

Szent István University

**ZIRCONIUM-DIOXIDE CERAMICS
TURNING**

Thesis of the doctoral (Ph.D) dissertation

Gellért Fledrich

Gödöllő
2011

The doctor's school:

designation: **Mechanical Engineering PhD School**

discipline: **Agricultural Technical Science**

head of school: **Dr. István Farkas**
professor, DSc
Szent István University,
Faculty of Mechanical Engineering

Supervisor: **Dr. István Pálincás**
professor, CSc
Szent István University,
Faculty of Mechanical Engineering,
Institute for Mechanical Engineering Technology

Co- supervisor: **Dr. habil. László Jánosi**
professor, CSc
Szent István University,
Faculty of Mechanical Engineering,
Institute for Mechanical Engineering Technology

.....
Approved by head of school

.....
Approved by supervisors

CONTENT

1. INTRODUCTION, OBJECTS	5
1.1. Actuality of the theme.....	5
1.2 The aim and tasks of the research work.....	5
2. MATERIAL AND METHOD.....	7
2.1. The materials tested	7
2.2. Cutting tests.....	8
2.3. Surface topographical tests	8
2.4. Friction tests.....	8
2.5. Complementary tests with thermo-camera	8
3. RESULTS	9
3.1. Results of cutting tests	9
3.1.1. Cutting tests results of ceramic	9
3.1.2. Cutting test results of lamellar cast iron	12
3.1.3. Cutting test results of globular cast iron	13
3.1.4. Edge test results of the cutting tool.....	13
3.2. Determining the cutting force in the function of parameters	14
3.3. Results of topographic surface tests.....	15
3.3.1. Results of microscopic examinations and 3D-al topographic surface tests	15
4. NEW SCIENTIFIC RESULTS.....	21
5. CONCLUSIONS, SUGGESTIONS.....	23
6. SUMMARY	24
7. PUBLICATIONS IN CONNECTION WITH THE THEME OF DOCTORAL DISSERTATION	25

1. INTRODUCTION, OBJECTS

1.1. Actuality of the theme

The engineering ceramics are such constructional materials which can be used at essentially higher temperature comparing to materials used till now, at under heavy physical and chemical load.

The claim to structural ceramics is continuously increases with the development of the industry and they can get important part just in this segment. The zirconium-dioxide is also such material. At long-term it is predicted to establish computer directed material structure starting from atomic level and to establish the conditions of product manufacturing. The development of manufacturing finished – and intermediate products claim the cutting of more and more complex surfaces. The more economical machining of spatial surfaces claims the further development of tools with regular edge. The zirconium-dioxide as basic material having lower hardness and other characteristics is suitable to machine by tool with regular edge, so in case of piece production or in case of small and medium series manufacturing, at quick prototype-manufacturing it can become potential material alike. Its cutting and machinability characteristics has to be known that this could be ensue. My research work concentrates to one part of this, in accordance with the recommendation of a company producing and developing zirconium-dioxide semi-finished product.

1.2 The aim and tasks of the research work

Greater material removal capacity can be reached by tools with regular edge than by grinding mainly in case of more complicated surfaces. The advantages can be perceptible in case of hole machining in particular. It can be established that the turning tool is significantly more rigid because of geometric dimensions if it is compared with the grinding tool. Because of smaller surface in contact the perpendicular force component is also significantly smaller. To utilize these advantages happens as expedient. The researches however are in the starting stage concerning this. The sources of literature provide minimal reference to the machining with turning of ceramics, thus to the zirconium-dioxide and to the aluminium-oxide. Nowadays the grinding is the machining after the generally wide-spread sintering.

Main chapters of realizing my research work:

- Based on the literature survey – as cutting data are at disposal limited – my object was the cutting of zirconium-oxide ceramic by tool with the regular edge-geometry. During machining I have set to reach the following aims:
- Testing the cutting characteristics of the engineering ceramic occurring in my tests in case of machining by single-point cutting tool at turning.
- Developing measuring system to measure the main – and feed rate direction forces during cutting.
- Topographic test of surfaces after machining with cutting parameters set. Analysing the micro-cracks formed possibly on the surface and the shell – like pittings.
- Examining the heat affected zone arising during cutting.
- Comparing the cutting characteristics of ceramic with the cutting characteristics of lamellar – and globular cast-irons.
- To compare the arising frictional characteristics in case of dry friction condition in case of ceramic – steel surface pairs machined with different sets.

2. MATERIAL AND METHOD

During tests I have machined the surface of ceramic with different settings. Based on preliminary measurements I established that it is expedient to choose the depth of cut between 0,01 and 0,05 mm, the feed rate should be between 0,01 and 0,05 mm/rev. immediately at the tool edge. I also carried out preliminary measurements concerning the approximate value of the cutting speed, this was around 50 m/min. After turning I made surface topography as well as electron microscopic exposures from the surfaces machined and I analyzed those. I have measured the dry frictional characteristics of the ceramic / steel material pair with comparing character as a further test of the surfaces turned and grinded of the ceramic.

2.1. The materials tested

Zirconium-dioxide ceramic specimen

The characteristics of the ZN 40 engineering ceramic is that it has got favourable physical and chemical characteristics at high temperature range. It has got high hardness (1250 HV), because of this it can be cut only with polycrystal diamond and with cubic boron nitride tools. The material tested is a zirconium dioxide ceramic stabilized with magnesium. The diameter of the cylindrical specimens was 16 mm used at turning tests.

Cast-iron specimen

I have formed the reference cast-iron specimens according to the geometric dimensions of the ceramic specimens. I made the specimens from raw workpieces by preliminary machining which diameter was 16 mm, their length was 30 mm because of the clamping allowance.

Steel specimen

To measure the frictional force I placed steel specimen to the ceramic surface. The material of the steel plates was St37F dimension 20x20 mm, thickness 1,5 mm. The contact surface was grinded, its average surface roughness was: $R_a=0,8$.

Single-point cutting tool

The cutting tool was a tipped turning tool with 12x12 –shank. I have carried out my tests with two kinds of inserts (tips) with cubic boron nitride (CBN) and with polycrystal diamond (PCD). It is expedient to carry out such hard cutting with these materials.

2.2. Cutting tests

To measure the axial and tangential components of the cutting force I applied resistance force-meter-tool head between the tool-head and tool shank developed and manufactured by me. It makes possible to measure the feed rate force (F_f) and the cutting force (F_c) in case of straight turning in this form.

2.3. Surface topographical tests

Because of the increasing requirements created against surfaces machined there is a need to evaluate many-sided the surface micro-topography which means the surface characteristics by writing up data collected from the sampling surface. I have made electron microscopic exposures from the ceramic surface machined with different cutting parameters as well as from surface grinded.

2.4. Friction tests

I have made an equipment to carry out tribological tests. During the test I pressure the steel counterface with determined normal direction force the casing surface of the rotating ceramic specimen and in the meantime I measure the value of the friction force with force meter cell. I have calculated the friction coefficient characterizing the system from the normal direction force and the friction force as well as I measured the wear of the steel specimen and its deformation.

2.5. Complementary tests with thermo-camera

The heat developing during cutting has got a great effect on the material removal process as well as it effects strongly the tool service-life. To study the heat affected zone developed I made exposures with thermo-camera during cutting. Considering that the basic material chosen by me for to be machined is significantly more rigid the heat deriving from internal friction presents oneself probably in smaller amount.

3. RESULTS

3.1. Results of cutting tests

During tests I have measured the values of the main – (F_c) and feed rate (F_f) cutting forces. The Table 1. contains the parameters set in the cutting system. I have determined the characteristic content and the exponents to given parameter of the empirical connection (feed rate, depth of cut, cutting speed) taking into also account the cutting speed from the values of main cutting force measured by using mathematical statistical methods.

3.1. table. Main characteristic of measuring

	Ceramic, ZrO_2	Globular cast iron, GJS-400-15	Lamellar cast iron, GJL 200
Cutting speed, v_c [m/min]	25 / 75		
Depth of cut, a [mm]	0,01 / 0,02 / 0,03 / 0,04 / 0,05		0,02
Feed rate, f [mm/rev]	0,01 / 0,02 / 0,03 / 0,04 / 0,05		
Ambient temperature, T [°C]	23		
Length of casing tested, s [mm]	per feed rate 3 mm, altogether 15 mm		
Tool material	PCD / CBN		

3.1.1. Cutting tests results of ceramic

The Figure 1. shows the characteristic values of measurements carried out with CBN – tool at uniformly increasing cutting speed. The cutting speed (v_c) measured along the horizontal axis the cutting forces (F_c ; F_f) can be found on the vertical axis.

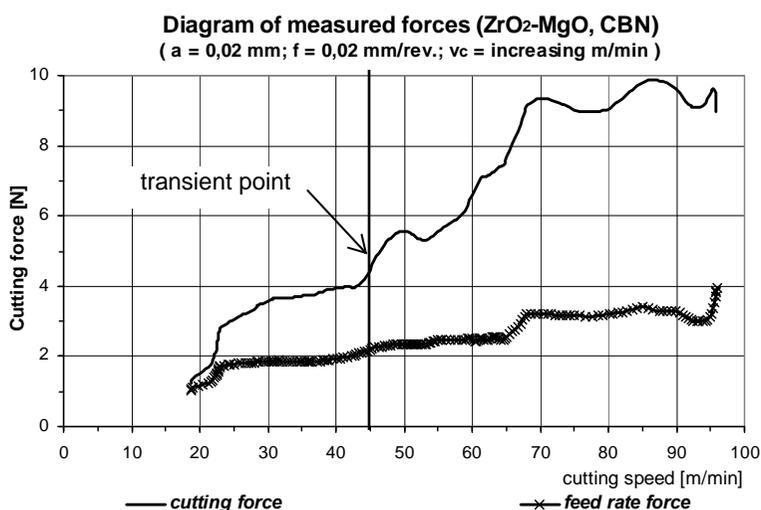


Figure 3.1. Diagram of main and feed rate forces.
($v_c =$ changing m/min., $a = 0,02$ mm, $f = 0,02$ mm/rev.; ceramic: zirconium dioxide, tool: CBN)

It can be seen that value of the small forces arising at the beginning of cutting increase. After the transient point the value of the main cutting force increased significantly with the increasing of the cutting speed at cubic boron nitride (CBN) tool.

In case of CBN-tool material the amount of feed rate forces are approximately the half of the amount of main cutting force. The value came about the cutting force with diamond (PCD) tool. The two forces at the two kind of tools show similar characters in their trends.

I also show the change of the cutting forces in the next diagram (Figure 3.2). I set the cutting speed to 25m/min. value. The value of the depth of cut was 0,02 mm. I changed the values of the feed rate according to $f=0,01;-0,02;-0,03;-0,04;-0,05$ mm/rev.

The main cutting force increases with the increase of the feed rate, however the value of the feed rate force almost hardly changes. At $a=0,04$ mm depth of cut the great degree deviation of the main cutting force allows to conclude to the damage of the cutting edge. That was proved later by microscopic exposures.

It is also significant the running up of the feed rate force in the beginning range. Both the ceramic and the tool are at ambient temperature in the beginning first point. During cutting significant amount of heat developed and warming up starts. As an effect of this the value of the force increases to a certain time then sets in a near constant value it can be seen in the diagram.

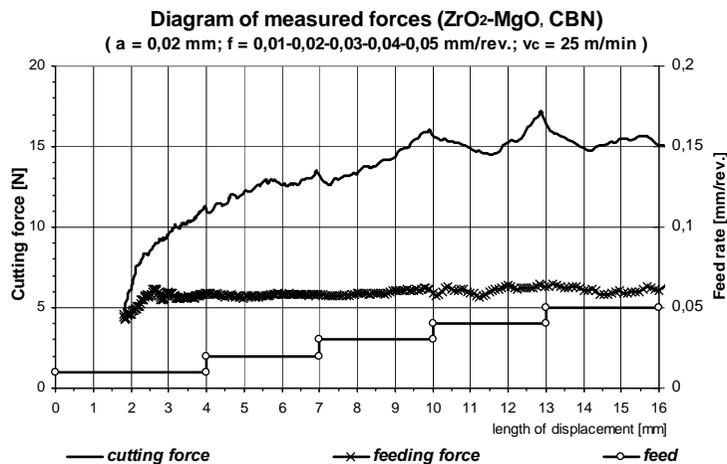


Figure 3.2. Diagram of main and feed rate forces.

I have also measured the changes of the main cutting force in accordance with the formers to the polycrystal diamond tool. The value of the cutting speed was, $v_c=25$ m/min. The value of the depth of cut was, $a=0,02$ mm. The values of the feed rate were, $f=0,01;-0,02;-0,03;-0,04;-0,05$ mm/rev.

The trends are similar to the cubic boron nitride tool. The cutting force shows increasing tendency, while the feed rate force set in to a certain value, then showed slight decrease.

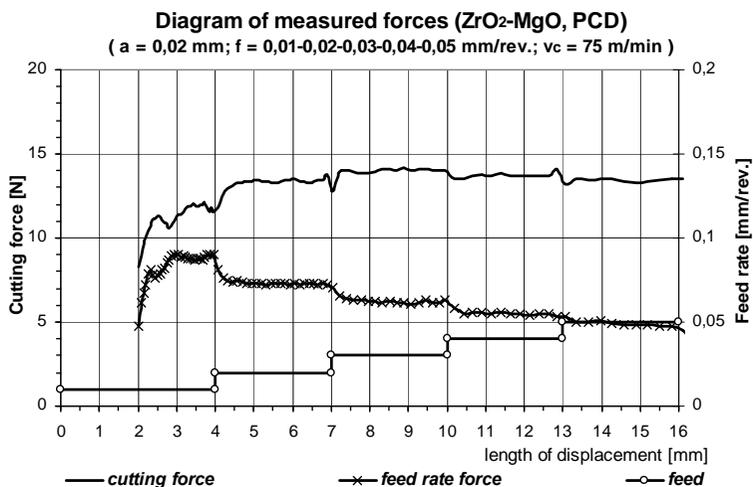


Figure 3.3. Diagram of main and feed rate forces.

The cutting force at higher cutting speed (Figure 3.3) set in a nearly constant value following a steep running up which was lower than at smaller ($v_c=25$ m/min.) cutting speed. The feed rate force following the running up or decreased or had got the same value. The tool edge caused the deviation of the feed rate force with great probability.

The diagrams so far showed the effect of the feed rate changing. I make known in the followings some diagrams at which I examined the effect of changing the depth of cut concerning to the main and feed rate cutting forces. I have set the cutting speed (v_c) to 75m/min. value. The value of depth of cut were, $a=0,05;-0,04;-0,03;-0,02;-0,01$ mm at casing turning. The values of the feed rate were, $f=0,02$ mm/rev. I carried out the tests only with PCD-tool giving more favourable surface characteristics.

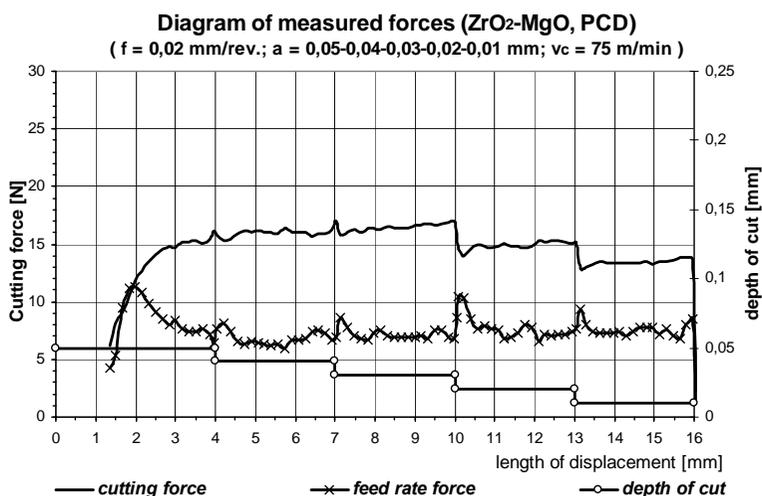


Figure 3.4. Diagram of main and feed rate forces.

The Figure 3.4 shows the change of the main cutting and feed rate forces taking place of changing the depth of cut. It can be stated that the changing of the depth of cut over $a=0,02$ mm doesn't effect significantly the value of the main cutting force. In case of machining with higher cutting speed ($v_c=75$ m/min.) comes about lower main cutting force values.

3.1.2. Cutting test results of lamellar cast iron

As I found minimal reference to the ceramics in the literature to the cutting parameters and characteristics, therefore I also carried out tests with lamellar (200-350 N/mm² tensile strength) and globular (400-700 N/mm² tensile strength) cast irons with similar settings with the view to comparison. I show these in the followings.

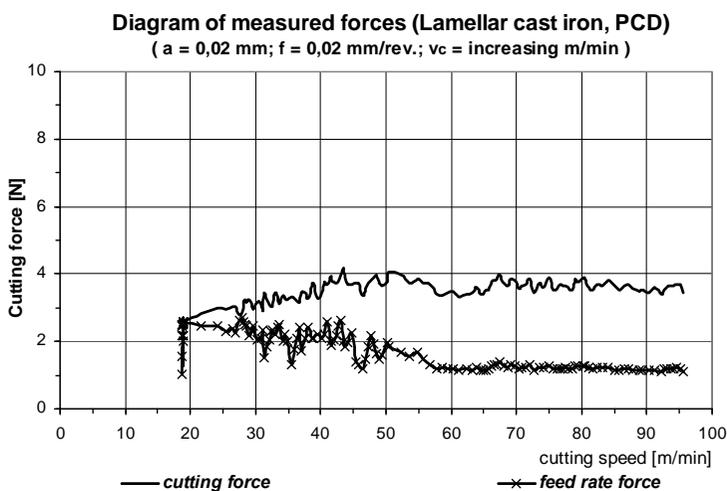


Figure 3.5. Diagram of main and feed rate forces.

It can be stated a synonymous similarity however that running up tendency can't experienced as at the ceramic. The values of cutting forces are different in case of two different tools. Which can be observed unambiguously the feed rate forces show also similar characters.

In case of lower ($v_c=25$ m/min.) constant cutting speed during machining with CBN-tool very small cutting force (2-3N) comes about.

It set to this value after $f=0,02$ mm/rev. The feed rate force has also got identical value and tendency.

In case of lamellar cast iron used as a reference material I also observed a transient zone to the cutting force in the $v_c=40-50$ m/min cutting speed range (Figure 3.5.) before that zone there is an increasing section that can be approximated with different inclining linear while following that the cutting force is constant or has got near constant value.

3.1.3. Cutting test results of globular cast iron

The globular cast iron is more tough than the lamellar cast iron. That was experienced during machining, too. As from the data got quick tool fracture could be expected in case of the polycrystal tool, therefore measurements were carried out only with cubic boron nitride tool material.

The tool holder reacted more sensible to the non optimal cutting conditions deriving from the toughness. As I carried out comparative tests it was necessary to set the former cutting values. The main cutting force and the feed rate force are similar to the machining tendency of the lamellar cast iron.

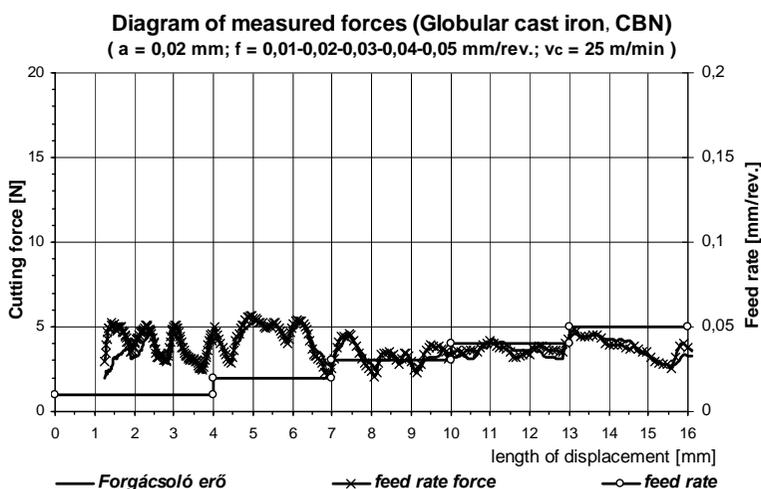


Figure 3.6. Diagram of main and feed rate forces.

The cutting force and feed rate force have almost the same value at lower ($v_c=25$ m/min.) cutting speed (Figure 3.6.). In case of smaller feed rate ($f=0,01$; $-0,02$ mm/rev.) the tool vibration was greater because the unfavourable parameter settings. Considering its value it was two times higher than at the lamellar cast iron.

3.1.4. Edge test results of the cutting tool

I have made exposures with optical microscope from the turning tool inserts (Figure 3.7). During cutting the main cutting edge got pitted in low-rate. This pitting also can be seen on the force diagrams. In the first exposure the original polycrystal diamond insert can be seen. In the second exposure already a piece pitted from the edge, the shell-like pitting can be seen. Other pittings were formed using the tool longer. These pittings change significantly the edge geometry although the tool remained suitable further on, too. The quality properties of the

surface cut by pitted insert are worse with high probability and show greater standard deviation than the inserts with regular edge geometry.

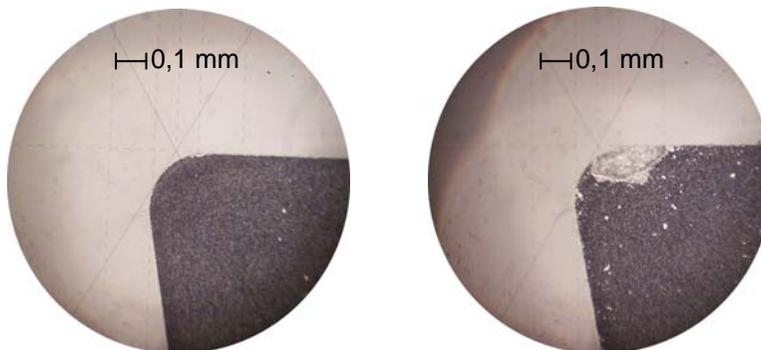


Figure 3.7. Microscopic exposures, PCD-tool, the original cutting insert, first pitting and further pittings

3.2. Determining the cutting force in the function of parameters

The sources of literature to the cutting force (Horváth and Co. 1995; König and Co. 1997, Dudás 2000) use a theoretical relation worked out first of all to steels which is the following in the function of cutting parameters:

$$F_c = C_v \cdot f^x \cdot a^y \cdot v_c^z \text{ [N]}$$

My aim is with the planned tests to be carried out to decide the usefulness of the preceding equation at cutting ceramic and to determine the necessary parameters with multivariate linear regression.

The mathematical function matched to the results of tests planned:

$$F = 477,183 \cdot f^{0,1646} \cdot a^{0,4397} \cdot v_c^{-0,2994}$$

It is important to mention concerning the usefulness of the equation that this relation describes the formation of the measuring results within the parameter – range determined in the test plan.

3.3. Results of topographic surface tests

3.3.1. Results of microscopic examinations and 3D-al topographic surface tests

The quality of the surface reflects well the cutting quality. Microcracks develop on the surface during machining deriving from the brittleness of ceramics. It is undesirable the developing of cracks because it is indispensable the proper choosing of cutting parameters. I have performed the microscopic examinations at several magnifications. (Figure 3.8). I examined the workpiece surface with the help of optical microscope and the pittings formed on cutting edge of the turning insert made known previously.

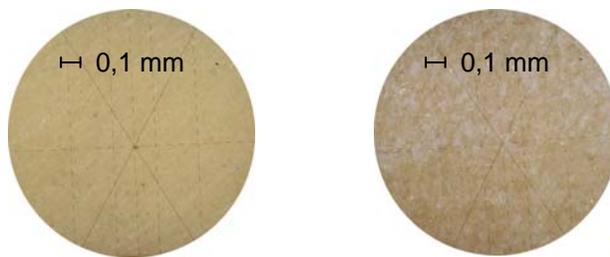


Figure 3.8. Microscope exposures, original grinded and turned ceramic surface

The 3D-al topographic measurements made numerical the surface roughness extending in space, the Figure 3.9. shows such a sample surfaces. The surface characteristics were nearly as good as the surface characteristics grinded in case of certain cases of the cutting settings.

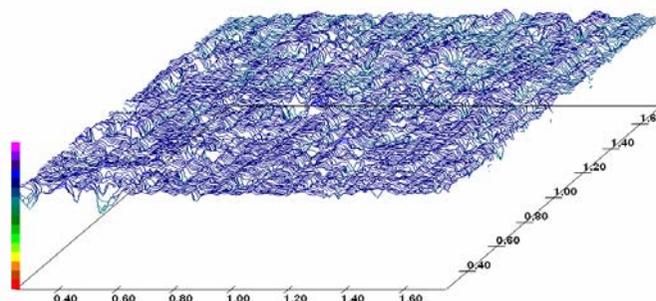


Figure 3.9. Ceramic surface turned with PCD-tool
($v_c=25\text{m/min.}$, $a=0,02\text{mm}$, $f=0,05\text{mm/rev.}$)

3.3.2. Results of surface check with scanning electron microscope

For the sake of greater magnification I have made scanning electron microscopic exposures in 100x, 500x then 2000x-times magnifications from the ceramic surface machined. I show some from these.

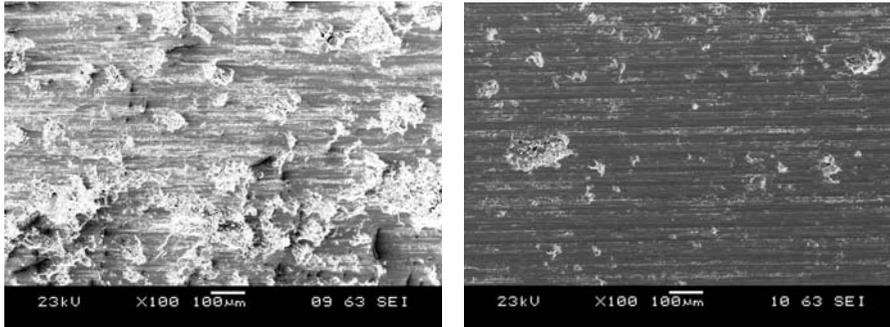


Figure 3.10. Ceramic surfaces turned with CBN and PCD tools. $v_c=75$ m/min., $f=0,04$ mm/rev., $a=0,02$ mm, $N=100x$

The machining is strongly slashed, very rough, cratered in Figure 3.10, on the exposure of surface machined with CBN-tool. The turning with PCD-tool resulted less and smaller craters. The cutting direction can be well seen. The tool point formed the surface into serrated.

The original grinded surface electron microscopic exposure can be seen in Figure 3.11. The amount of craters as a result of machining can be considered identical with the machining with PCD-tool. (Figure 3.10.). However the dimension of craters formed are 30-40% greater. This dimensional difference can increase the lubricant keeping capacity of the surface. The grinding grains made also the surface into serrated but because of the smaller dimension of grains the ditches, grooves, scratches dimension are also smaller:

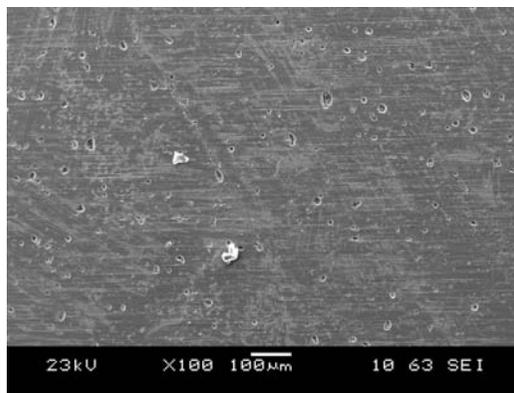


Figure 3.11. Ceramic surface grinded

The exposures with 2000x magnification prove the producing plastic (ductile) chip removal (Figure 3.12) which shows favourable surface-continuity. This proves the applicability of turning with polycrystal diamond.

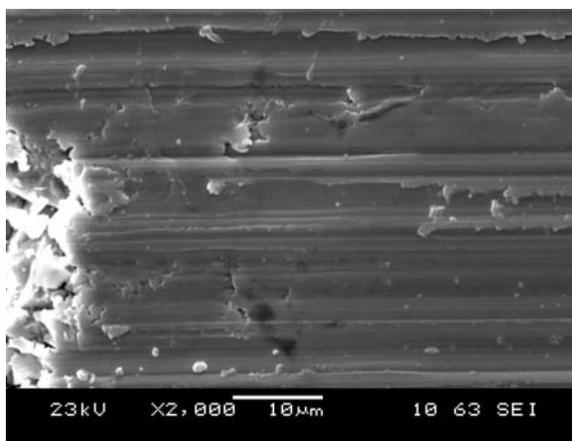


Figure 3.12. Surface turned with PCD-tool
 $v_c=75\text{m/min.}$, $f=0,04\text{ mm/rev.}$, $a=0,02\text{ mm}$, $N=2000\text{x}$

As a recommendation the whole number multiple is a given of the natural logarithm basis (“e” number) of the hardness of material to be cut as the hardness of the tool material in the practice. The diamond as an usable tool material for machining ceramics is suitable for this requirement. There are such experiments rising as a possibility the machining with lower hardness material as a significantly different conditions can take place compared with machining steels. However these are not suitable for industrial purpose, yet.

3.4. Results of frictional model tests and their interpretations

I analyze in the followings the values of the friction coefficient, wear and deformation got in the friction model testing system produced during my research work. The polycrystal diamond tool material proved to be suitable from the two tool materials used during machining ceramic. Because of this I have carried out the frictional tests with the specimens cut with PCD tool as well as with the original surfaces grinded.

3.4.1 Results of friction and wear and their evaluation

On the casing surface of ZrO_2 ceramic tested at $v_c=25$ and 75 m/min. cutting speed and 5 different feed rate ($f=0,01;-0,02;-0,03;-0,04;-0,05\text{ mm/rev.}$) machined surface can be found. The width of these are 3 mm one by one. Figure 3.13 shows the value of arising friction force developed between the ceramic and the steel specimen. I distinguished the different surfaces with various colours and

marks. The “k” marks the grinded surface while the numbers “1, 2, 3, 4, 5” mark the feed rates set during turning in hundredth millimeter.

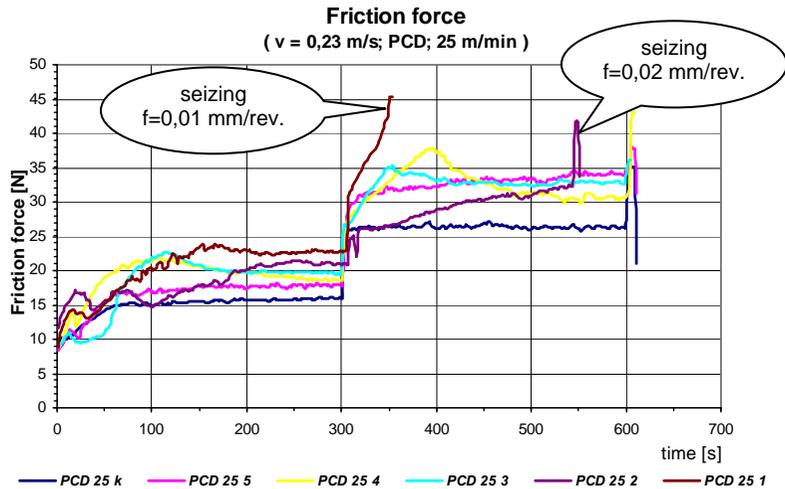


Figure 3.13. Friction force diagram
(between steel/grinded and ceramic surface cut)

The friction force didn't show significant change on the surface grinded within identical load section. It set in a nearly constant value within short time (50s). The grinded surfaces also seized with imposing maximum load. It is striking on the diagram that the friction force increased in such a great extent on the 2. load level on the ceramic surfaces cut with 0,01 and 0,02 mm/rev. feed rate, that the surfaces seized in this section. The seizing ensued on the 3. load level on surfaces cut with greater feed rate.

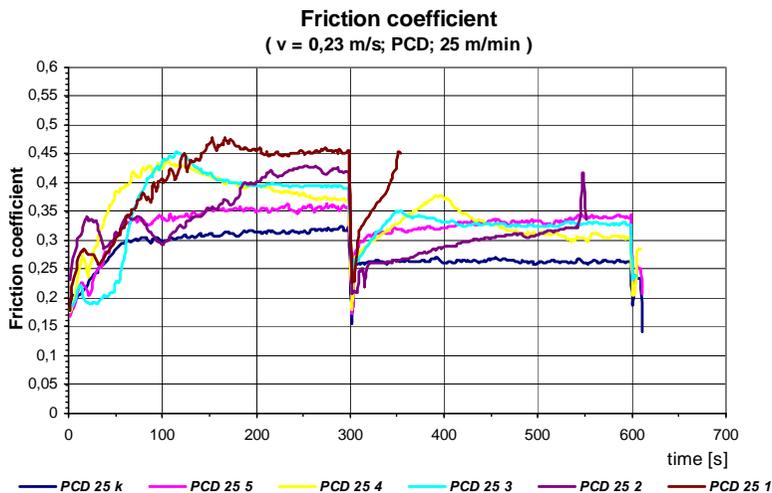


Figure 3.14. Diagram of friction coefficient
(between steel/grinded and ceramic surface cut)

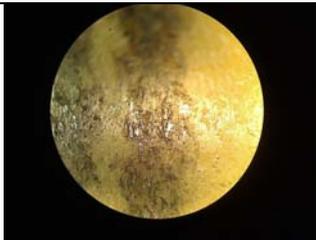
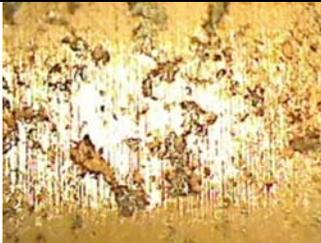
It is evident from the values of friction coefficients (Figure 3.14) that higher μ values characterize the surfaces machined with smaller feed rate. The value of friction coefficient on the surface turned with $f=0,05$ mm/rev. feed rate remained at nearly constant value in the sections tested similar to the grinded surface. Fluctuating friction coefficient, characterizing seizure can't be observed.

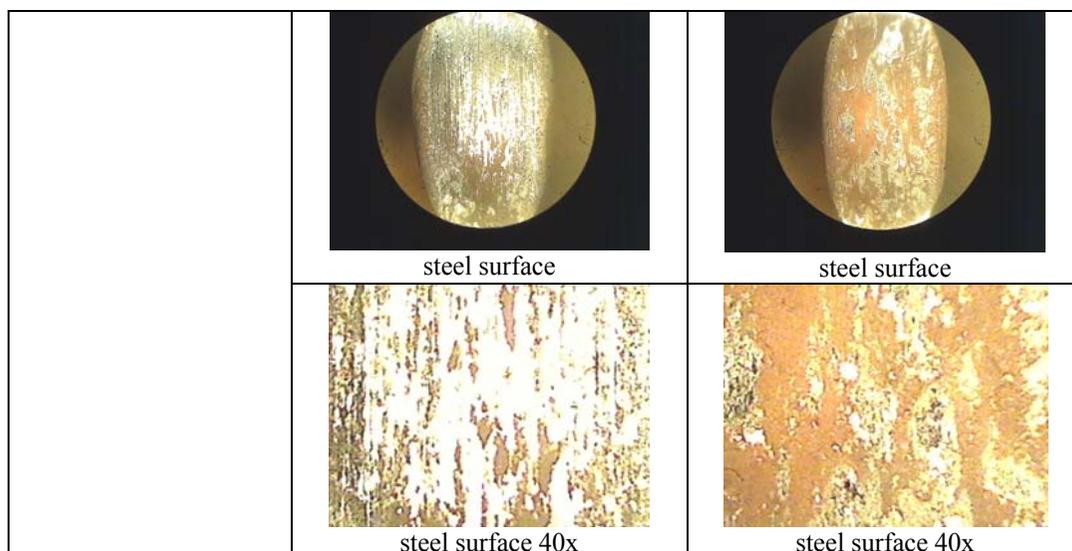
3.5. Microscopic comparison of sliding surfaces

I have made exposures from the dry sliding surfaces of ceramic and steel. The maximum magnification of the microscope was 40x. Two exposures are at disposal from both surfaces. One shows the whole sliding surface, the other shows a part of the sliding surface with 40x magnification. I show the sliding test carried out on the surface machined with a given feed rate in Table 3.2. Further exposures made from the surfaces can be found in the No. 2 supplement.

It can be seen well on the microscopic exposures of sliding track that at lower speed ($v_c=25$ m/min.) the machining is more rough, it resulted greater craters on the ceramic surface. These craters cut the steel surface in a greater extent during sliding test and thus they were filled up with steel faster. After this adhesive connection could develop at certain places between identical materials (steel plate and steel particles stick into craters). This accelerates the seizing process significantly.

Table 3.2. Microscopic exposures of sliding surfaces (machining parameters: $v_c=25$ m/min., 75 m/min.; $f=0,02$ mm/rev.; $a=0,02$ mm; test parameters: $v_k=0,23$ m/s; $F_n=50$ N, 100N; 150N).

tool: PCD	cutting speed 25 m/min	cutting speed 75 m/min
feed rate $f = 0,02$ mm/rev.	 ceramic surface	 ceramic surface
	 ceramic surface 40x	 ceramic surface 40x



3.6. Results of complementary tests with thermo-camera

The thermo-camera exposure of the heat affected zone developed during cutting can be seen in Figure 3.15. The exposures prove unambiguously that because of the good heat insulation of ceramic at the tool point on the workpiece a heat ring is formed increasing significantly the thermal load of the tool point. The first exposure was made at the beginning of cutting, here rather the tool point warms up. The temperature of the tool and the ceramic also increase significantly with increasing the cutting length. The second exposure shows this. In the lower two exposures the red colour shows the heat ring developed on the workpiece and the tool point, that is the hottest point.

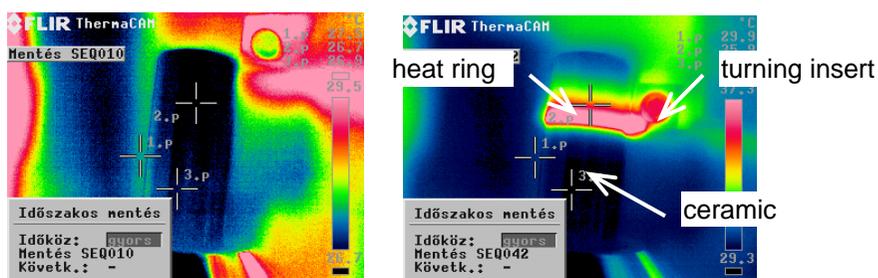


Figure 3.15. Exposures made by thermo-camera after cutting.

I have evaluated these tests only with comparing characters, I didn't take into account exact temperature results. I was convinced of that because of the bad heat conductivity of ceramics the cutting process causes such heat shock on the surface to be machined (heat ring) and on the tool alike which puts the ceramic turning an entirely other basis considering metals. Thermal search of quasi-adiabatic cutting system is a new chapter in the field of technological developments.

4. NEW SCIENTIFIC RESULTS

The demand increased in great scale to ceramics with special characteristics by satisfying environment protection standpoints, too. Different parts can be produced in average $\pm 0,5-1,5\%$ accuracy to gauge after sintering (Fritz, 2007). So in many cases surfaces given has to be also machined in their hard ($\sim 1200-1400\text{HV}$) condition. Economical use of semi-finished products during part production is only expedient in case of developing methods with greater material removal. The forming of microcraks is a serious problem of machining in hard condition. Reducing these presumes the more favourable machining beside the suitable material selection.

Based on my research work I have made the following scientific statement:

1. I establish in the test field that in case of ZR40 ($\text{ZrO}_2\text{-MgO}$) ceramic basic material with the CBN and respectively PCD tool types having regular edge geometry chosen by me can be reached plastic (ductile) chip removal during turning in the cutting parameter field set ($a=0,02$ mm; $f=0,01-0,02-0,03-0,04-0,05$ mm/rev.; $v_c=25-75$ m/min.).
2. I have proved with my measurings that in the upper range of the cutting speed of test field the polycrystal diamond tool is more favourable at turning zirconium-dioxide ceramics stabilized with magnesium it can be used with smaller cutting force than the cubic boron nitride tool. Furthermore I have established that the polycrystal diamond (PCD) resulted cutting force similar to the cubic boron nitride at lower ($v_c=25$ m/min.) testing cutting speed. The occurrence experienced at different frictional processes. I verified with thermo-camera exposures the forming and different heat rings taken place.
3. I have established in the test field that the cutting force at uniformly increasing cutting speed in case of zirconium-dioxide ceramic and lamellar cast iron shows increasing tendency-contrast with the connection concerning steel machining to be in the technical literature. In case of lamellar cast iron used as reference material in $v_c=40-50$ m/min cutting speed range a transient zone comes about to the cutting force, before which there is an increasing section to be approximated with different incline linear depending on the tool, while following that the cutting force is constant or it has got a nearly constant value. The transient zone also can be measured at turning with PCD-tool in case of 40-50 m/min cutting speed but the trend is contrasted: at lower speed nearly constant cutting force can be measured, above this a continuously increasing force-trend appears. In case of CBN tool there is also a transient zone belonging to 40-50 m/min. cutting speed at which in case of lower speeds appeared a continuously increasing cutting force, after the transient zone the force increase is still steeper respectively.

4. I have proved with mathematical-statistical methods that the connection concerning the main cutting force $F_c = C_v \cdot f^x \cdot a^y \cdot v_c^z$ [N] to be found in the technical literature in the tested parameter field ($f=0,02-0,04$ mm/rev.; $a=0,02-0,04$ mm; $v_c=25-75$ m/min.) can be extended to turning ZrO₂-MgO ceramic with PCD tool (with the edge geometry defined). I have determined with my measurements the values of the constant and exponents – $C_v=477,183$ - - $x=0,1646$ - - $y=0,4397$ - - $z=-0,2994$ – and I proved that the connection can be applied with 95% probability with on the parameter interval tested.
- 5.
- 5.a. I established with digital picture – analyses based on microscopic exposure that at cutting with cubic boron nitride (CBN) type tool $\approx 57\%$ surface damage (microcrack, shell like pitting, etc.) rose on the surface machined – concerning to unit zirconium-dioxide surface – already in that case when the depth of cut was only 0,02 mm, the feed rate however was only 0,04 mm/rev. Greater depth of cut and feed rate than this resulted still more unfavorable surface. The turning of ZR40 ceramic with this type of tool material is only suggested restricted.
- 5.b. I have established beside the conditions of the test system that the turning with polycrystal diamond (PCD) turning tool as well as the grinding process resulted shell-like pittings, microcracks alike on the ceramic surface. The amount of surface damages in unit surface during turning with PCD approximately was $\leq 8,5\%$ and differs in character and dimension the 8-9% surface damage experienced at grinding. The effect of difference influences the sliding characteristics which I proved with sliding measurements.
6. I have proved with SEM exposures (2000x) that the wrinkles indicating the phase transformation formed to the effect of the great passive force at grinding don't appear on the ZrO₂ ceramic surface machined in case of using polycrystal diamond (PCD) turning tool ($\gamma=0^0$).
7. I have proved with friction tests (block-on-ring tribological system, St37F grinded steel ($R_a=0,8$ mm) “block” surface, without lubrication, ceramic “ring” specimen) that at high turning cutting speed ($v_c=75$ m/min.) and at small feed rate ($f=0,01-0,02$ mm/rev.) the friction resistance is smaller on the ceramic surface. The surface grinded has got smaller dimension but into the great number shell pittings the steel worn particles seat quickly, which transforms the ceramic/steel friction connection into steel/steel characteristic friction, which increases significantly the adhesive component of the friction force.

5. CONCLUSIONS, SUGGESTIONS

The literature sources don't refer to the turning machining concerning ceramics, thus zirconium dioxide and aluminium oxide. Nowadays the grinding is the machining after the generally wide-spread sintering. The development of the finished- and semi finished products' manufacturing requires cutting ever more complex surfaces. The more economical machining of 3D-al surface requires the further development of tools with regular edge. The zirconium dioxide as basic material is suitable to machine by tool with regular edge deriving from lower ceramic hardness and from other characteristics so in case of piece production or small – and medium series production, at quick prototype production can become potential material alike. To that this should be ensued its cutting, and machinability characteristics has to be revealed.

The cutting with traditional machine-tool in the mechanical engineering is followed by high speed (HSC) “hard” machining controlled by computer (CNC). Nowadays it is possible to machine complex 3D-as shape and profile with the newest 5-axis HSC milling for example with machining-centre on such materials as copper, graphite, plastic and steel up to 70 HRC hardness. My research work helps to spread the turning to this field. Based on the research program worked out I gave answer to the following unexplained questions:

- Explanation of turningability with single point tool in case of zirconium dioxide ceramic basic material.
- Developing suitable measuring system to measure the rising main and feed rate forces during ceramic cutting.
- Topographic tests of surfaces after machining with cutting parameters set. Analysing the microcracks, shell-like pittings formed on the surfaces possibly.
- Formation of heat affected zone during cutting.
- Clearing analogy or possible connection among the cutting characteristics of lamellar and globular cast-irons as well as the ceramics tested.
- Comparing the arising friction characteristics in dry friction conditions in case of ceramic-steel surface pairs machined with different settings.

Two main directions can be drawn up to carrying on resarches.

- Extending the applicability by changing the technological parameters,
- Technology optimization to be suitable to application-technic standpoints.

Further comprehensive elaborating of these fields can be realized with the co-operation and initiating of companies manufacturing ceramic materials and parts. The attainable further results entail with extending the technological database significantly.

6. SUMMARY

The importance of ceramics used in engineering practice is more and more greater. After the manufacturing process often occurs post-accuracy to dimension to be needed to reach the final dimension, as well as in the repair industry is needed machining to a certain dimension. Because of the high hardness of ceramics this is reached with grinding in the overwhelming majority of cases. The grinding accuracy to gauge is appropriate but it results small rate of stock-removal. In some cases because of the characteristics of ceramics and of the surface pressure of grinding grains cracks can develop on the surface, which can cause the ceramic product fracture. The aim of my research work was to choose such turning tool as well as to determine turning parameters by which the ZrO₂-MgO ceramic can cut favourably.

During surveying the technical literature I have written up several domestic and international scientific articles. I have summarized the machining possibilities of ceramics, I made know the connection concerning the cutting force.

I have planned and accomplished an individual measuring system for turning ceramic. During turning I measured the main cutting forces and the cutting forces in feed rate. To evaluate the practical applicability of ceramic surfaces turned and grinded originally, to compare the tribological behaviour I have also assembled a laboratory measuring equipment by which I measured the frictional force on steel counter-surface grinded at dry friction condition.

I have determined with mathematical-statistical methods the variables of the main cutting forces connections to be found in literature from the measuring results of cutting force. After tests I have analysed the electron-microscope exposures of the surfaces cut concerning the surface cracks and pittings. I also determined the 3D-al surface characteristics with surface topography measuring method. I proved with complementary, comparative thermo-camera examinations the forming of arising heat-circle at the contact of cutting tool.

Based on my research work carried out I also extended to the ceramic turning the possibility of calculating the turning cutting force, I cleared the frictional application-technique possibility of ceramic surface machined, notwithstanding that I studied the process of tool deterioration and damage. As a result of this I drafted the effective application boundaries of the PCD turning tools.

Extending the cutting parameters is one direction to take on further the researches. This is necessary concerning partly the feed rate, the depth of cut also examined till now, but still rather concerning the cutting speed ($v_c=150-200$ m/min).

The utilization of research results presented in the dissertation indicates advance in the field of machining ceramics spreading better and better in the mechanical engineering practice.

7. PUBLICATIONS IN CONNECTION WITH THE THEME OF DOCTORAL DISSERTATION

Articles in foreign language:

1. Eberst O., Pop S., **Fledrich G.** (2009): The sticking particularities of industrial plastics. International multidisciplinary Conference, Serie C, volume XXIII. North University of Baia Mare. pp. 137-143
2. **Fledrich G.**, Pálincás I. (2009): High performance engineering ceramics in the practice. International multidisciplinary Conference, Serie C, volume XXIII. North University of Baia Mare. pp. 147-151
3. **Fledrich G.**, Pálincás I. (2009): Machinig questions of engineering ceramics (Zirconium-dioxide ZrO_2). Trans-Trio Sciences. Mechanical Engineering Letters. Volume 2. pp. 114-120.
4. **Fledrich G.**, Pálincás I., Keresztes R. (2010): Turning ZRO2 ceramics. International Review of Applied Sciences and Engineering. Volume 1. 2010 December Numbers 1-2. pp. 3-6.
5. **Fledrich G.** (2010): Machining the zirconium-dioxide engineering ceramics. Sustainable Construction & Design. Vol. 2010/b, pp. 37-41.
6. **Fledrich G.**, Pálincás I., Keresztes R., Zsidai L., Petróczki K. (2011): Turning specialities of ZrO_2 ceramics. Sustainable Construction & Design. (in print)

Articles in Hungarian language:

7. **Fledrich G.** (2009): Kerámiák forgácsolása szabályos élű szerszámmal (cirkónium-dioxid esztergálása). Mezőgazdasági technika. L Évfolyam, 2009. szeptemberi szám. 2-3. o.
8. **Fledrich G.** (2010): Kerámiák forgácsolása szabályos élű szerszámmal. Mezőgazdasági technika. L I Évfolyam, 2010. júniusi szám. 2-4. o.
9. **Fledrich G.**, dr. Pálincás I., dr. Keresztes R. (2011): Forgácsoló erő kutatása cirkónium-dioxid (ZrO_2) esztergálásánál. Gép, 2011. (in print)