Indian Journal of Engineering & Materials Sciences
Vol. 23, August 2016, pp. 254-260

Analysis of wide-range dependence of cutting parameters and the coating impact in deformation zone

Zuzana Murčinková[a]*, Karol Vasilko[a] & Jaromír Murčinko[b]

[a]Faculty of Manufacturing Technologies with seat in Prešov, Technical University of Košice, Bayerova 1, 080 01 Prešov, Slovak Republic

[b]ProTech Coating Service, Ltd., Ku Surdoku 35, 080 01 Prešov, Slovak Republic

Received 9 April 2015; accepted 01 February 2016

This paper deals with analysis of wide-range dependence of cutting parameters and describes and interprets physical-mechanical-thermal changes in such range. The paper experimentally evaluates the coating impact on cutting and deformation process, on shape and structure of the chip, nature of the tool wear and tool life and surface roughness. Moreover, the paper analyses and evaluates the advantages of the selected monolayer and multilayer coatings in terms of roughness of the work-piece and tool wear. Influence of coating thickness and temperature in coated and uncoated cutting tool is evaluated by numerical simulation.

Keywords: Coating, Cutting parameters, Roughness, Tool life, Tool wear, Stress

The reasons why the coated cutting tools started to be used consistently in protecting the tool surface, reducing tool wear, the possibility of using higher cutting speeds (feeds and depth of cut) and thus increasing productivity[1-3]. The new fields such as surface engineering, coating technologies and new methodologies for measuring their parameters were developed[4-6]. Mechanical properties of coatings are significantly higher than those of the substrate material. Mostly, their thickness ranges from 1 to 20 μm creating the micro-layers that change the cutting zone and deformation. High quality coated tool is basically a synergistic combination of the coating properties, substrate and coating technology.

The present paper does not discuss the particular properties of coatings or coating technology influence on the coating properties[1,5], but it examines the contribution of the coating presence on the dry machining and deformation process, impact on the shape and structure of the chip, the nature of the tool wear and tool life. Moreover, the advantages of the selected monolayer and multilayer PVD (physical vapor deposition) and CVD (chemical vapor deposition) coatings are analyzed in terms of roughness of the work-piece and tool wear. The paper compares the measured experimental results and evident effects of uncoated and coated tools and it evaluates the most preferred coating of monolayer and multilayer PVD coatings available for authors in terms of roughness of the machined material and tool life. To determine the contribution of the coating, we analyze the cutting process parameters without coating in wide-range.

PVD is vacuum coating process in which the employed material is physically removed from a source by evaporation or sputtering[1]. PVD coatings for cutting tools can be deposited at temperatures lying in the range of 450-550°C. CVD is a heat-activated process based on the reaction of gaseous chemical compounds with suitably heated and prepared substrates[1]. Typical deposition temperature range is from 800 to 1200°C.

The comparison of deformation zone parameters in machining by coated and uncoated tool is not analyzed and compared by many authors. Researchers prefer to analyze wear characteristics, wear mechanism, tool life, surface roughness, interface temperature, material removal rate of coated cutting tools by experiments and/or by FEM modeling in turning or milling of specific work-piece materials by various PVD and CVD coated cutting tool materials and geometries[7-12].

On the basis of a metallographic study, Vereshchaka[13] defines an interesting scheme of chip formation in machining by classical and coated sintered carbide, shown in Fig. 1. According to Vereshchaka[13], coatings (TiC; TiN) on tool surfaces results in shortening of the length of the chip contact

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*Corresponding author (E-mail: zuzana.murcinkova@tuke.sk)

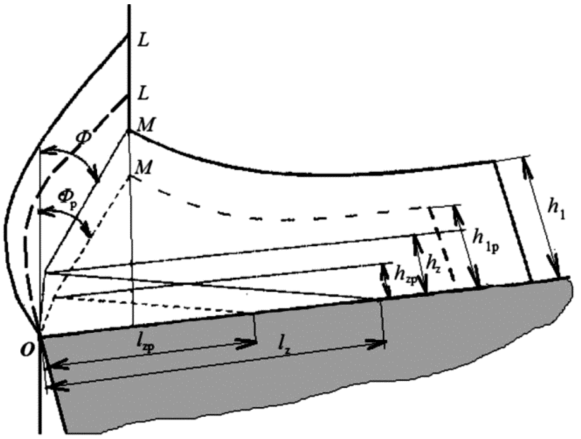

Fig. 1 – Scheme of deformation zone transformation in cutting by the coated tool (dashed line) and without coating (l_z - length of tool-chip contact, h_1 - actual thickness of cutting layer, h_z - mean thickness of the cut layer, Φ - angle of plastic deformation boundaries; indexes *p* are for coated tool)

with tool face by 40-60%, chip compression by 20-30%, cutting force by 20-30% and increasing the angle of the border of plastic deformation Φ [13]. The dimension (h_z) of the braked layer considerably decreases and the zone of primary plastic deformation OLM narrows. The mentioned values represent a significant improvement of each of these parameters. The changes in deformation zones and impact on roughness, wear and chip shape are described.

At present, the usage of computer aid is a standard in various fields of engineering activities, e.g., classical construction. To simulate the machining process and to predict, e.g., magnitude of cutting forces, wear, temperature, etc., it is possible to use the specialized commercial FEM software[1,7]. However, the machining process is characterized by many physical changes that are difficult to describe mathematically to obtain reliable computational results consistent with the experimental data. In addition, these calculations require high computing power and expensive software with a quality computing analyst. The paper provides also stress analysis for coated tool and it defines its critical points.

The experiments were conducted using of lathe. Measurements were made by profilometer Mitutoyo and measuring microscope Alicona. Experiments were performed on various sample materials (steel C45, titanium, aluminum alloy, cast iron) by cutting tools of cemented carbide P20, K10 and ceramics Al_2O_3 involving TiN coating applied by PVD and CVD technologies, respectively. Moreover, the metallographic microsections were made. For numerical experiments, the commercial software of finite element method was used.

Wide-range Cutting Process Parameters

The physical, mechanical and thermal parameters in deformation zone change due to cutting process conditions. In this section the parameters such as the average maximum height of profile (*Rz*), cutting speed (v_c) and cutting forces(F_c tangential force, F_f, axial force, F_p radial force) are analyzed in wide ranges. Generally, two fundamentally different, but interacting, processes can be observed in the cutting process, namely: (i) chip formation - separation of the machined work-piece material layer and (ii) chip flow - outgoing of separated material layer from the deformation zone.

The dominant influence on the nature of the mentioned processes in the cutting process is shown by the mode of the cutting force load in the cutting zone, namely the value and direction of the cutting force and its components on each surface of the tool. The cutting forces and physical changes in the cutting process are influenced by[14]:

(i) Cutting tool geometry: it directly changes the load mode, deformation conditions in chip formation process, friction conditions, size of contact surfaces etc.

(ii) Cutting tool material: it changes friction conditions on the face and flank surface taking sufficient material strength and particular stress, temperature and other cutting conditions into account.

(iii) Cutting conditions: they influence the value and direction of cutting forces, they affect speed and intensity of elastic and plastic deformation, friction conditions etc,

(iv) Machined (work-piece) material: it mainly influences the character of chip formation and friction conditions.

(v) Cutting medium: it directly affects only friction conditions in the cutting zone, similarly as cutting material; the deformation changes are influenced indirectly by heat flow from the cutting zone.

Most of above mentioned parameters are process parameters affecting the selected machining quality characteristics of turned parts. Aggarwal *et al.*[15] present Ishikawa cause-effect diagram of CNC machining. Diagram summarizes the parameters in terms of the quality of machined parts involving, e.g., also machine-tool parameters as accuracy and stiffness. Vasilko and Murčinková[16] analyzed the geometric and dimension accuracy of turned work-pieces regarding the clamping and work-piece stiffness.

Ra, roughness average, is the most commonly used roughness parameter. According to measurements, the parameters *Ra* and *Rz* show the same behaviour. The parameter *Rz* is more illustrative since the height of profile is formed as trace of the tool tip. Thus, it is possible to monitor the size of tool wear directly through the parameter *Rz*. Whereas, the parameter *Ra* is the area between the roughness profile and its mean line. Moreover, there is a theoretical relation for calculation of *Rz*:

$$Rz = \frac{f^2}{8.r_\varepsilon} \qquad \text{... (1)}$$

where *f* is feed (mm) and r_ε is tool tip radius (μm).

If we are to compare the results of this theoretical relation with the experimental results, we can observe significant differences, especially for steel. Figure 2 shows experimentally dependence of *Rz* on the feed rate *f* for different types of machined materials which are machined at the different cutting speeds as following: VT 3-1 titanium v_c = 25 m.min^{-1}; brass v_c = 80 m.min^{-1}; aluminum alloy v_c = 160 m.min^{-1}; cast iron v_c = 45 m.min^{-1}; C45 steel v_c = 100 m.min^{-1}.

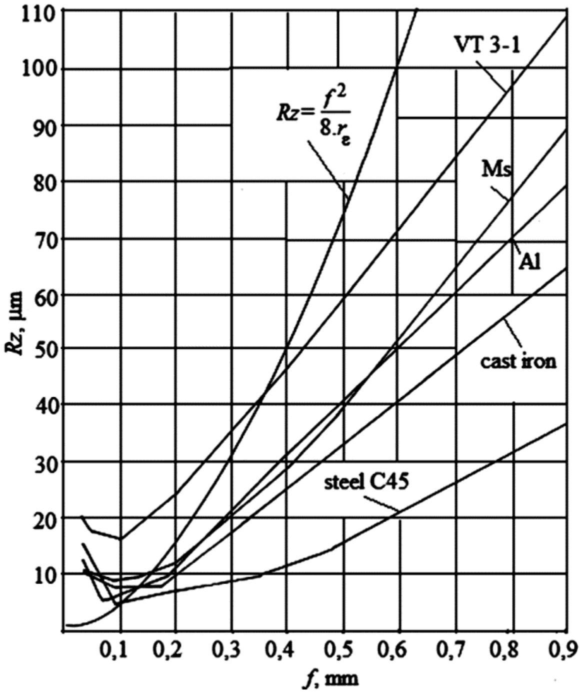

Fig. 2 – Experimental dependence *Rz=f(f)* for different types of work-piece materials

Limit feed rate *f* is 0.1 mm. If $f \leq 0.1$ mm, the practical *Rz* values are larger compared to Eq. (1). Conversely, if $f \geq 0.1$ mm, all practical values of *Rz* are lower than theoretical ones. This leads to errors in practical prediction of *f* in the required *Rz*.

Equation (1) does not include the cutting speed. However, it is obvious that the cutting speed significantly affects the *Rz* values. The relationship between the average maximum height of profile *Rz* and cutting speed v_c is an important dependence in cutting that is shown in Fig. 3.

A large number of statistical measurements produces an interesting curve. The worst surface is obtained with minimal cutting speeds at which the material has a room temperature and it is brittle. The machined surface quality is affected by crack-forming process. At a cutting speed of 20 m.min^{-1}, the machined material becomes plastic because the temperature in the cutting area is approximately 200°C. Further increase in cutting speed (also temperature) causes reduction of the material strength but it increases adhesion between machining and cutting material on the tool face and the built up edge is created that significantly worsens quality of the machined surface. The maximum value of *Rz* in this case is at a cutting speed of 80 m.min^{-1} (the temperature between chip and tool face is approximately 800°C). Upon further increase of cutting speed up to 100 m.min^{-1} and more, the built up edge does not appear, the chip is in a plastic state and the machined surface is plastically "smoothed". Thus *Rz* continuously decreases.

The interesting fact is that the same character of the course is observed with cutting forces (Fig. 4).

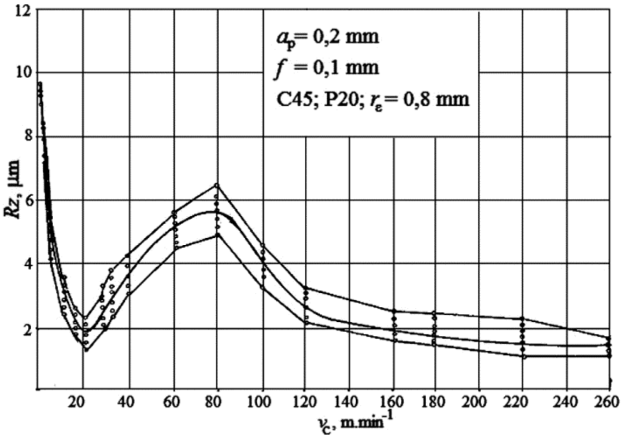

Fig. 3 – Experimental diagram of dependence of ***Rz*** on the cutting speed

The cutting tool has to overcome high material strength at low cutting speeds. The material strength gradually decreases and thus causing also reduction of cutting forces. Further increase of cutting forces is due to built up edge and their further decrease is caused by reduction of the machined material strength. The F_f / F_c ratio at each cutting speed determines friction coefficient between the tool face and chip.

There is a question of estimation of optimal cutting speed. It is obvious that the significant large tool life exists at minimum cutting speeds. The chip is brittle and it shortly contacts the tool face so there is no reason for intense abrasion of the tool. Gradually, the work-piece material becomes more plastic, its strength decreases due to temperature and it results in lower cutting forces but adhesion of chip and work-piece with the tool occurs. This results in pulling out the particles of the cutting material. The intensity of wear increases. The largest intensity of wear, and therefore the minimum tool life is at the cutting speed of 20 respectively 60 m.min^{-1} (for steel). Then the built up edge arises and chip only sporadically contacts the tool face. The tool life increases. In this case, the maximum tool life is in at the cutting speed of 80 respectively 140 m.min^{-1} depending on feed. Then it gradually declines due to a significant reduction of real strength and hardness of the cutting material. The shape of the graph curve significantly copies the graph curve Rz-v_c, respectively $F_{p,f,c}$-v_c. Furthermore, they all actually depend on tribological conditions between machining and cutting material.

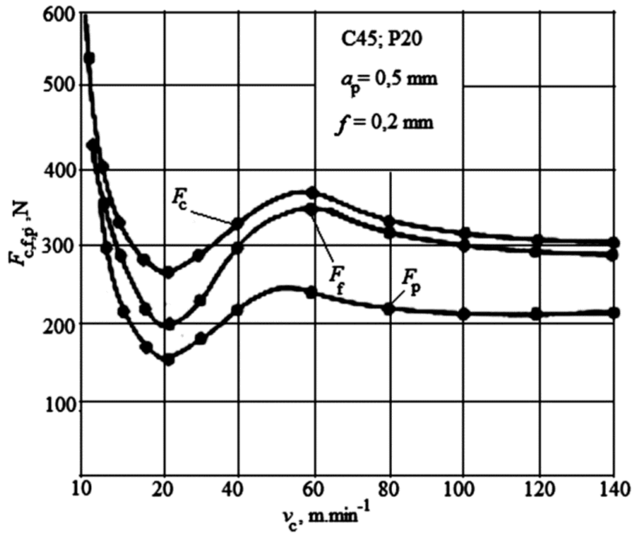

Fig. 4 – Experimental dependence between cutting force and cutting speed

Coating as a Factor Changing the Deformation Zone

In practice, it is necessary to fulfill two opposing requirements at once. We need low machined surface roughness value and long tool life. One solution is to add an additional factor into the cutting zone - the coating. Material properties of the thin layer significantly change conditions of the tribotechnical interface chip – the tool face that has a major impact on the change of the deformation zone.

The shape of the tool wear significantly affects the micro-geometry of the machined surface. Typical tool wear of the coated and uncoated cutting tools is given in Fig. 5. The minimal wear on coated face is visible. The coated tool has considerably smaller intensity of the face wear, the cutting tool edge radius increases, and the typical crater is not formed at the face (see Fig. 5). It is obvious that uncoated tools (cemented carbide P20, K10) are characterized by a deep crater after the same machining time. The cutting tool edge radius declines significantly and the real face angle increases. It changes the geometric shape of the cutting wedge. Increasing wear on the face and the back of the cutting wedge causes increasing values of *Ra* and *Rz* and it is a source of reducing the surface quality and dimension accuracy.

Furthermore, experimentally found dependence of flank wear *VB* on machining time τ_S showed the less intense flank wear of coated tools than uncoated ones. *VB* values are substantially smaller. Comparing coated and uncoated cutting tools, more significant difference is in the face wear.

In short-term evaluation, the *Rz* values are lower for uncoated tool and this seems advantageous in terms of surface quality. The long-term measured

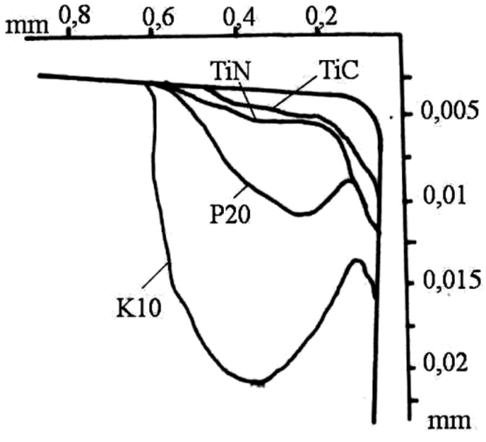

Fig. 5 – Profile of wear crater for the classical and coated tools after the samemachining time

results give the advantage to the coated tool. The coated inserts ensure equal quality of the machined surface in long-term horizon. At that time it showed minimal wear. The best results provided TiN coating of thickness of 10 μm being applied by CVD technology.

The different processes of wearing result in the different behaviours of chip forming during cutting. The chip shape is not changed during cutting by the coated tool (not even by the flank wear). The coatings that reduce friction coefficient between the tool face and chip and thereby they reduce the contact area, provide a fundamental change in the face wear.

More detailed analysis of coating effect on the tool life can be obtained by constructing dependency of tool life in a wide range of cutting speeds. Figure 6 presents such detailed relationship for the tools of cemented carbide and ceramics. It is obvious that coating significantly increases the tool life of both cutting materials: P20 and Al_2O_3. In this case, the cemented carbide P20 has the longest tool life at cutting speed of 65 $m.min^{-1}$ and tool of Al_2O_3 at a cutting speed of 95 $m.min^{-1}$. It is interesting to observe the area of minimum tool life (30-40 $m. min^{-1}$), as well as the area of minimum cutting speeds with significant increasing of tool life. These relations are necessary to know if we want to determine the optimal cutting speed in terms of long tool life.

Cutting Tool Stress Analysis

In the process of machining, the tool face and chip are in contact. The effect of tool on machined material evokes machining forces which can principally be characterized by force F_n causing normal pressure of the chip on tool rake and friction force F_t acting along the surface of the tool and formed chip contact[17]. The unwanted effect is the peel-off damage of the coating caused by subsurface stress in the contact of tool face – chip. The concentration of subsurface stress breaks adhesion of the coating either to substrate or to another layer. The relationship of coating layer thickness h_p and location of subsurface stress is important.

Figure 7 presents the results of stress analysis coating - substrate without considering the influence of temperature under static normal force load without considering friction in the area of elastic deformation. In the analyzed model, the values of stress peaks are located in the coating – substrate interface and are more than two-times larger compared with stress in the uncoated tool (P20). Material properties of coating and stress state allow that stress peaks do not break coating itself; however, under critical load they can lead to coating peeling off (damage). It is necessary to realize that also substrate material is under larger load in comparison with uncoated tool (Fig. 7). The distribution of shear stress is same as the distribution

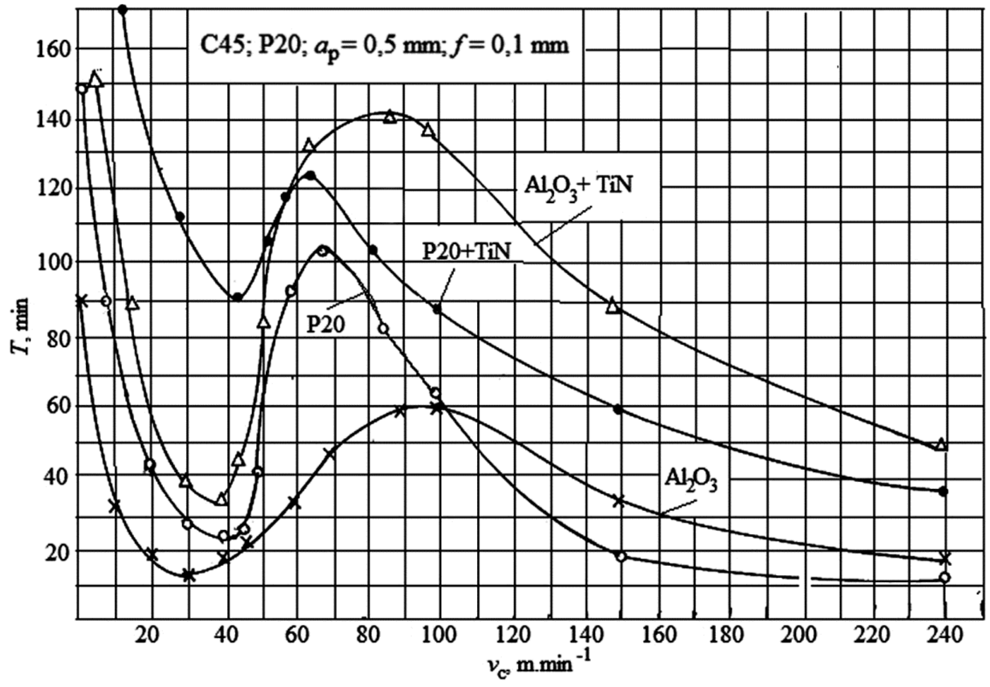

Fig. 6 – Experimental T-v_c dependence obtained by changing of cutting materials (HSS-high speed steel, P20-cemented carbide, Al_2O_3-oxide ceramic, TiN--coating)

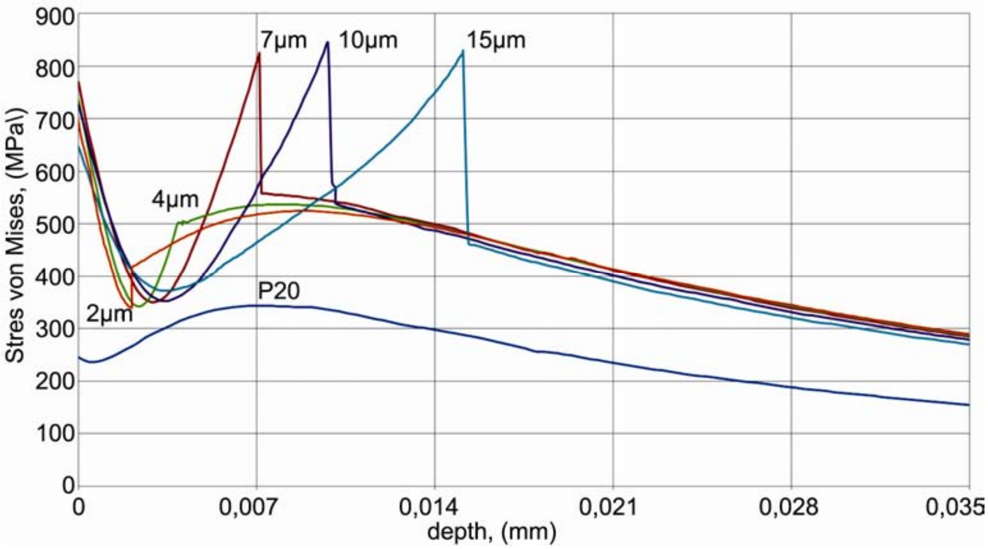

Fig. 7 – Mises stress distribution depending on the depth for sintered carbide tools: conventional and coated. Coating thickness: 2-15 μm

of Stress von Mises. Their maximum values are under contact surface in a thin surface micro-layer and quickly decrease towards the surface.

If coating thickness is $h_p < h$ (h, depth where subsurface maximum Mises (Shear) stress is situated in case of uncoated tool) then maximum stress is concentrated on the tool surface and thus contributes to the higher tool wear. If coating thickness is $h_p > h$ then maximum load stresses are placed on coating – substrate interface. Such coating thickness is more suitable in terms of tool wear, but means higher requirements on coating adhesion quality.

The contact of tool face and chip is situated in the secondary zone of shear deformation. It is the interface chip layer where the material movement speed grows from zero on the tool face up to the chip speed on the border of this layer and the friction coefficient becomes strongly important. It can be supposed that the surface and subsurface stress would increase considering friction and the influence of temperature along the contact involving the influence of friction and plastic deformation of the machined material. The values of subsurface stress increase under the influence of the tangent friction force and the location of maximum subsurface stress increases towards the surface.

Temperature causes that maximum stress is situated on the interface coating – substrate no matter what is the coating thickness. The second most stressed zone is the outer surface due to increasing temperature. It can be supposed that during turning, considering cutting resistance, friction forces and different cutting conditions which influence the values of cutting forces and temperature, the position of the most stressed zones alters in two positions (interface and outer surface). It is a dynamic, multi-parametric process which can be simulated only with certain simplifications. Analyzing the results it is necessary to realize that the original structure of the work-piece material is supposed to be homogenous and isotropic. After chip formation, the chip material can no longer be considered to be isotropic material because of the fibrer-like structure with increased strength and hardness.

Conclusions

The cutting process is a multi-parameters process. The obtained wide-range dependence show that cutting process and its results are influenced by physical-mechanical-thermal changes directly in deformation zone. The wide-range dependence help to understand the nature of physical-mechanical-thermal processes in deformation zone. Moreover, the wide range dependence can help to estimate the optimal cutting speed for achieving the longest tool life that directly depends on cutting conditions and the pair of the tool and machined material. The coating introduces other parameters such as adhesion, coating thickness, hardness, the coefficient of friction etc. into the cutting process. On the basis of experiments, we examined the change of cut layer material separation, chip formation, the change of wear for coated tools and we realized a comparison with the uncoated tools of sintered carbide and ceramics. The coating provides "stability" of *Rz* values what is caused by the different mode of wear of coated tools. The crater wear does not occur on the face of coated tools (that are the wear resistant coatings). Neither due to flank wear, the chips shapes does not change. In some stage of flank wear, the coating is removed. The presented analyses open a wide field of study and research of coating technology, designing multilayered coatings, nanocomposite coatings, adhesion of coatings, layer thickness, material properties of coatings and substrate for high temperatures etc.

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