SURFACE MICRO-TOPOGRAPHY AND ITS CONTROL BY MACHINING PROCESS SCHEDULING

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Abstract: The paper presents the results of experimental research on the surface micro-topography in case of machining. The cutting edge geometry (including its roughness) and its trajectory relative to the workpiece generate what we call the nominal micro-topography of the machined surface. The real micro-topography differs from the nominal one due to: *i)* the deviation of the surface longitudinal profile with respect to the tool trajectory, caused by chip separation of the workpiece material, and *ii)* the deviation of the surface transverse profile with respect to the cutting edge profile, caused by plastic deformation of the detached material. This is way the actual roughness is usually higher than the nominal one.
In other works, we have proposed a machine tool control technique based on optimal reactive process scheduling. Unlike current feedrate scheduling techniques, the proposed technique includes the process quantification into small sequences, called process quanta, and separately optimal setting, for each process quantum. This setting refers to the basic process parameters, namely: *i)* the uncut chip shape, *ii)* the uncut chip dimension, and *iii)* the cutting speed.
This paper addresses the relationship between the scheduled process parameters and the deviation of the actual micro-topography with respect to the nominal one.
Basically, the proposed idea is the control of the longitudinal profile deviation by the adiabatic character of the cutting process and of the transverse profile deviation by the thermal field which appears in the section of the uncut chip.
Using profilography, electron microscopy, and atomic force microscopy, are investigated the relationships between the nature of the part material and cutting conditions, on the one hand, and the surface topography, on the other hand, in the case of interrupted turning.
Finally, it is presented how the research results should be used in optimal process scheduling and what is the performance level, which can be obtained.
Key words: adiabatic cutting process, surface roughness, surface topography, minimum chip thickness, process quantum, machining process scheduling

1. INTRODUCTION

It is currently accepted the idea that if the cutting speed is increased significantly then the amount of heat recovered by tool may drop, and its negative effects are reduced (Guillot et al., 2008 and Tsai, et al., 2005).
Different opinions on this idea emerged in terms of significant differences between the temperatures of the chip and cutting tool, and between these two and part temperature durring processing (Tuğrul et al., 2005).
According to (Tuğrul & Erol, 2007), at the highest possible cutting speeds, 90% of heat generated is recovered in the chip, 5% in the part and 5% in the cutting tool. Others (Puerta Velásquez et al., 2006) suggested that 80% transfers in the chip and 10% in the cutting tools and processed part.
However, all agreed that at high speed cutting the heat remains in chip, making its temperature to rise, while the finished parts remain relatively cold. The decreased time in which heat can diffuse in part material makes this plausible.
On the other hand, the cutting edge geometry (including its roughness) and its trajectory relative to the workpiece generate what we will call the nominal micro-topography of the machined surface. The real micro-topography differs from the nominal one due to: *i)* deviation of the surface longitudinal profile (in direction along of the cutting speed) with respect to the tool trajectory, caused by chip separation of the workpiece material, and *ii)* deviation of the surface transverse profile (in direction perpendicular to the cutting speed) with respect to the cutting edge profile, caused by plastic deformation of the detached material. Therefore, the actual roughness is almost always higher than the nominal one.
In other works (Marin et al, 2009) we have proposed a machine tool control technique based on optimal reactive process scheduling. Unlike the current feedrate scheduling techniques, the proposed technique consists in dividing the process into small sequences, called process quanta, and separately optimal setting, for each process quantum. This setting includes the basic process parameters, namely: *i)* the uncut chip shape, *ii)* the uncut chip dimension, and *iii)* the cutting speed. Consequently, the process optimization problem is

solved for each process quantum, and not for the entire process. On the other hand, the restriction set includes the surface roughness restriction.
This paper addresses the relationship between the scheduled process parameters and the deviation of the actual micro-topography with respect to the nominal one. The aim is that by controlling this deviation, the process productivity can increase, in cases when the productivity is limited by the surface roughness restriction (which often is the case).
Basically, it is proposed the idea of controlling the longitudinal profile deviation by the adiabatic character of the cutting process, and of the transverse profile deviation by the thermal field which appears in the section of the uncut chip. Specifically, as control variables of the two aspects are proposed the minimum chip thickness and the cutting speed, while the cutting edge geometry (including its roughness) is considered constant for a given machining process (Leonte, P. et al, 2010).
The physical experiments are represented by interrupted turning, to which the successive interruptions are the milestones that mark the process quanta that the process has been divided.
In this paper, the interrupted turning with high cutting speed is experimentally studied. The aim is to assess whether the thermal aggression to which is subject the layer of the machined surface can be diminished, in order not to generate significant surface roughness. Under these conditions, the surface roughness is almost exclusively due to its nominal topography, which, in turn, is directly dependent on the geometry and microgeometry of the tool edge.
Further, by appropriate changing of the tool edge geometry, surface roughness can be reached as to be equal to edge roughness, which would allow an economical part finishing. To this end, the cutting process was approached as adiabatic process that takes place in a specific cutting thermodynamic system. Then, through physical simulation, has been studied adiabatic nature of the cutting process.
The paper is arranged as follow: the next section presents definition, modeling and assessment of the cutting thermodynamic system. The third section sums up the experimental investigations as regard the surface topography, in the case of adiabatic interrupted turning. The fourth section shows how the surface micro topography is controlled by reactive process scheduling. A conclusion sumarises the main results presented and discusses about the idea of finishing the surfaces by turning.

2. CUTTING THERMODYNAMIC SYSTEM

2.1 Modeling of the cutting thermodynamic system

a) Modeling as open system

The cutting thermodynamic system will be modeled as a thermodynamic system in steady flow. Such thermodynamic system is composed of a material that performs a series of energy transformations during flowing. Let us consider *m* the mass flow of material input in the thermodynamic system, having specific internal energy u_1. At the output of the system, there is the same material flow but having specific internal energy to become u_2. Material flow is given by

$$m = \rho v s t \tag{1}$$

where: ρ - is the density of material;
v – cutting speed;
s – feedrate;
t – depth of cut.

In addition, we used heat flows q_m, q_p, q_s which is the amount of heat per time unit changed with the environment, part, and tool, respectively, as can be seen in Figure 1. Material that supports the energy transformations is the detached material. The cutting thermodynamic system is limited by the following (Fig. 1):

- the limit between the thermodynamic system and the part P is the AD area of the surface resulting from the cutting process;
- the separation limit from tool S is the AB surface between the chip and tool;
- the separation limit from enviroment is the C_1C_2 surface of the workpiece.

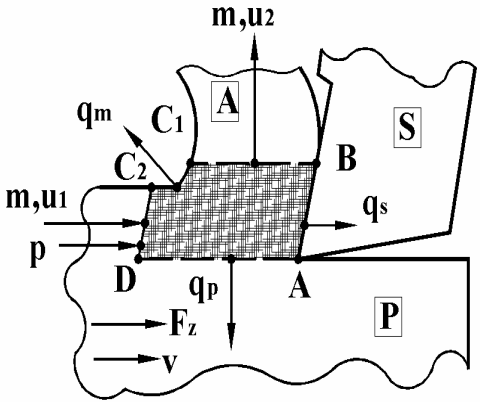

Fig.1. Modeling as open system

Input surface of the material flow is the non-deformated section of the chip, DC_2, and the exit surface of the material flow is the BC_1 section of the deformed chip.
During the thermodynamic cycle the system is exchanged mechanical work, which is given by consumed cutting power *p*, expressed by the relation:

$$p = F_z v \tag{2}$$

where F_z is the cutting force;
The heat exchange *q* is given by:

$$q = q_m + q_p + q_s \tag{3}$$

The internal energy variation Δu is given by:

$$\Delta u = m(u_2 - u_1) \tag{4}$$

The thermodynamic cycle, in which the detached material is subjected, meets the first law of thermodynamics, which in this case is given by:

$$mu_1 + p = mu_2 + q \quad (5)$$

b) Modeling as closed system

Let us consider a limited operation period of the cutting thermodynamic system. An example could be given as the particular case of interrupted cutting. Cutting thermodynamic system can then be designed as a discrete thermodynamic system (Fig.2).

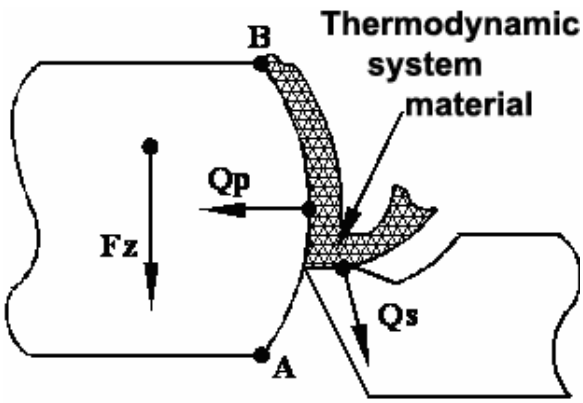

Fig. 2. Modeling as closed system

In this case, as thermodynamic system limits can be considered the final surface resulting from the movement of the tool and the contact surface between tool and chip.

Material that supports the energy transformation in this case is the chip detached by the tool, having mass M, given by:

$$M = \rho stl \quad (6)$$

where l is the length of the cutting, equal to AB arc.

Mechanical work L is computed by considering the cutting force F_z performed along length l of the tool trajectory, according to the relation:

$$L = F_z l \quad (7)$$

The exchange heat Q, is given by:

$$Q = Q_p + Q_s \quad (8)$$

where Q_p and Q_s represents the heat dissipated in part, and tool respectively.

The internal energy variation ΔU is given by:

$$\Delta U = Mc\Delta T \quad (9)$$

where: c - specific heat of workpiece material;

ΔT - is the increase of the detached material temperature.

First principle of thermodynamics, in this case is written as:

$$\Delta U = Q - L \quad (10)$$

2.2 Definition of the adiabatic cutting process

In thermodynamics, adiabatic transformation is studied along with other transformations as isotherm, isobar and izocore transformations. In the case of the thermodynamic system associated with the cutting process, we consider that transformation supported by the detached material is adiabatic if the total heat exchange between this material and the surface layer is zero.

Consequently, the cutting process is adiabatic if the amount of heat transmitted to the superficial layer by conduction, internal stressis and residual deformation is zero. In other words, the surface layer during cutting is subject to a thermomechanical avoid load.

In nature, a perfectly adiabatic transformation it does not exist. Therefore adiabatic transformation is just a reference, any real transformation have an adiabatic character more or less pronounced. Similarly, we consider the adiabatic cutting as a reference, which could mean a cutting process where: *i)* the "aggression" of the thermomechanical field to the surface layer is zero, *ii)* the limit of separation between the surface processed and the actual size of the piece is strict, and *iii)* the mechanical work of cutting force is fully recovered as change of the internal energy of the material detached by cutting.

Starting from the above considerations, we study the conditions affecting the "adiabatic" attribute of the cutting process, considering the fact that, the cutting is more adiabatic as much as the superficial layer is less affected. The metric of the „cutting adiabatics" should be based on assessment of the total heat exchange or the effect of the total heat exchange, last being an alternative more attractive in terms of industrial practice.

2.3 Adiabatic index of the cutting process

To assess the "cutting adiabatics" we propose a metric based on the "adiabatic index", IA, given by:

$$IA = 1 - \frac{\Delta T_s}{\Delta T_a} = \frac{T_a - T_s}{T_a - T_0}$$

where: T_a – chip temperature;
T_s – superficial layer temperature;
T_0 – detached material temperature.

If IA=1, then the cutting is adiabatic. If IA=0, then the cutting is izoterm.

In Fig.3 is presented the processed surface temperature, measured with a thermovision camera (Fig.5), along the cutting speed and perpendicular on this direction. The refresh frequency of the thermovision camera is 50 frames per second. It was noticed that in the points near cutting zone, be it before or after tool passing, the temperature is the same. This observation show that T_s=T_o aproximativelly which prove that cutting process was an adiabatic one.

3. EXPERIMENTAL INVESTIGATION

3.1 Experimental set-up

It was experimentally researched the interrupted

adiabatic turning process. We used a steel disk with a diameter of 500 mm, which is located on a frontal numerically controlled lathe. The eight brands of steel samples was cut with dimensions 60x60x25 mm (Fig. 4) and was turned with cutting speeds of up to 36 m/s. We used two types of cutting tool Garant, one being a metal carbide insert, HB712 degree mark, and another one being a boron nitride (CBN) insert. The experimental set-up was builded as shown in Fig.5.

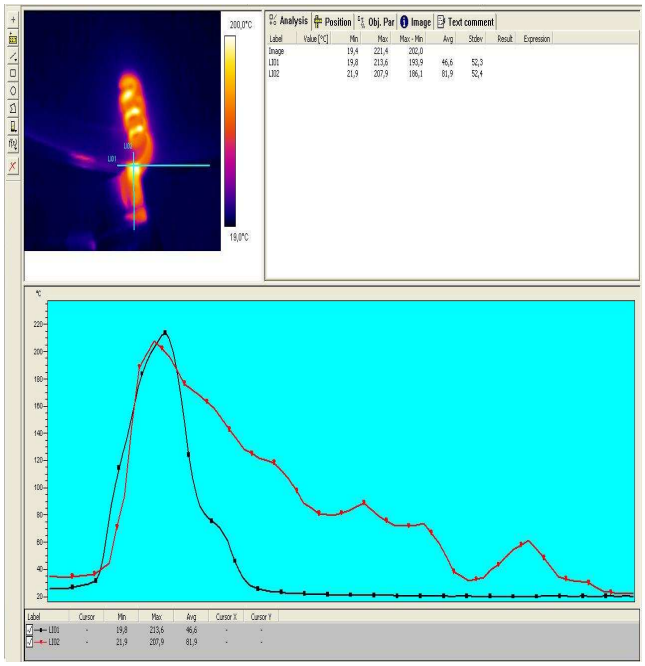

Fig. 3 Temperature variation along the cutting speed and perpendicular to its direction

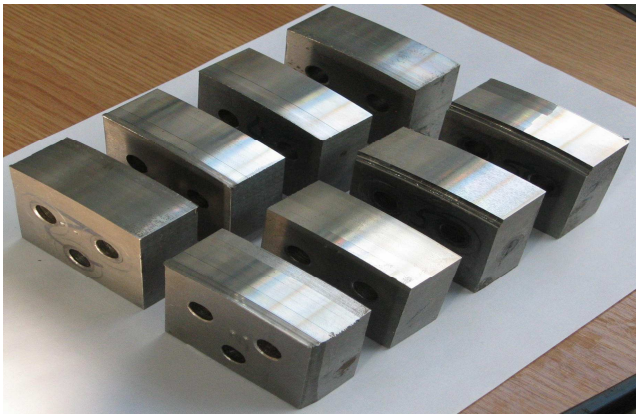

Fig. 4 Processed samples

3.2 Transverse profile distortion

It was noticed that between nominal and real transverse profile there is a difference (Fig.6), which varies with cutting conditions, part material, and even cutting tool material (Fig.7). This was explained by the fact that the profile is resulting from plastic deformation processes whose development is influenced by significant disturbance, ultimately leading to a distortion of the transverse profile.

As a result, there was the need to assess the distortion of the transverse profile. To this end, we used the comparison between nominal profile and actual profile analytical model obtained by regression as a polynomial two degree function.

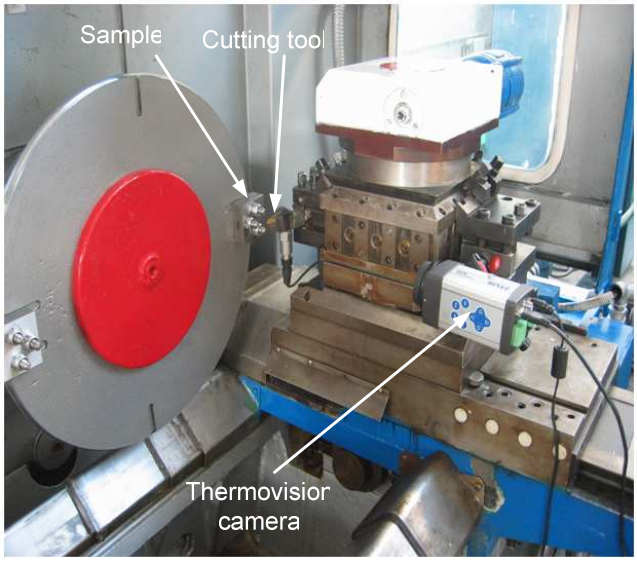

Fig. 5 Experimental set-up

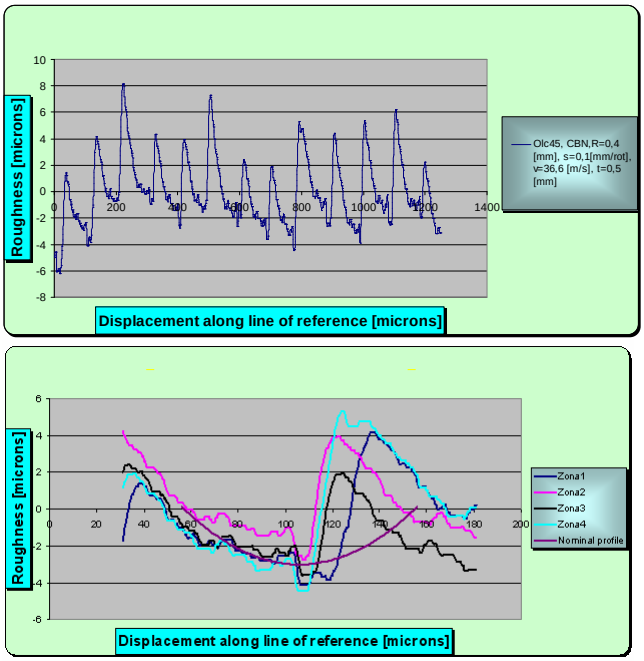

Fig. 6 Transverse profile of the longitudinal roughness in various areas of the surface and the nominal profile

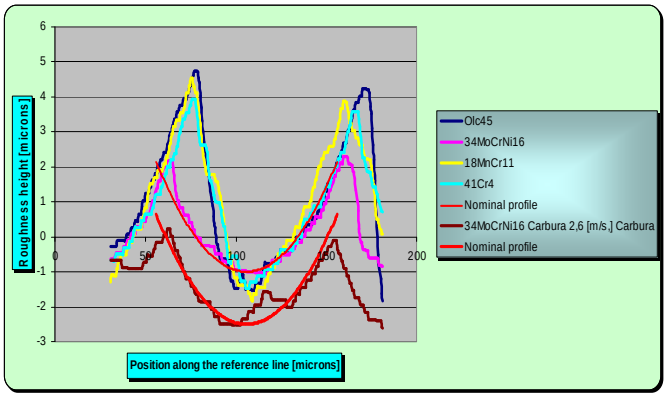

Fig. 7. Transverse profile of the longitudinal roughness for various processed materials

In Fig. 8, are presented the actual and the nominal transverse profiles, and the analytical models for the two profiles.
The nominal profile is an arc with 0.4 mm radius. For the actual profile, the radius of the curvature *r* was calculated as follow.
Analytical model of the actual profile is given by:

$$y = ax^2 + bx + c$$

The profile curvature C has the expression:

$$C = \frac{1}{r} = \frac{y''}{[1+(y')^2]^{3/2}}$$

The radius of curvature *r* is given by:

$$r = \frac{[1+(2ax_0+b)^2]^{3/2}}{2a}$$

where x_0 is the abscissa of peak.

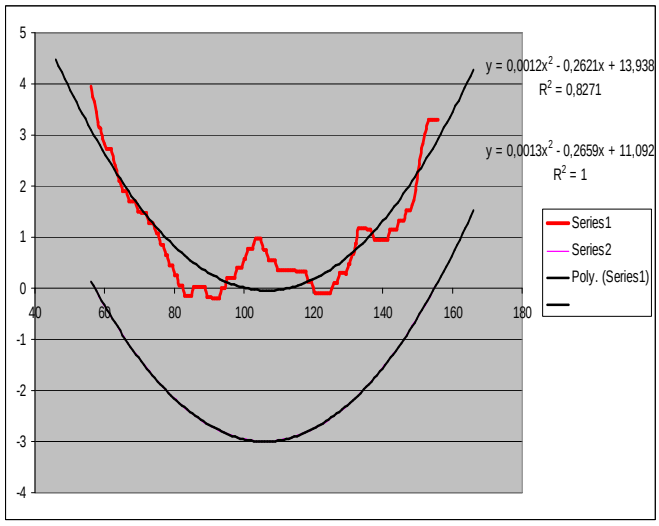

Fig. 8 Evaluation of the real transverse profile distortion compared with the nominal profile

The tip radius of curvature *r* and the variance related with the nominal profile R^2 was used as evaluation criteria for level of distortion of the transverse profile relative to the nominal one.
In Fig. 9 is presented the variation of the curvature radius *r* with respect to the nominal value r = 400 microns, for different cutting conditions, processed materials, and tools.
It is noted that in the case of 34MoCrNi16 material the radius of curvature of the profile differs very little in relation to the nominal value of 0.4 mm, which is kept on all cutting speeds investigated.
It is also obvious how it is distorted the profile in all cases, since the actual values of the curvature radius is obviously lower than the nominal ones. This means that the distortion is represented by the decrease of the curvature radius, likely associated with increasing of the profile height (i.e. the real roughness increase compared with the nominal).

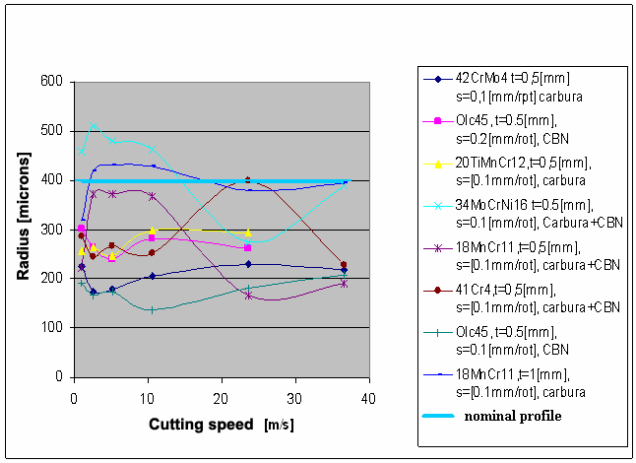

Fig. 9. Real transverse deflection profile compared with the nominal profile

In case of some materials, such as OLC45, 42CrMo4, curvature radius is 0.2 mm at all speeds tested. This indicates that the materials deformation processes that produce transverse profile distortion are important in all cases.
Moreover the profile distortion assessed with variance R^2 of the actual profile compared with the nominal profile varies significantly depending on the processed material as evidenced by the data presented in Fig. 10.

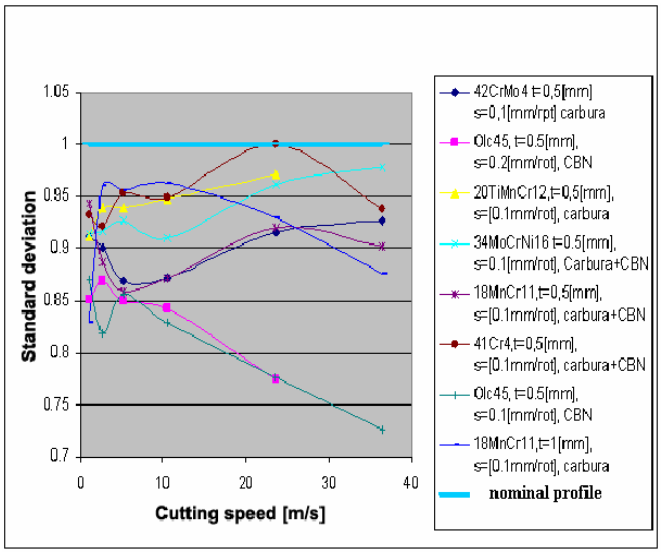

Fig. 10. Variance R^2 of the real profile for different tool materials and processed materials

It is noted that a group of materials such as 41Cr4, 20TiMnCr12, 34 MoCrNi16 the variance R^2 is close to the unit value, which shows a good correlation between actual profile and cutting edge micro-profile. In contrast to these, in case of OLC45 the variance R^2 has much lower values, both in case of federate value of s = 0.1 mm/rev, as well in case of federate value of s = 0.2 mm/rev, which indicates a less favorable behavior regarding the correlation between tool profile and surface micro profile.
Except this material, to all other we observed an

increase in variance with increasing cutting speed.

3.3 Minimum chip thickness

In order to explain the difference in shape between the actual transverse profile and the nominal one we considered the link between this difference and the thickness of the chips detached. From Fig. 12 is observed that the difference is always in the CB area of the nominal profile where the chip thickness value are low, tending to zero.

As the nominal chip shape is shown in Fig.11 the chip thickness varies greatly and this happens especially in the area where the tool generates profile across the surface roughness profile. Considering that the tool edge is not perfectly sharp, and is the result of connections with the edge faces, with the sharpening radius of about 3…5 micrometers, results that the profile distortion occurs when the thickness of chips is less than the nominal range of edge sharpening radius.

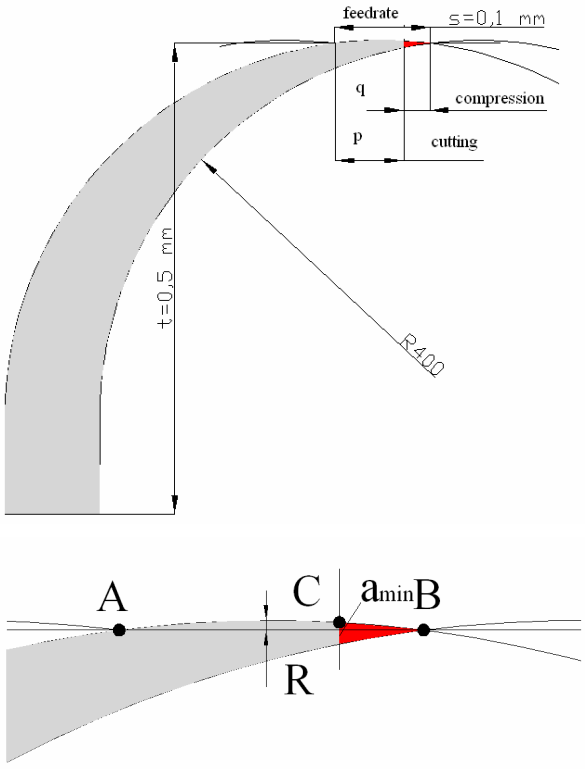

Fig. 11 Scale representation of the nominal chip shape and detail

Examining the experiments conducted in the laboratory, we noticed a correlation between point C of the nominal profile, where nominal chip thickness becomes comparable to the sharpening radius of the cutting edge, and the point where transverse profile distortion starts. It can be said that there is a CB zone of width q, where instead of cutting is compaction (Fig. 11). Chip thickness corresponding to the nominal point C will be called the minimum chip thickness. Its value varies with cutting speed (Fig. 13).

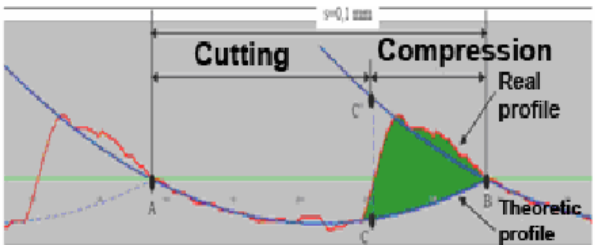

Fig. 12 Actual and nominal profile represented at the same scale, both horizontally and vertically

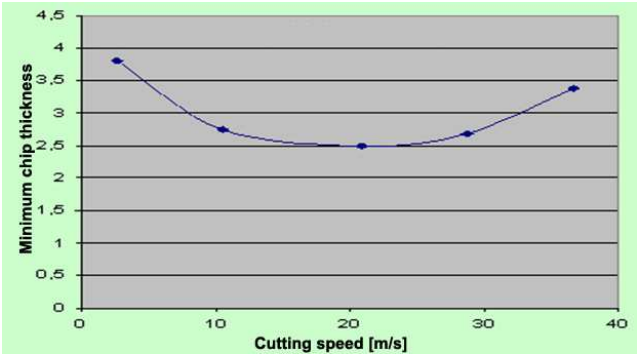

Fig. 13 Minimum chip thickness versus cutting speed

3.4 Surface topography

In order to view the processed surface topography we used its 3D representation. As a first stage the processed surface was scanned with the device Surtronic 3 +, successively at intervals of 0.01 mm.

The profiles obtained were then represented using Matlab software resulting from profilography surface topography (Fig. 14). The scale on X direction is the same as in the Y direction, however the Z direction was deliberately increased by approx. 100 times for observing the specifics profiles. It is noticed the fact that on one flank the cutting edge clearly left its mark, while the other flank is affected by the phenomenon of compression of the material. The same is observed in case of the topography study using the electron microscopy (Fig.15).

3.5 Performance experimental testing in the case of interrupted adiabatic turning process

During performance testing of the adiabatic finishing, the surface longitudinal and transverse profiles obtained are presented in Fig. 16. The surface roughness is decreased till R_a=0.4 microns.

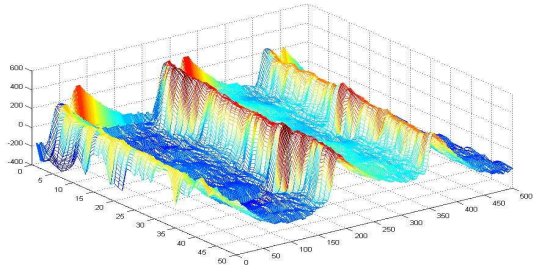

Fig. 14 Topography area studied by profilography

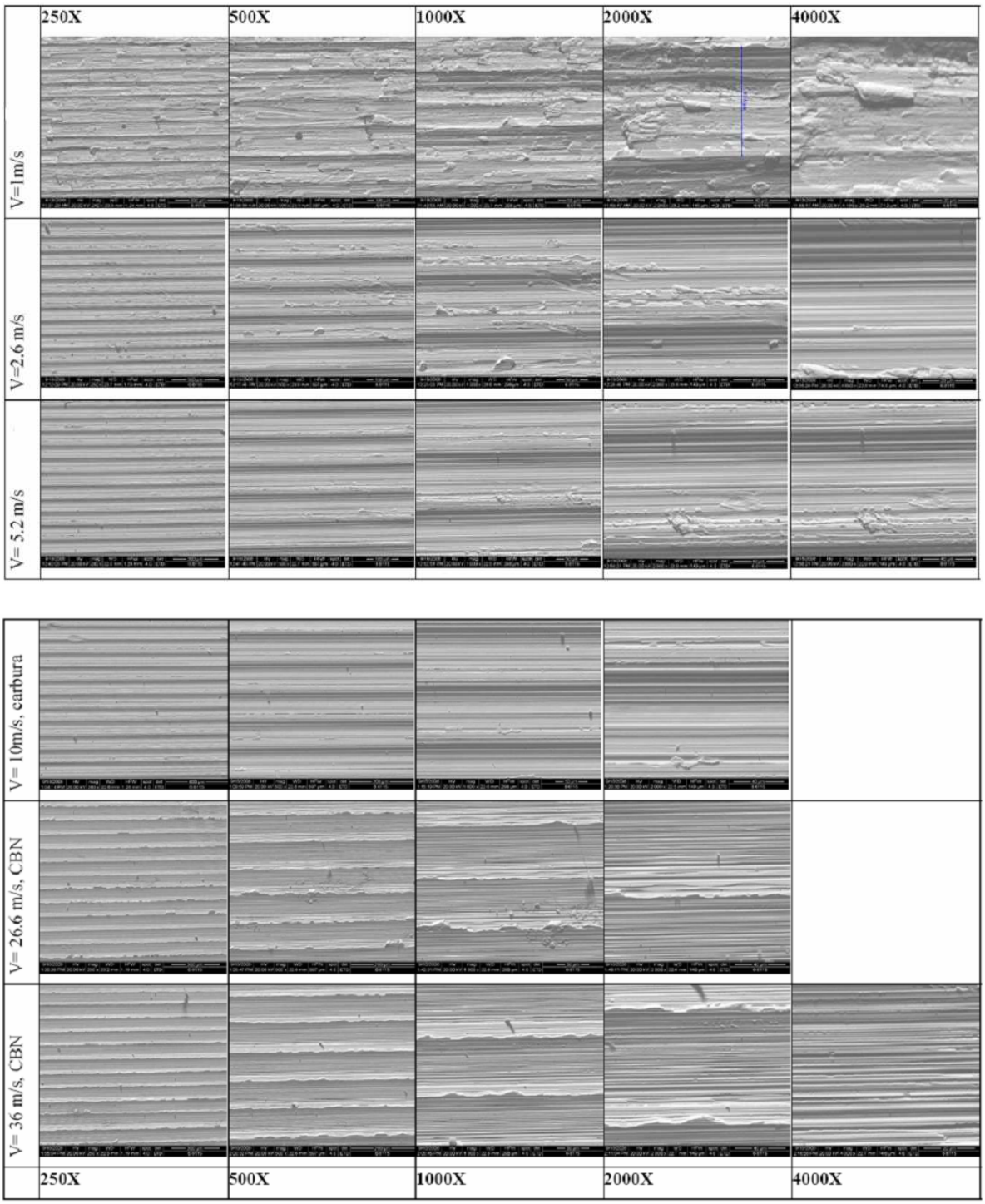

Fig.15 Surface topography studied by electron microscopy

4. SURFACE TOPOGRAPHY CONTROL BY PROCESS SCHEDULING

Scheduling process means considering a number of process quanta where each quantum has its own set of basic parameter values. As shown in Fig.17, in case of turning, the machining consists of wrapping of the surface final profile 1.2 ..(i)..(l), with tool edge profile 1.2 ..(j) .. m of the cutting edge while the initial profile of the surface is 1..2..(k)..(n).

A quantum consist in the displacement of the cutting edge from previous location, where is tangent in A point to final profile, to current location where is tangent in B point at the some profile. Points N, B, C, and M limit the uncut chip.

The movement from previous to current location occurs during Δt_{AB} time and consists of X_{AB} and Z_{AB} translations performed by the tool and rotation φ_{AB} performed by the workpiece. Quantum optimization involves maximizing the A'AB area in terms of meeting the following restrictions: $L_{AB} < L_{adm}$, to avoid instability; $a_{AB} < a_{adm}$ to avoid destruction of cutting edge; $R_{AB} < R_{adm}$ to avoid exceeding the permitted level of roughness and $\alpha_{AB} > 90$ degrees to avoid real micro-topography deviation compared to the nominal one.

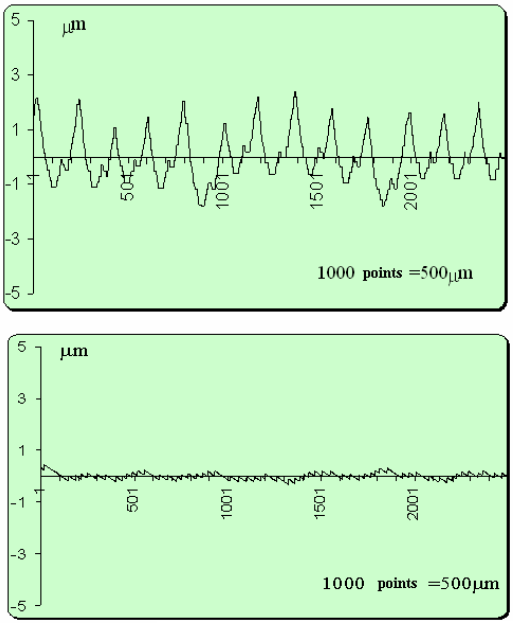

Fig. 16 Transverse profile (top) and longitudinal profile (below) in the case of finishing by adiabatic turning

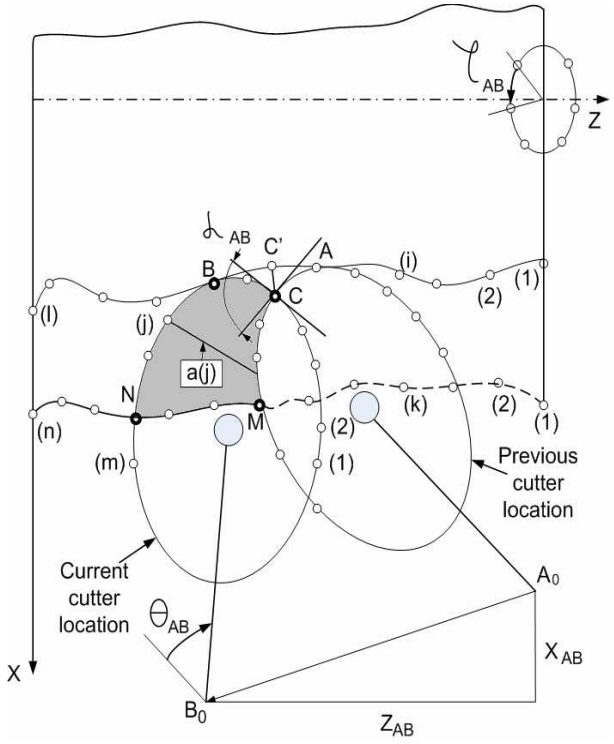

Fig.17 Process quantum basic parameters:
a) cinematic parameters: X_{AB}; Z_{AB}; θ_{AB}; φ_{AB}; Δt_{AB},
b) uncut chip parameters: L_{AB}=NBC; a_{AB}=max{a(j)}; A_{AB}=Area(NBCM); R_{AB}=CC'; α_{AB}.

5. CONCLUSIONS

Analyzing the results, we can conclude:

• Studying the shape of the roughness transverse profile in the case of adiabatic turning is observed that one side is close to the nominal shape and the other side, namely that in the area where the chip thickness is smaller than minimum value, is different.

• As a result of the roughness study by profilography, scanning electron microscopy as well as by atomic force microscopy, it is confirmed the surface topography resulting with different speed machining.

• By finishing tool cutting edge, it is possible to obtain a cutting surface whose roughness is significantly decreased.

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