Proceedings in Manufacturing Systems, Volume 6, Issue 2, 2011 ISSN 2067-9238

PHYSICO-CHEMICAL STATE STABILIZATION OF HIGH STRENGTH STEELS MACHINED SURFACE

Rozmarína DUBOVSKÁ[1,*], **Jozef MAJERÍK**[2], **Henrieta CHOCHLÍKOVÁ**[3]

1) Prof., Ing., DrSc., Professor, Department of technical subjects, University of Hradec Kralove, Czech republic
2) Ing., PhD., Lecturer, Department of technical subjects, University of Hradec Kralove, Czech republic
3) Ing., PhD Student, Department of technical subjects, University of Hradec Kralove, Czech republic

Abstract: *The aim of this contribution was to assess the impact of cutting speed in grinding quality of the test samples surface layer of heat-and chemically processed steel. To fulfil these objectives experimental and computational methods have been achieved, including statistical evaluation. Technology grinding was performed without cooling recess manner. The grinding wheels-porous A9980K9V and A9980K13V were used. As machined materials the followings were selected: tool steel 19436.4, cemented and hardened steel 14109.4 and 16420.4. The steel hardness is in the range of* $HRC = 61 \div 62$*. The work follows the qualitative indicators to assess the integrity of the most common finished surfaces. These characteristics create conditions for influencing the fatigue strength, wear, corrosion stability, and quality.*

Key words: *speed grinding, surface integrity, porosity, microgeometry, microhardness and surface hardening, microstructure, cutting forces.*

1. INTRODUCTION

Grinding is characterized mainly by its machining capabilities expressed for a number of material, taken per time unit and by achieving high quality surface. Due to the layout and operation conditions of grinding, it is a very complex process. Therefore, the increase of efficiency eventually together with optimization of grinding is not an easy task. It requires the assessment and improvement not only of individual articles of the operation, but also of their interaction on the final result [3 and 4].

At present, there was a great boom in the grinding process, particularly regarding the speed. The complexity of the grinding process and a large number of input parameters of the cutting tool and grinding wheel influenced the theoretical and experimental study of significant problems. Research requires not only the use of new cutting materials, tools and new methods, but also consistent automation, safety and greening in machining. The conventional method of grinding begins slowly o be replaced by speed grinding way. Speed grinding can be considered for a grinding cutting speed of 35 ms^{-1}. Slovakia is currently in an early stage of development and thus, of course, of usage.

Another big important factor is the grinding wheel. The idea of seeking estate prices and high quality grinding wheels (diamond and CBN grinding wheels), which are now produced by foreign companies is not exactly what is needed. Therefore, we seek "compensation", which is financially far more acceptable in the field of application.

Finally, the efforts to complete the concept of quality of the surface layer (surface integrity) are starting materialized only in recent decades. It is based on technological processes and their effect on the depth and distortion of the surface layer of the workpiece. Extensive application possibilities of grinding can be split by fields of application, e.g. production of automobiles, turbines, bearings, instruments and so on, by the type of grinding process, for example, cylindrical grinding inner and outer, surface grinding and so on, and type of technology, for example plunge, with the reciprocating shift etc. Implementation of each operation requires a corresponding grinding tool – grinding wheel, grinding machine, ensuring dressing systems, cooling/lubrication and technological conditions that ensure compliance with user requirements. Development of methods of grinding is to be viewed comprehensively connected to the requirements of the finished surface (dimensional and shape accuracy, surface finish), although often it responds to the challenges of a production area.

2. HIGH STRENGTH STEELS

Fundamental importance of using steels with high strength lies in reducing the stressed part bearing sections and reducing the total weight of machinery and structures. Reducing the load-bearing sections is limited by the requirement of sufficient rigidity of bodies. The basic characteristics for the assessment of materials with high strength can be considered as absolute values R_{p0} R_m, 2, and also as a basic criterion, the value of ratio $R_{p0,\,2} / E$, which is the rigidity of the body taken into account. Materials with a value $R_{p0,\,2} / E > 1 / 150$ are high strength materials, which are often called super-materials [5].

---

[*] Rozmarina Dubovska: Rokitanského 62, 500 03, Hradec Králové,
Tel.: (+420) 49 333 1135
Fax: (+420) 49 333 1135
E-mail addresses: *rozmarin.dubovska@uhk.cz* (R. Dubovská), *jozefmajerik@yahoo.com* (J. Majerík), *henrieta.chochlikova@gmail.com* (H. Chochlíková)

The demanding for cyclically loaded machine parts, which are also reflected in significant loads as centrifugal and inertia forces, another criterion value ratio $R_{p0,2}$ / ρ (ρ – density) is considered. The maximum value of this ratio is an important material requirement, being required the lowest mass structure (aircraft, etc.).

The development of advanced technology associated immediately with the development and use of new metallic materials, which have special properties, e.g. wear resistance to high temperature, high strength and durability in aggressive environments. It is known that the improvements in the properties of metallic materials are usually worse regarding the technological properties. To reduce the difficulties associated with making components from these materials, the engineers need to develop new technological processes.

Machining, however, still remains the primary method for effective production of parts made of such materials. The principal cause of poor machinability (in this case it is characterized by cutting machinability rate that corresponds to a defined tool life in machining with a defined cross section of chip and optimal design of the cutting edge on the workpiece) it is the difficulty to machine steels and alloys due to generation of considerable forces and temperatures in the cutting zone [4 and 5].

3. PLANAR TECHNOLOGY OF GRINDING

Grinding is mainly used for machining parts with higher requirements for shape and dimensional accuracy and surface quality. With the development of efficient grinding wheels and grinding machines, the importance of extending is the original field of finishing and machining to production machining. Grinding is characterized by specific conditions of chip formation and machined surface. As a result of large plastic deformation and the external and internal friction is a part of the chip is heated enough to melt metal and create droplets, or burn ed (arcing). Individual abrasive grains have an irregular geometric shape, high hardness, temperature resistance, irregular cutting edge radius r_n of a few thousandths of a millimetre. Abrasive grains generally have a negative angle γ_n front and back relatively large angle α_n. As the cutting speed in grinding is considered the peripheral speed of grinding wheel, which is given to other methods of machining, it is relatively high.

The grain size and hardness of the grinding tool are chosen according to the size of contact surface between wheel and workpiece. Generally, the larger the contact surface is, the grinding wheel has to be softer and thicker [3].

3.1. Experimental sample preparation

Peripheral grinding wheel speed is chosen:

- in tough materials from 25 to 32 ms^{-1};
- for brittle materials from 18 to 25 ms^{-1}.

For the plane grinding wheel circumference the cutting conditions are selected from Tables 1 and 2 according to the type of disc.

For the grinding test samples a surface grinder BRH 20.03 F (Fig. 1), which is a planar type grinders with horizontal spindle and rectangular desk.

Table 1

The choice of material for planar grinding wheel circumference

Grinded material	Grinding wheel quality
steel soft carbon, hardened	A 99 40-32 I-K V
hardened carbon and alloy	A 98, A 99 40-25 I-K V A 99 40 J 13 V
High-speed soft	A 99 40-32 I-K V
Hardened high-speed	A 98, A 99 40-32 H-J V
Corrosion resistant	A 99 40-25 H-J V

Table 2

Specified cutting conditions for planar grinding wheel circumference

Longitudinal reciprocating table:	
mild steel	10 to 18 m.min^{-1}
hardened steel	8 to 12 m.min^{-1}
cast iron	10 to 15 m.min^{-1}
Transverse feed motion:	
for roughing grinding	2/3 to 4/5 wheel width
for finishing grinding	1/2 to2/3 wheel width
especially for fine grinding	1/10 to 1/5 wheel width
Infeed for stroke:	
for roughing grinding	0.015 to 0.040 mm
for finishing grinding	0.005 to 0.015 mm
Circular movement of table:	
Peripheral speed of the roughing grinding	20 to 60 m.min^{-1}
Peripheral speed of the finishing grinding	40 to 60 m.min^{-1}
Infeed for stroke:	
for roughing grinding	0.005 to 0.015 mm
for finishing grinding	0.005 to 0.010 mm

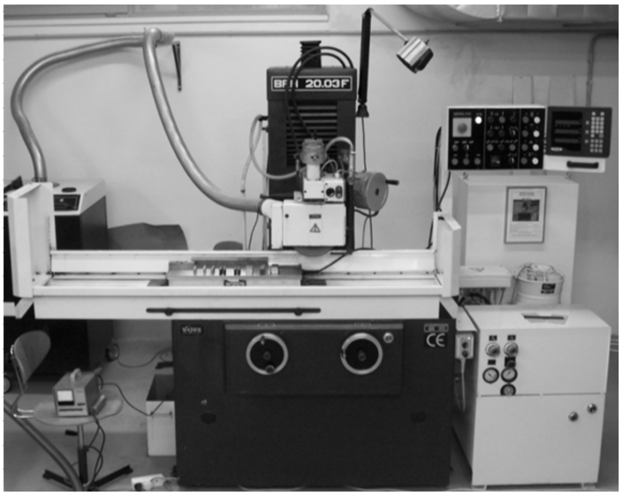

Fig. 1. Grinding machine BRH 20.03 F (FT UTB Zlín Department machining).

They are designed for sanding flat and contoured surfaces of parts made of steel, iron and other metallic materials, which are required to achieve high quality and precision machining. Sharpening (dressing) is mostly made in grinding wheel circumference. Samples can be machined by grinding because of their shape, being clamped directly to the electromagnetic plate or through suitable clamps to the base table. 20.03 F grinders operate in a closed automatic working cycle. To control the automatic cycle, the machine includes a digital indication FAGOR NV 300E company, which serves to track vertical and lateral displacement at work in manual mode. The management of vertical displacement is in automatic cycle.

Technical parameters of the machine tool are:

- Working surface: 200 × 630 mm.
- Dimensions of grinding wheel: ∅250 × 20 – ∅50 × 76 mm.
- Infinitely speed adjustment: 1 to 30 m. min^{-1}.
- Maximum grinding spindle speed: 2 550 min^{-1}.

In the process of experiments we used two types of grinding wheels-type A99 K80 9V and 13V with dimensions of 250 × 76 × 10. It is an electro corundum grinding wheel with ceramic binder with difference in porosity. Samples used were made of steel 14 109.4, 16 420.4 and 19 436.4. Each of these samples was drawn to size 50 × 50 × 8 mm. Sample preparation was carried out in the company Ltd KONSTRUKTA Industry Trencin, and the grinding of samples, measurement and evaluation of cutting force components at TBU Faculty of Technology. Selected types of grinding wheels from Best Companies Ltd Kunštát Morava were used.

Fig. 2. Surface grinding of the sample circuit blade clamped in a two-component strain-gauge dynamometer.

Fig. 3. Replacement of the A99 K80 9V OPEN F 20.03 grinding wheel in the process of experimentation.

Steels were chosen for their inferior (low) grade of grinding machinability in order to verify the expected decreases of cutting force components in grinding with high porosity abrasive wheel.

Steel 14 109 belongs to a group of steels for the manufacture of rolling bearings. It contains about 1.0% C, 0.8 to 1.6% Cr and about 1% Mn to enhance hardening penetration. It is characterized by high hardness, wear resistance and high compressive strength [3].

Steel 16 420 contains 0.14% C, 0.27% Si, 0.75% Cr and 3.7% Ni. It is characterized by good formability as well as heat and good machinability in considered conditions. It is suitable for the production of highly loaded machine parts, which are subject of hardening and hardening to high strength and toughness up to the core, namely shafts and gears [3 and 4].

Steel 19 436 belongs to the alloy – chrome tool steel. It contains 1.80 to 2.05% C, then 0.20 to 0.45% Mn, 0.20 to 0.45% Si and 11.0 to 12.5% Cr. The properties of this steel are as follows: very high compressive strength, low toughness, good dimensional stability during heat treatment. This steel is used for highly stressed and difficult to shape tools, shaping tools and cutting tools for example broaching or extrusion mandrels, knives, cutters for lower cutting speeds, etc. [5].

4. MEASUREMENT OF THE CUTTING FORCES IN GRINDING

When operating with the grinding abrasive wheel, cutting and centrifugal forces occur. Since the cutting forces are small due to centrifugal forces, when considering the strength of the grinding wheel they are neglected. The process component operates as the resultant force F, which is the sum of the elemental forces of individual grains. It is decomposed into three components:

- tangential force F_c;
- radial force F_p;
- axial force F_f.

These components are used to calculate:

- power to the wheel spindle and workpiece (force F_c);
- stiffness of the machine system – workpiece – tool, precision machining (force F_p);
- the power stroke (force F_f).

Since the abrasive grains have negative face angles, we can assume that the cutting force F_p will always be greater than the force F_c. Experimental measurements confirm that the radial force F_p is about 1.5 to 3 times larger than cutting force F_c. Force F_f is quite a little bit smaller than the force F_c. It is considered that the cutting force in grinding is the sum of elementary forces exerted on the material by the individual abrasive grains. Individual grains extend to different depths, elemental forces are therefore substantially different.

The cross-section area has a complex shape, unlike the cutting tools with defined geometry. It is possible to determine the analytical calculation of cutting forces in grinding. We start from identifying the actual cross-cutting of one layer by the abrasive grain S_z spanning the same number of grains in the desired depth of cut, etc., grain size and structure of the disc. The measurement of cutting forces in grinding was done on two-component strain-gauge dynamometer (Fig. 4).

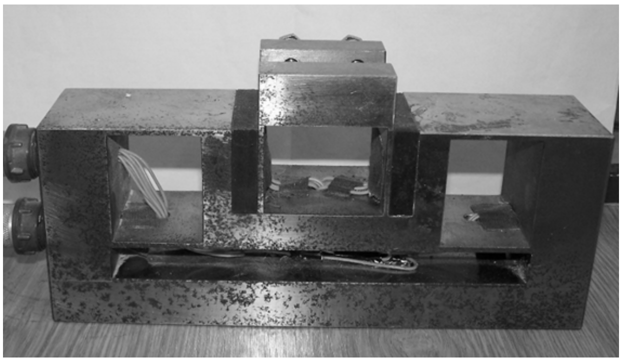

Fig. 4. Two-component strain gauge dynamometer validating the tangential and radial component of the resultant cutting force.

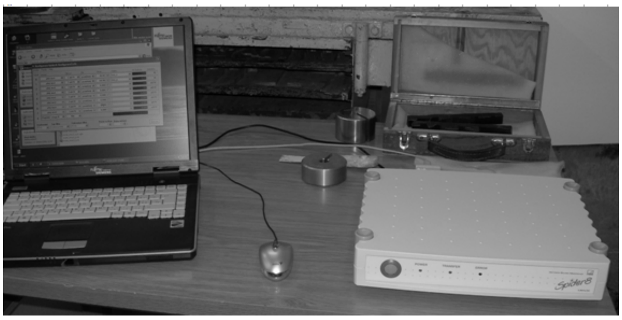

Fig. 5. Measuring device for cutting forces in machining type Conmes Spider along with evaluation software and PC components of cutting forces depending on cutting parameters.

This device was mounted on a desktop machine and test specimens of hardened steel were clamped. The dynamometer was connected by wires to the measuring system Conmes Spider, who was connected to a PC (Fig. 5), where the registration and evaluation of measured data were achieved.

5. RESULTS AND EVALUATION

The measurements were performed on the presented surface grinder. Regarding the technological conditions of plane grinding for the experimental measurement of cutting forces, we opted for the normal conditions used in practice. For all three types of steel they were the same (foe a easier processing)), namely the cutting depth a_p and feeding speed v_f:

- a_p = 0.01, 0.02, 0.03, 0.04 mm;
- v_f = 7, 12.5, 16.5, 23.5 m.min^{-1}.

For example, for the traverse speed of 7 m.min^{-1}, we changed the depth of cut a_p = 0.01 to a_p = 0.04, doing this for all four traverse speed.

From Figs. 6 and 7 to see at the depth of cut a_p = 0.03 mm the decrease in cutting forces for the wheel A99 80K 13 V (Fig. 7), while for steel 14 109.4 it occurs almost linear to the curve for both curves (Figs. 6 and 7). Steel 16 420.4 also has a linear shape of both curves, the decrease of cutting forces (F_p), about 8N. Curves for steel 19 436.4 are of square (Fig. 6) and logarithmic (Fig. 7) shape with a strong decline of about 20 N. Size of cutting forces (Figs. 8 and 9) (F_p) for a depth of cut 0.04 mm for steel 14 109.4 is nearly the same for both grinding wheels. An accentuateed force decrease in high porosity grinding wheel is seen for steels 16 420.4 and 19 436.4.

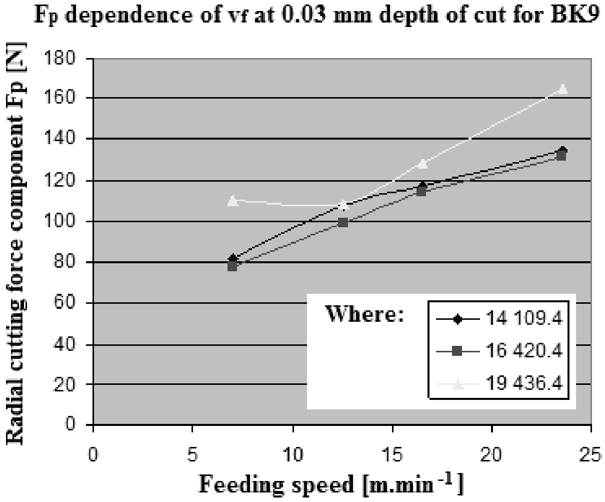

Fig. 6. Graphic representation of the radial component of cutting force *Fp* depending on the traverse speed.

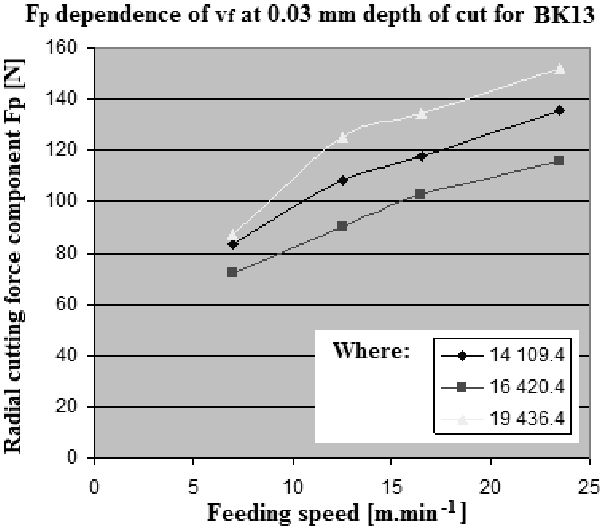

Fig. 7. Graphic representation of the radial component of cutting force *Fp* depending on the traverse feeding speed.

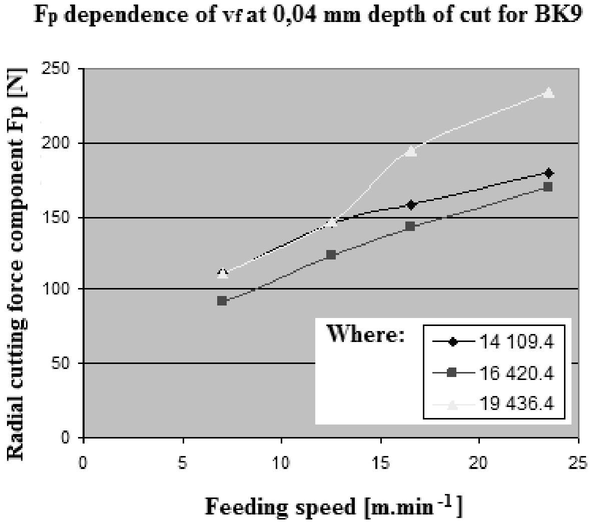

Fig. 8. Graphic representation of the radial component of cutting force *Fp* depending on the traverse feeding speed v_f measured in [mm.min^{-1}].

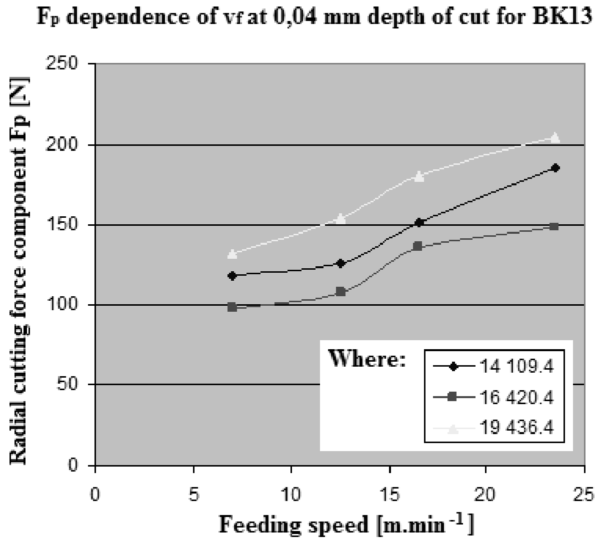

Fig. 9. Graphic representation of the radial component of cutting force *Fp* depending on the traverse feeding speed v_f.

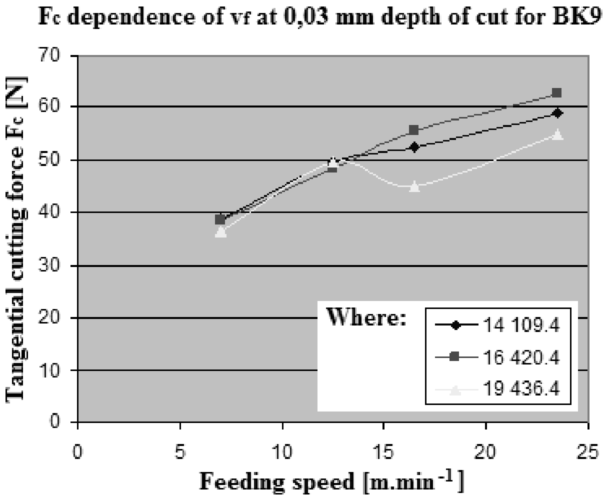

Fig. 10. Graphic representation of the tangential component of cutting force *Fc* depending on the traverse feeding speed.

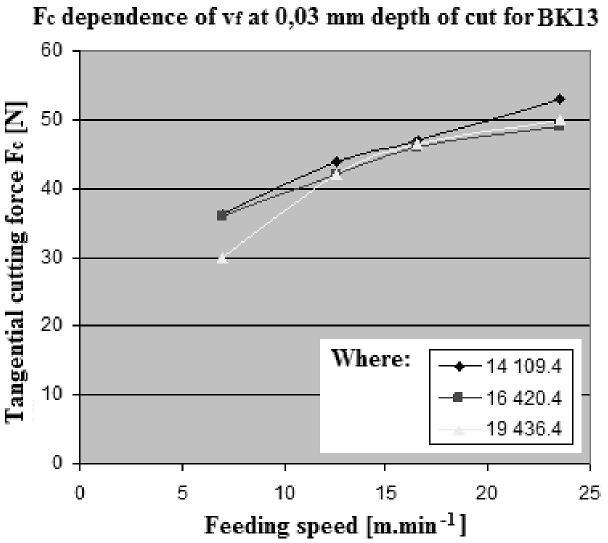

Fig. 11. Graphic representation of the tangential component of cutting force *Fc* depending on the traverse feeding speed.

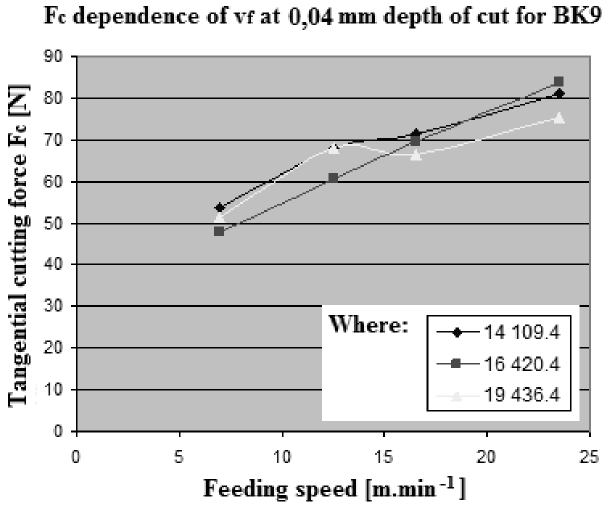

Fig. 12. Graphic representation of the tangential component of cutting force *Fc* depending on the traverse feeding speed.

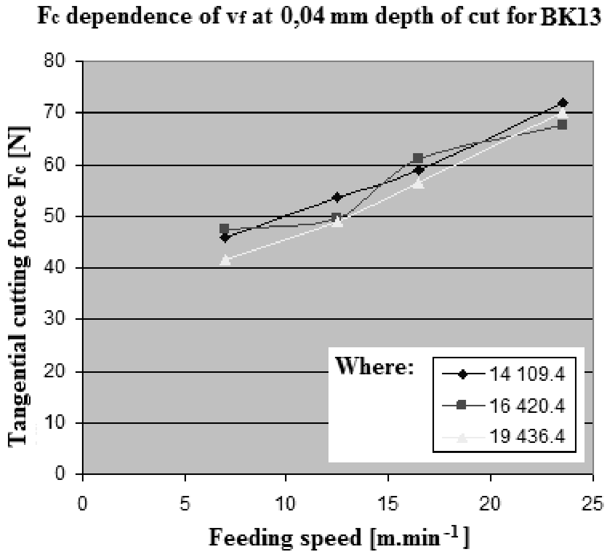

Fig. 13. Graphic representation of the tangential component of cutting force *Fc* depending on the traverse feeding speed.

The size difference between the tangential component of cutting force F_c (Figs. 10 and 11) at 0.03 mm depth of cut is noticeable when comparing the graphs (Figs. 10 and 11). Radial component of cutting force exhibits the lowest values for steel 16 420.4 for the four dependences (Figs. 6, 7, 8, and 9) which can also be caused by higher content of nickel (Ni = 3.7%). Conversely, the steel 19 436.4 shows the highest values of cutting force (F_p) due to the high content of chromium (Cr = 12.5%) and carbon (C = 2%), what it is seen in the steel 14 109.4 [1].

It is interesting to 19 436.4 high speed steel that the radial component of cutting force (Figs. 6, 7, 8, 9, 10, 11, 12, and 13) is the largest one compared with other steels, since the tangential component is the smallest.

In Figs. 14 and 15 the records from the monitor of measuring device SPIDER 8 are shown, where for the sample measured field (50 mm) there is a high shear strength at the initial contact with the grinding wheel of cropped area. In a further stroke there is a significant decrease in cutting forces (result of sharpening [2]).

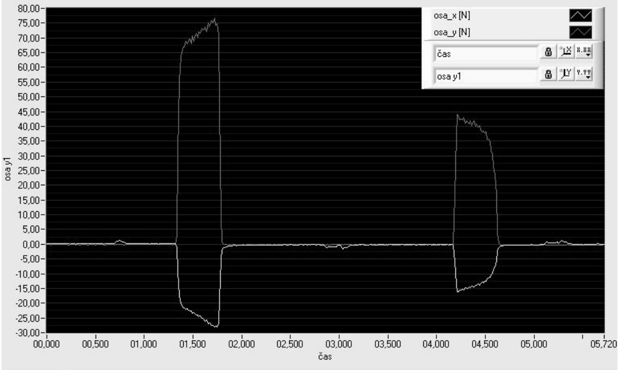

Fig. 14. Chart of cutting forces for ground steel 19 436.4 9, disc displacement at 7 and depth of cut 0.02 mm.

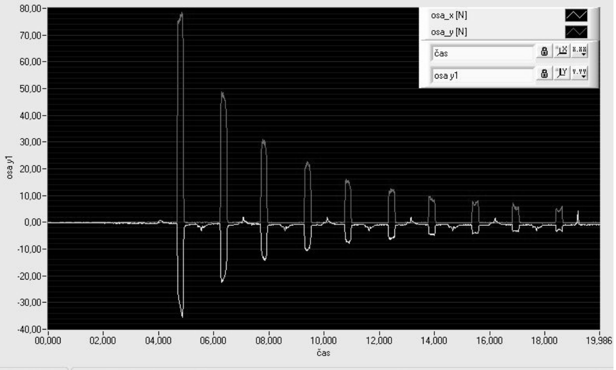

Fig. 15. Chart of cutting forces for ground steel 14 109.4 9, disc displacement at 12.5 and 0.02 mm depth of cut.

5.1. Creation of mathematical model of measured values of cutting forces in a plane grinding

In developing a mathematical model based on the readings, we have several options. The choice always depends on the shape and structure of the processed file i.e. the number of input parameters to their direct, respectively, indirect dependencies. In seeking to manage between several variables as in this case, it can be very difficult to estimate the form of the model and therefore the methods such as the method of least squares and minimax method. For this reason, we have to estimate the chosen mathematical model by using a combination of two statistical methods, namely "Monte Carlo" [1] and point estimators [2]. As model formula we used [1]

$$F_c = C_p v_s^{0,7} f^{0,7} a_p^{0,6}. \tag{1}$$

We decided to create a model in the form:

$$F_c = pC_p v_c^{\alpha} v_f^{\alpha} a_p^{x}. \tag{2}$$

We identified the material constant for the sharpening for a particular material. For example, for the material 16 420.4, as well as for other materials, we used concrete chemical composition and hardness of steel, 16 420.4 steel has a hardness after hardening about 62 HRC, which is about 745HV. Constantly, we get multiple constants of chemical composition and constant hardness K_{chs2} and K_{mh}. For steel 16 420.4 we got $C_p = 13.73$ [1].

The coefficient α was gradually chosen 0.2, 0.3, to 0.8, 0.9 in the Eq. (3) to get a solid set of possible outputs

$$x = \log_{a_p} \frac{F_c}{pC_p v_c^{\alpha} v_f^{\alpha}}. \tag{3}$$

We designed this method of parameter estimation and calculated the standard deviation. We considered that it is an acceptable model, where the standard deviation is the smallest. The situation in the porosity of disc occurred for a cutting depth of 9 mm, thus the model we adopted for this situation is:

$$F_c = 53{,}245 C_p v_f^{0,5}. \tag{4}$$

Two-component strain gauge dynamometer was calibrated to a value of 9.81 N on a mass of 1 kg. When the components of cutting forces are measured, the measurement error must be taken into account. Readings at various depths of cut depending on changing traverse rate raise almost linearly. While our main aim is to experimentally demonstrate, then to calculate (the creation of a mathematical model) that the cutting force components decrease in porous discs. The expected experimental and simulation aim has been to prove that the main cause for this decrease of cutting forces is a better heat dissipation in the cutting zone.

6. CONCLUSIONS

The work deals with grinding hardened steel 14 109.4, 16 420.4 and 19 436.4, and measuring cutting forces by changing the depth of cut and speed. The experiment revealed a visible impact of the workpiece material properties on the structure of the grinding wheel and also of the technological conditions on the final size of the cutting forces. Overall, the larger the depth of cut material and also feed rate, the higher the value of the cutting forces. Also, the conducted experiment shows that with the increasing depth of cut also the values of the axial component of cutting force F_p and the tangential component of F_c increase in all species of studied steels. In addition, all these are confirmed by the fact that there is a decrease of cutting forces in grinding with high porous grinding wheel, unlike the disc with a lower degree of porosity. This is due to a smaller number of active grains, better heat dissipation from the point of cutting zone and better chips because of higher porosity disc (higher unit volume = cutting more dissipated material).

REFERENCES

[1] S. Bajčík, *Stabilizácia fyzikálno-chemického stavu obrobených povrchov vysokopevných ocelí* (The stabilization of the physico-chemical state of the machined surfaces of high strength steel), Dissertation work, 2008, p. 132, FST TnUAD, Trenčín.

[2] S. Bajčík, J. Majerík, *Porovnanie elektrokorundových brúsnych kotúčov pri experimentálnom meraní rezných síl* (Comparison of electro-corundum grinding wheels with experimental measurements of cutting forces), Nové smery vo výrobných technológiách, pp. 190–200, June 2008, TU FVT, Prešov.

[3] J. Majerík, *Verification and possibility of grinding replacement the hard turning in terms of surface integrity,* Dissertation work, 2004 p. 136, FST TnUAD, Trenčín.

[4] J. Majerík, *Náhrada brúsenia kalených ocelí tvrdým sústružením* (Replacement of hard turning by grinding of hardened steel), Mechanical Engineering Journal, Vol.XII, No.5, 2008, pp.170–171.

[5] J. Šandora, J. Majerík, M. Martišková, *Hard machining and machined surface integrity,* pp. 33-37, september 2005, VŠB TU, Ostrava.