, an analytical solution is limited to some extent. Mathematical equations are set up by an application of all known marginal conditions. Unfortunately, they do not solve the problem as the equations are too complicated. For example, the analytical approach to forming operations (a chip formation during metal working) results in unsolvable equations, especially when deformation hardness, and difficult tool and workpiece geometry are considered. (Jinyuan, 2008)

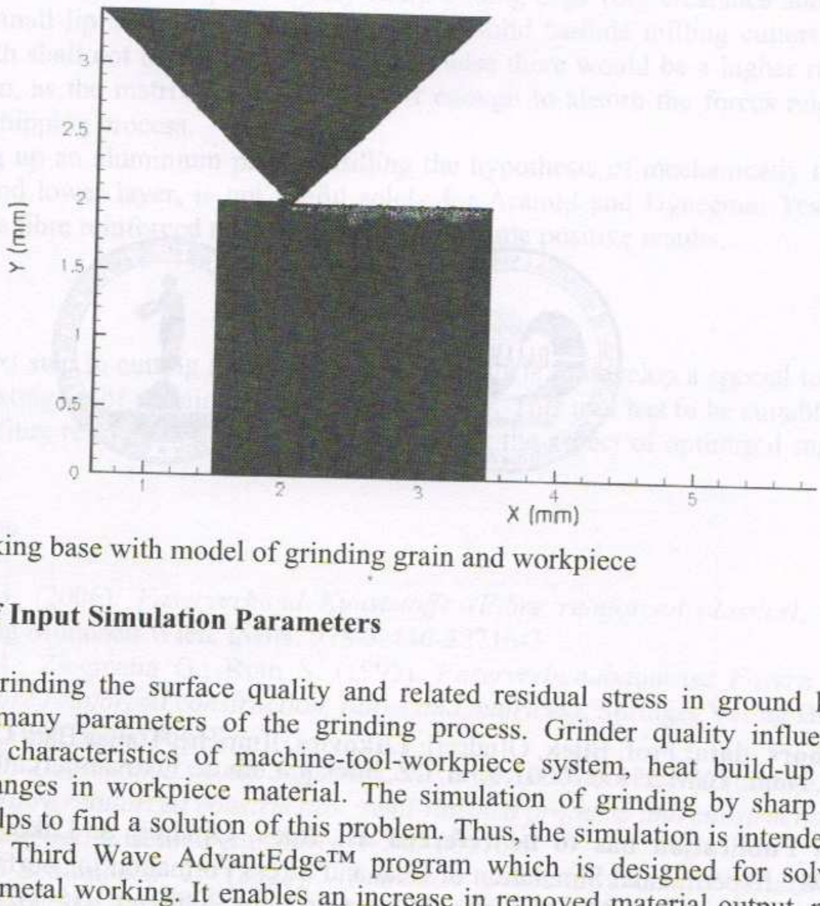


Fig. 1. Working base with model of grinding grain and workpiece

2. Setting of Input Simulation Parameters

After grinding the surface quality and related residual stress in ground layer depend on many parameters of the grinding process. Grinder quality influences deformation characteristics of machine-tool-workpiece system, heat build-up and resulting changes in workpiece material. The simulation of grinding by sharp and blunt tool helps to find a solution of this problem. Thus, the simulation is intended to work in the Third Wave AdvantEdge™ program which is designed for solving problems of metal working. It enables an increase in removed material output, parts quality and tool optimization without necessity of being physically tested. Although the program is mainly used for the simulation of milling, drilling and turning, it is also suitable for grinding when its limits are taken into account. Set parameters are shown in table 1.

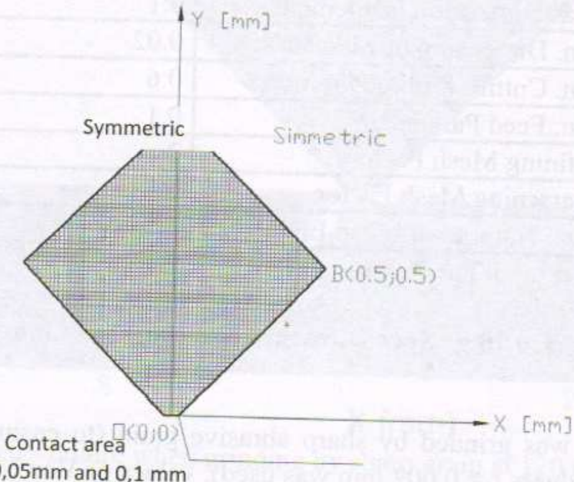


Fig. 2. Shape of worn grinding grain

The following simulation was done for optimal state of grinding by one grain. Dependence of deformation, stress and temperature on cutting speed was measured when grinding by sharp and blunt grain. Two possible ways of grinding by blunt grain (0.05 mm and 0.1 mm) were chosen, as well as cutting speeds 30, 60, and 120 m/s. Removed material output was 0.01 mm in all cases. Dulling of grinding grain was determined by a size of a contact area of the grain and material. Figure 2 shows the model for simulation by blunt grain. Workpiece material was chrome steel 100CrMn6 - (CSN 14 209). Length and height of the grinded area (in X direction) were 2 mm.

Workpiece characteristic	
Material	14 209 – 100CrMn6
Height X Length h x l [mm]	2 x 2
Tool	
Material	CBN
Rake Angle	45°
Relief Angle	45°
Cutting Edge Radius[mm]	0.002
Process Parameters	
Feed [mm/rev]	0.02
Cutting Depth [mm]	0.01
Cutting Speed [m/s]	30, 60, 120
Initial Temperature[°C]	20

Friction Coefficient	0.2
Simulation Parameters	
Method of Simulation	Rapid
Max. Dimension of Element	0.1
Min. Dimension of Element	0.02
Min. Cutting Curve Parameter	0.6
Min. Feed Parameter	0.1
Refining Mesh Factor	2
Coarsening Mesh Factor	6
Max. Number of Mesh Elements	12000

Tab. 1. Simulation Input Parameters

3. Influence of Cutting Speed when Grinding by One Grain on Tension Formation

If material was grinded by sharp abrasive grain (to ensure functioning of the simulation, roundness r = 0.002 mm was used), values of Von Misses stress were σ = 2407,43MPa for cutting speed v_c= 30 m/s and σ = 2332,3MPa for v_c= 60 m/s. As can be seen, there was a slight variation of the results. Values of the following parameters were: temperature of the workpiece and the tool, press of grinding, generated heat, shear stress and Von Misses stress. When simulating grinding by sharp grain at v_c= 120 m/s the software failed to determine the desired values. The volume model revealed consistency imperfection that resulted in crack – Fig.5. Although the simulation ran through, the data were inapplicable.

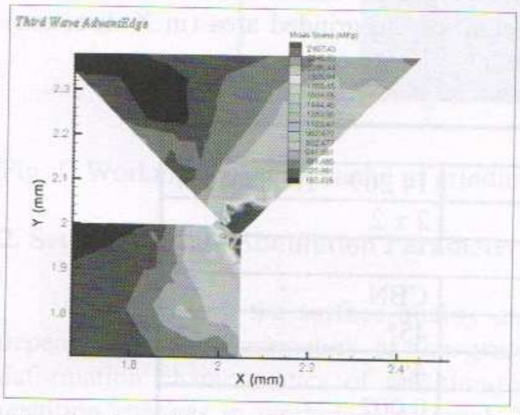


Fig. 3. Von Misses Stress gained from grinding by sharp grain at cutting speed 30 m/s

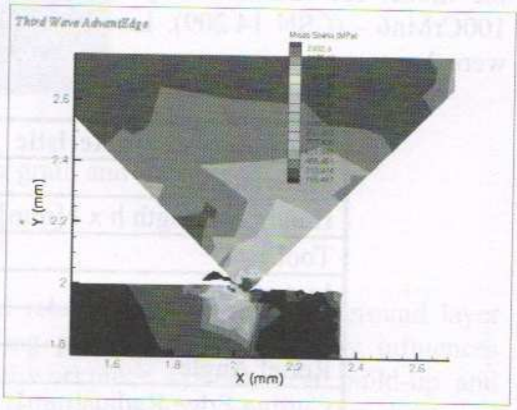


Fig. 4. Von Misses Stress gained from grinding by sharp grain at cutting speed 60 m/s

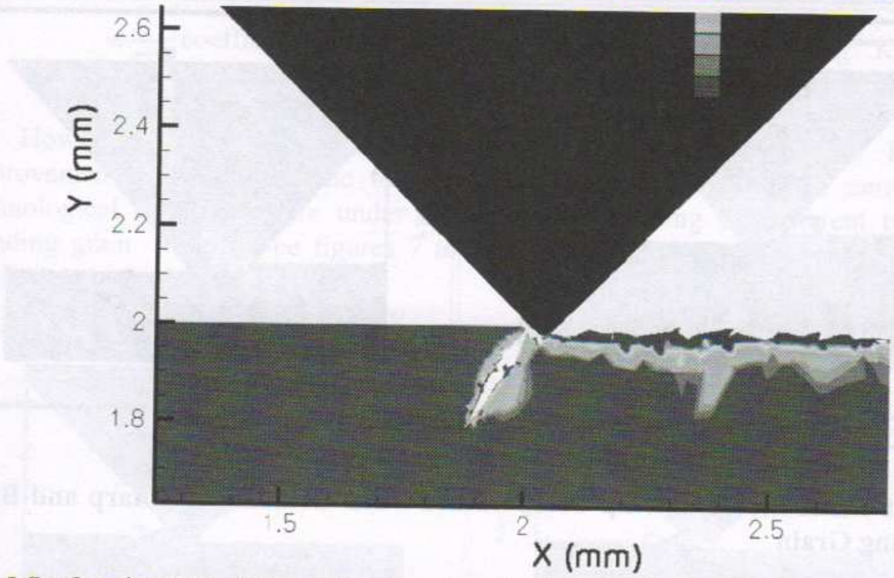
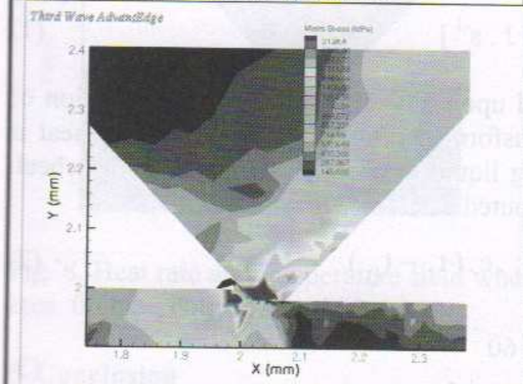
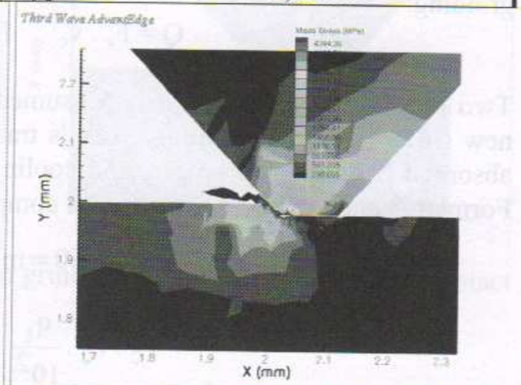


Fig. 5 Surface integrity failure when grinding by sharp grain at 120 m/s

Model also demonstrates that wear of grinding grain has increasing tendency with rising value of contact surface. As Fig. 6 shows Von Mises stress is twice larger in case of contact surface 0,1 mm compared to contact surface 0,05 mm. However, it is not evident, that blunt grinding grain causes grater stress generation. In relation to sharp grain model, stress values are the lowest when the grinding grain is blunt with contact surface equal to 0,05mm.

Type1 – contact area 0,05 mm	Type2 – contact area 0,1 mm
	

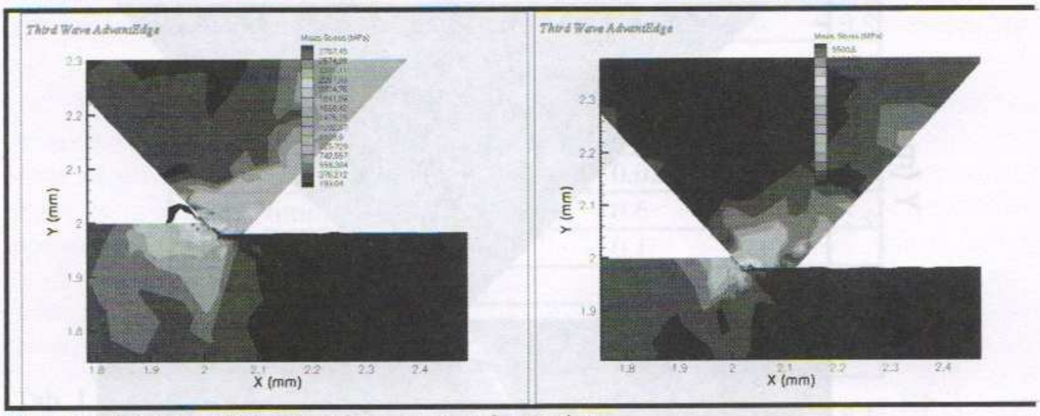


Fig. 6 Influence of blunt grain on stress formation

4. Heat Generation and Chip Temperature when Grinding by Sharp and Blunt Grinding Grain

Grinding is widely used method to finish surfaces- achieves proper dimension accuracy and quality of the surface. High temperature between grinding wheel and workpiece is generated while grinding. Established temperature field leads in outer layers of the surface to local plastic deformations. Temperature field can be the main reason of surface corruption. The transient temperatures generated while grinding by friction, implement residual stresses into the outer surface layers and moreover can lead to micro-cracks. Subsequently, workpiece with high ratio of surface/volume can be distorted as a whole. Not only dimension accuracy of the workpiece is disturbed, but also possible faze changes in surface layer can be observed. To eliminate this effect, mathematical equation is known to acquire the amount of arisen heat when grinding:

$$Q = F_c \cdot v_c \qquad [\,J \cdot s^{-1}\,] \tag{1}$$

Two percent of cutting work is consumed upon lattice deformation and creation of new surfaces; 98% of cutting work is transformed into heat. The amount of heat is absorbed by chips, workpiece, and cooling liquid (medium) and by grinding wheel. Formation and output of chips can be computed as:

$$Q = F_c \cdot v_c \cdot \frac{q_t}{10^2} \cdot 60 = m_t \cdot c \cdot (t_t - t_0) \tag{2}$$

$$t_t = \frac{F_c \cdot v_c \cdot \frac{q_t}{10^2} \cdot 60}{m_t \cdot c} + t_0 \tag{3}$$

Where:

F_c -	cutting force in the direction of main movement	[N]
v_c -	cutting speed	[m.s^{-1}]
q_t -	heat amount in the chips	[%]
m_t -	mass of chips	[kg.min^{-1}]

c - coefficient of heat capacity of workpiece [J.kg^{-1}.K^{-1}]
t_0 - ambient temperature [°K]

However, this requires the knowledge of grinding dynamics. Possible improvement was made in the following simulation. Workpiece, at same given technological condition were under simulation of grinding by different types of grinding grain. Results (see figures 7 to 8) show the heat rate and temperature of workpiece and grinded surface.

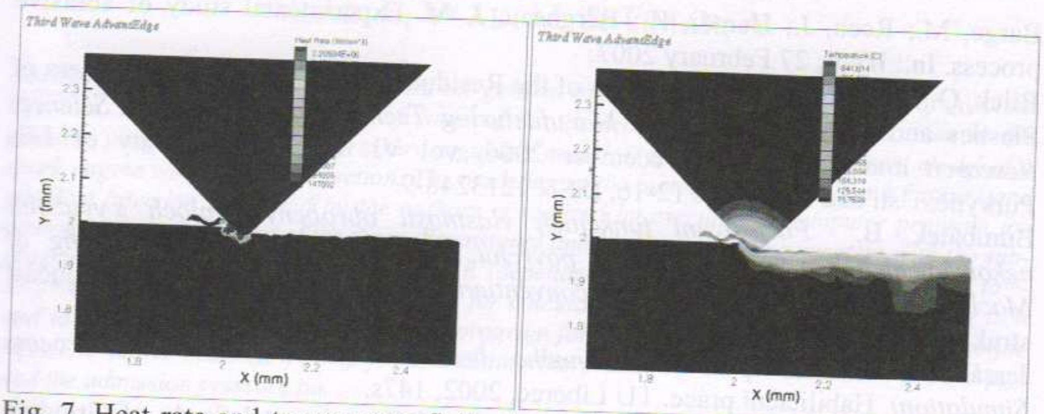


Fig. 7. Heat rate and temperature field when grinding by sharp grinding grain (r = 0,002mm; cutting speed 30 m/s)

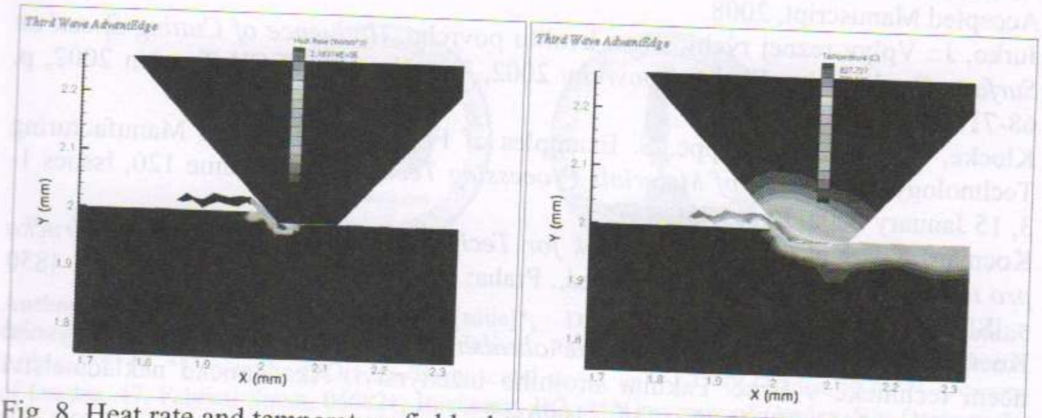


Fig. 8. Heat rate and temperature field when grinding by blunt grinding grain (contact area 0,1mm; cutting speed 30 m/s)

5. Conclusion

The aim of this paper was to create primary model further used for application in computer studies of conventional and high-speed grinding. Analytical methods nowadays cannot enlarge knowledge about this process. Its deep survey and understanding enables the further development of the new and optimization of the existing technologies. Both of them are necessary for preserving of competitiveness.

This study should be taken as a preliminary.

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FEM SIMULATION FOR IMPROVED GRINDING WHEELS

LUKOVICS, I. & BILEK, O.

Abstract: Article deals with behaviour of the grinding wheels within rotation. The main dependences of the grinding wheels on the physical and mechanical properties are investigated. State of stress simulation was prepared in the FEM solver Cosmos DesignStar. Moreover, results of high-speed grinding are shown in relation to the technological conditions upon the output grinding parameters.

Key words: FEM, Grinding, Critical Velocities, Simulation, Grinding Wheels

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1. Introduction

Rising the grinding speed up requires special demands on the grinding machine, and different grinding condition. One possibility to achieve high-speed of the grinding wheels is to reduce tensile stresses within rotation to ensure higher working life. The way, described in the article, change the shape of the grinding tool. Model of the wheel within the rotation was created.

Great importance in the manufacturing process has grinding, which except for traditional finishing cutting method becomes increasingly to the foreground as an alternative of other cutting methods. Besides common grinding method, its modifications such as high-speed grinding, in-depth grinding and efficient grinding have been used more widely. The high-speed grinding means grinding over commonly used cutting speed i. e. above 35 ms^{-1}. In-depth grinding is possible to characterize by withdrawing of the entire material allowance of one stroke (for example the whole depth of groove). Combination of high-speed and indepth grinding denote as efficient grinding. Integrated using of these methods means technological progress, which importance some researchers equate to implementation of sintered carbide in the early forties. (Jurko, 2005)

Conventional grinding uses cutting speed of 30-35 ms^{-1}. Increase of the cutting speed decreases the withdrawn chipping; i.e. it is possible to increase output – withdrawn amount – by increasing feeding rate or offset (Jersák, 2005). Results achieved at higher cutting speeds show influence of cutting speed on unit of the withdrawn amount of material in reference to finished surface quality and other parameters at Fig. 1. Diagram features changes in specific withdrawn amount of quenched material where providing constant normal component cutting resistance were preserved, i. e. invariable surface force affection providing compliance with constant roughness. Dependencies are exponential, thus they rationalized the use of the highest cutting speeds.

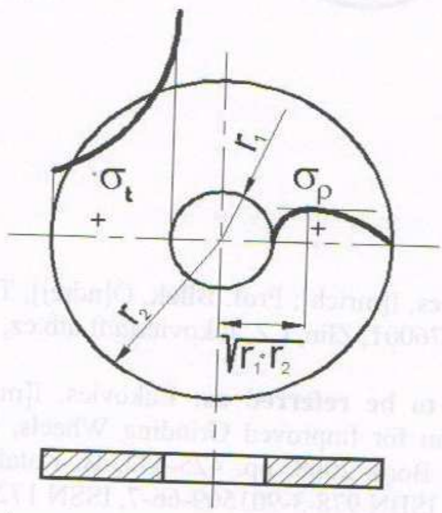

Fig. 1. Stress progression in rotating wheel

This endeavor roughness changes cutting speed – which is decreasing parabolic function as well as cutting force change, abrasion and residual tension dependences on cutting speed.

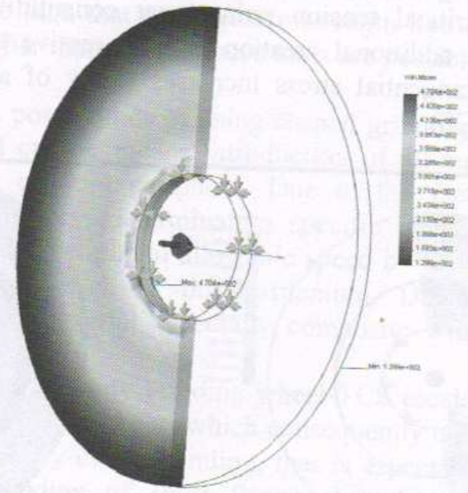

Fig. 2. Simple grinding wheel under circular speed $\omega = 2770\ ms^{-1}$

The disadvantage of increasing cutting speed is in quadratic growth of centrifugal force and appreciable development of heat inside of cutting areas related to the linear electric input growth and cutting speed. These facts demand splash proof machine, cooling system reconstruction and magnification of input driving mechanism of production facilities. One of the biggest problems of high-speed grinding is to guarantee safety of a grinding wheel. Research in this range guarantees new firm tool together with development of shaping grinding wheel.

2. Wheel Shape of the Homogenous Strength

Benefits of high-speed cutting require the use of formed disc and the application of special grinding materials. When determining individual stress component in rotating wheel we come out from applied equilibrium of internal forces acting mass element annulus shaped segment, delimitated of the main plane tension. After assessing equilibrium formula in axis of symmetry direction, neglecting differential term secondary and high-order, implementation of conditions of compatibility and providing the validity force of Hook's law for fragile grinding specimen, we obtain duration of stress.

Using conditions of uniform material grinding wheel utilization, that's provided that $\sigma_\rho = \sigma_\tau = \sigma_{Pt}$ and provided that border conditions are implemented. We obtain wheel shape variable in thickness, in the form:

$$b = b_2 \left[\exp \left(v_k^2 - v_\rho^2\right).\gamma / \left(2\ g\ \sigma_{Rt}\right)\right] \quad (1)$$

To form exponential variable width-shape wheel for experiments is, however, very sophisticated. Adjusting these tools when grinding would be difficult, inconvenient and unreal. From specific production compromise experiment has raised tool shape for high-speed grinding (Fig. 2). Experimental tools have cylindrical working part and critical tension point (near constitutive hole) bigger latitude. Because of possible additional creation of compressive tension tools, which at a superposition with tangential stress increases safety of a tool, they have tapered clamping surface (TCS).

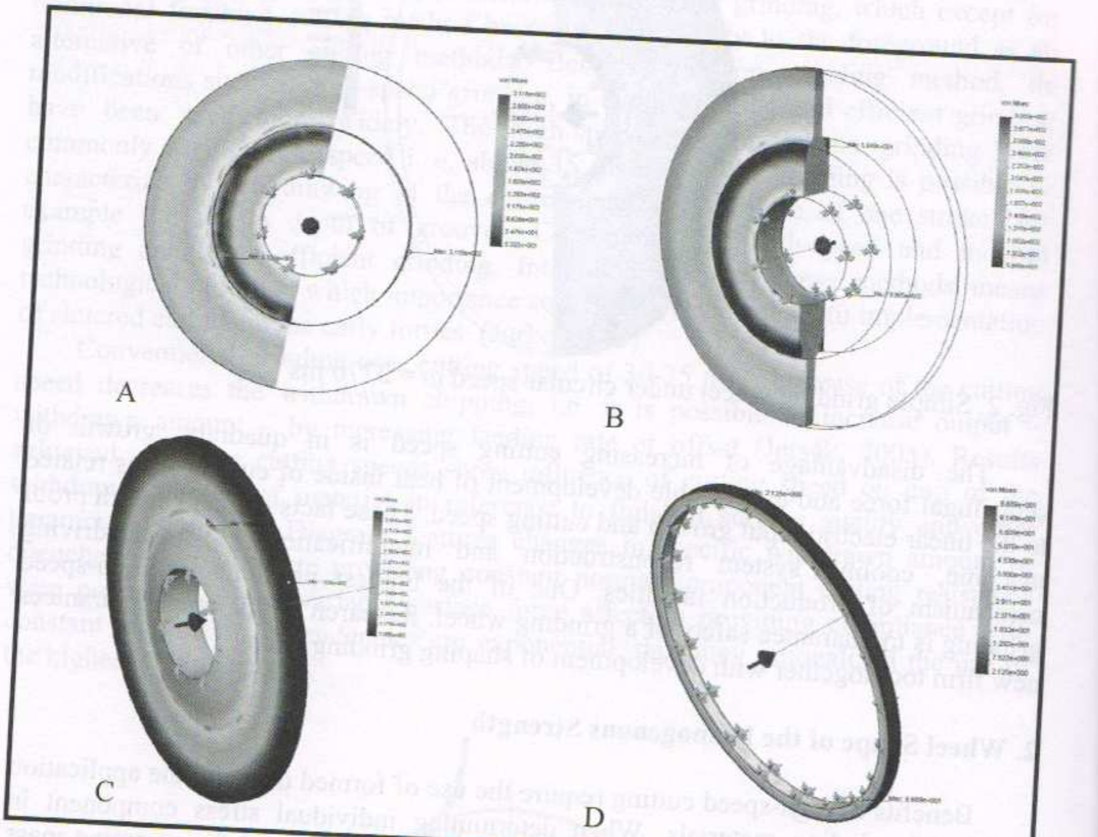

Fig. 3. Different types of grinding wheel subjected to the same circumferential speed

Results of accomplished shaped wheel experiments (TCS) show that for high-power grinding the usage of high hardness grinding tools and small size grinding grains is needed, which is in certain contradiction with requirements on maximum efficiency.

It is also shown, that increasing wheel width near hole markedly increases possibility of using this wheel for super-high-speed cutting. Tapered clamping part does not only increase safety factor (entrap appropriate biggest weight crack-up parts), but also markedly increases grinding wheel strength by subtracting compressive tension from tangential stress rising as a consequence of rotation.

From the aspect of strength in rotation tools without holes are beneficial. However; there are technical difficulties with clamping and accurate establishment of these wheels. Rotating wheel segments with taper clamping, where limitation element in tapered clamping flange is allowable compressive state of grinding material stress are preferable. Due to the fact, that compressive strength limit of grinding material can be up to six times higher than tensile, these tools are possible to use on markedly higher cutting speeds.

Evolutionary leap in possibilities of using shaped grinding wheels for grinding especially for high speed cutting means introduction of all-metal grinding wheels with thin abrasive layer on tool periphery. Due to the fact that in functional dependencies for state of stress determination specific weight of rotating wheel appear, it is possible to raise peripheral allowable speed by using metallic materials with lower specific weight such as dural, titanium. Discussions show wider possibility using polymeric material especially composite with kevlar or metallic fibers.

Certain possibility of a capacity grinding wheel TCS escalation increase offers increasing of vertex angle of tapered part which consequently call into existence new tooling method of so-called fly-cutter grinding, that is especially suitable for high-speed and high-power grinding of short flange shaped parts. Such a tool is advantageous in terms of safety, better possibilities of inlet ways of procedural liquid to the cutting place, cutting stability, chances of using grinding segment, etc.

3. Simulation

Calculated magnitude of critical velocity was used in computer simulation software (Cosmos DesignStar) to assume state of stress in the rotating wheel. A model was a wheel with hole, 250mm outer diameter, 76mm hole and thickness of the wheel was 10 mm. Steel was set up as a wheel material, details are shown in the Table 1. Type of the model: linear elastic – isotropic.

First approach was to create simple wheel of the homogenous material with hole. This solid model was then exposed to circular speed ($\omega = 2770\ ms^{-1}$), that is thought to be critical speed for steel material and shape. Results of the Von Mises stress of the simple wheel are shown in the figure 3. Can be seen highest stress located in the area of the hole. This relates to the theory, described before. Although, the maximum stress is 2 times lower than fracture limit of the steel, in some cases can lead to the rip of the wheel.

Description	Value	Units
Elastic modulus	2e+011	N/m^2
Poisson's ratio	0.28	NA
Shear modulus	7.7e+010	N/m^2
Mass density	7800	kg/m^3
Tensile strength	4.13613e+008	N/m^2
Compressive strength		N/m^2
Yield strength	1.72339e+008	N/m^2
Thermal expansion coefficient	1.1e-005	/Kelvin
Thermal conductivity	18	W/(m.K)
Specific heat	460	J/(kg.K)

Tab. 1. Material characteristics of the solid model

Ratio between the lowest and highest stress is vast, difference is 340,5 MPa. The way to reduce tensile stress in the model is to reshape that.

Secondly the model was created in order to lower the stresses. Regarding to theory and calculations, shape of the model has to be: large thickness closer to the hole of the wheel crossing to the standard thickness.

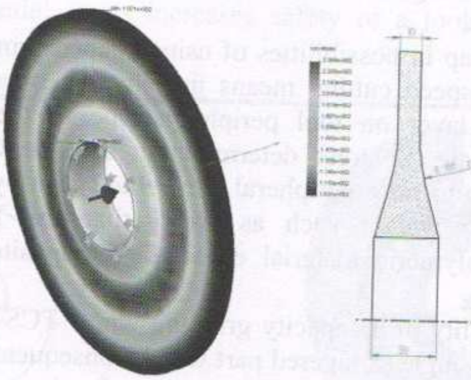

Fig. 4. Model of the quasi equal-strength wheel

Results of the simulation are shown in the Fig. 4. Tensile stress achieve at maximum 236,8 MPa and difference between low and high stress peak is 134,7 MPa. Setting up same simulation condition excepting shape of the wheel, gives better stress behaviour than simple wheel.

4. Results of Experimental High-Speed Grinding

High speed grinding is a special application of high speed cutting. Grinding is complicated process because a lot of variables are there. Conventional grinding (up to 35 ms^{-1}) has low productivity due to kinematics and strength limits of machine tool and grinding tools. The output of grinding, which can be characterized by material removal or area of tooled surface, could be increase by increasing of some technological conditions (it leads to higher power requirement). Material removal in case of grinding is directly proportional to cutting speed, in-feed velocity, peripheral velocity of workpiece etc. Another possibility is deep-depth grinding when the material removal is realized by one stroke of grinding wheel. As we noted above, the conventional grinding speed is currently about 35 ms^{-1}; higher speed leads to decreasing of chip thickness. Influence of cutting speed on some parameters of grinded surface is described in Fig. 5. It seems that high-velocity grinding is efficiency from point of view of productivity and also surface quality.

Combination of high-speed grinding and depth grinding could be call high power grinding. Surface roughness is very important parameter from point of view of such fundamental problems as friction, position accuracy, wear etc. Surface roughness as a function of cutting speed is shown in Fig. 4. Grinding as a finishing operation highly affects whole quality of machined parts. Especially in case of dynamic stress, where's dependence of residual stress on some technological conditions. It is clear that suitable residual stress distribution (compression stress) can be obtained by increase of feed, decreasing of specific wear or by application of new grinding materials such as CBN. Increasing of cutting speed leads also to very suitable surface quality. Experimental results were obtained on condition standard quality conservation.

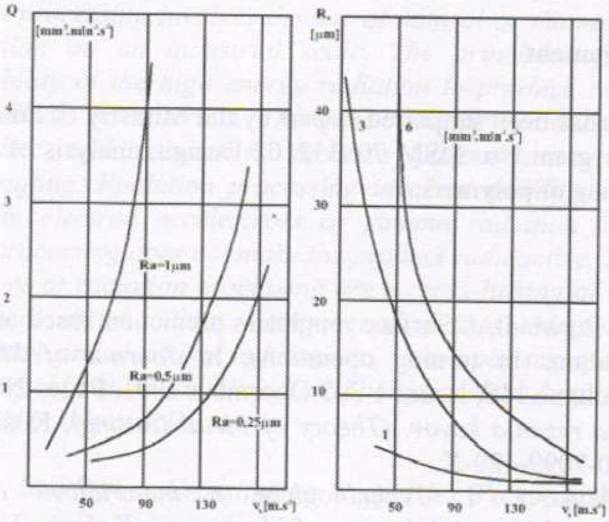

Fig. 5. Productivity, surface roughness and cutting forces under various condition when high-speed grinding

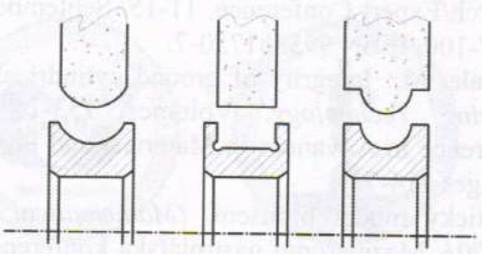

Fig 6. Examples of high power grinding in the production of technological devices

5. Conclusion

Analyses and results of experiments show possibilities of the escalation of tool strength under rotation by constructional adaptation of grinding wheel. The article mentions possibilities of the shape improvement and quality material for grinding, combining newly developed firmer adhesives, if needed all-metal grinding tools, enables safety application of cutting speed markedly excessing 100 ms^{-1} and thus, productivity improvement of grinding operation.

Interesting possibility of grinding wheels shaping for super-high-speed grinding is using of patented circular grinding. This method shows possibilities of marked tuning grinding. Engineering design arrangement on circular grinding allows relatively simple automation of the process with multiple productivity increases in elements for industry.

High speed and high power grinding upon grinding metals and plastics considerably improve accuracy and surface quality. Cutting forces are lowered, whereby the dimension stability of grinded products is better. Described technology allows higher quantity taken over thus can replacement of rough grinding.

6. Acknowledgement

This work has been supported in part by the Ministry of Education of the Czech Republic under grant No. MSM 708352102 Design, analysis of processes and tools for manufacturing of polymers.

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