Proceedings in MANUFACTURING SYSTEMS
Proceedings in Manufacturing Systems, Vol. 5 (2010), No. 2 ISSN 2067-9238

OPTIMIZATION OF CUTTING CONDITIONS WHEN FIVE AXIS MILLING USING BALL NOSE END MILLS. THEORETICAL STUDY

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Abstract: *This paper tackles the concept of parametric graphical design of the undeformed chip when five axis milling with ball nose end mills. Based on this model, the assessment of the cutting conditions and the optimization of these conditions with respect to the cross sectional area of the chip, the contact length of the cutting edge with the undeformed chip and the tool tilting angle. These cases will be studied and summarized and based on the results, experimental validation will be proposed.*

Key words: *undeformed chip, contact length, cross sectional area, ball nose end mill.*

1. INTRODUCTION

Modeling the metal cutting process has been a constant concern of researchers in this field [1–5], etc. Nevertheless, so far, no model has been developed to be efficient enough in order to render the conditions during the cutting process and estimate the output of the metal cutting process on account of these.

Every case/attempt to model the metal cutting process has a certain scope which takes into account certain input variables.

As for ball nose end mills, the modeling of the cutting process is more complex than in the case of simple end mills, as the cutting speed varies along the main cutting edge, laid on a hemisphere, in straight line or in spiral.

These mills are used to machine complex sculptured surfaces, on three and five axis machines. By tilting the tool with respect to the surface to be machined, the modeling process becomes more complicated through the range of input variables.

Theoretically and practically, these tools can be tilted depending on the possibilities of the machine tool and the allowance of the piece configuration, by one or two directions, i.e. by the feed direction, by the pick feed direction or by a combination of the previous two (Fig.1).

In the topic-related studies, the tilt of these tools is studied only by one direction (either by the feed direction, or by the pick feed direction).

Regardless the nature of the modeling type used in these studies, it is noticeable that most of them tackle the tool tilts at one of the angles 10°, 15°, 30°, 45°, 60° or 75° [6–10] and the list goes on. There is a workpaper which mentions the tool tilt at an angle of 17° on the pick-feed direction (θ_n) [11], yet, without justifying the choice of this angle.

Another conclusion drawn from these studies is that there isn't a formula which allows the calculation of the effective cutting diameter of the tool when using it tilted by both directions. This effective cutting diameter is very important when the worker wants to maintain the cutting speed recommended by the tool manufacturer for a type of material to be machined. Based on the effective diameter, the rotation of the tool can be assessed in order to obtain the desired cutting speed representing also the effective cutting speed (V_{eff}).

In this paper a parametric graphic model will be described. This model's purpose is to solve the above mentioned problems. Through parametric design one can understand the operation of inter-relating the graphical entities that compose the model. In this way when one of the entities is modified, it will affect all the related entities as well.

Parametric design is realized by means of CAD application CATIA V5 but it can be achieved with all the CAD software applications that allow these types of inter-relating and boolean operations with solids.

2. DESCRIPTION OF THE MODELING PROCESS

2.1. Modeling the cutting process

In this case a graphical model was chosen as a starting point because these models have the advantage of a good representation of the final result as well as the possibility of identifying and correcting the mistakes as they appear while building the model.

The starting model is the one proposed by Cosma M. [9] in his doctoral thesis, for the case of three-axis milling. This model is to be implemented in parametric design for a better and quicker use, the extension for the case of five-axis milling, the simulation of the feed movement and the optimization of cutting conditions based on the desired outcome of the process.

This model generates geometrically the undeformed chip based on the parameters of the cutting regime i.e. the tool radius, the feed/tooth, the axial depth of cut and the radial depth of cut.

The main purpose of this parametric model is to identify the optimum tool inclinations correlated with the

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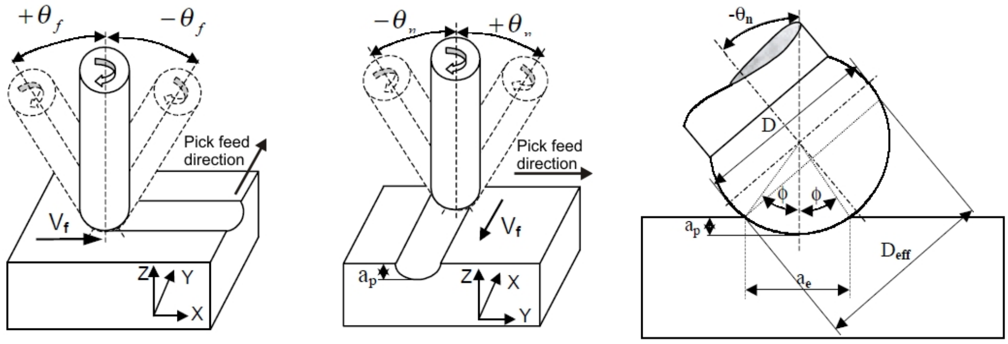

Fig. 1. Tool tilting by one of the two directions (feed or pick feed direction) (adapted by [12]).

cutting regime so as to obtain the desired cutting conditions (desired variation of cross sectional area of the undeformed chip and the contact length of the cutting edge with the undeformed chip).

These cutting conditions are important when designing equipments by means of the results from the cutting processes involved in their making.

The first step for the making and parametric design implementation of the model for the situation of five-axis milling using ball nose end mills is to identify the entities/parameters that influence the outcome of the cutting process.

The identified input variables that determine the shape of the undeformed chip are the following:

- tool radius R;
- feed/tooth f_z;
- axial depth of cut (a_p / a_a);
- radial depth of cut (a_e / a_r).

In addition to this list there are the variables that contribute to the cutting edge's conditions of entering and leaving the chip:

- feed direction tilting angle θ_f (Fig. 1);
- pick feed direction tilting angle θ_n (Fig. 1).

This model is also destined to obtain the effective cutting diameter D_{ef}, based on the parameters previously listed. This diameter will be useful when calculating the effective cutting speed V_{ef} and consequently when setting the proper spindle speed for a certain type of material to be machined.

The model was created using the Part Design module assisted by Generative Shape Design. The first step was to define the parameters R, f_z, a_p, a_e. The next step was to associate these parameters with the graphical entities that contribute to the formation of the undeformed chip. These entities are described by Cosma, in his paper [9] as follows:

- a plane (1) situated at a distance of $R - a_p$ from the center of the spherical tip of the mill, representing the initial surface of the workpiece:

$$z = R - a_p\,; \tag{1}$$

- a sphere (2) representing the first rotation of the tool:

$$x^2 + (y - f_z)^2 + z^2 = R^2\,; \tag{2}$$

- a sphere (3) representing the second rotation of the tool:

$$x^2 + y^2 + z^2 = R^2\,; \tag{3}$$

- a cylinder (4) representing the previous pass of the tool:

$$(x - a_e)^2 + z^2 = R^2\,. \tag{4}$$

The undeformed chip is obtain, according to [9], by intersecting the cylinder, the two spheres and the plane. Based on this model the actual model was defined, replacing the spheres with the effective shape of the tool, for a better visualization and for highlighting the tool inclination with respect to the surface to be machined (Fig. 2).

Associating the parameters described above to these entities, it becomes very easy to modify the geometrical characteristics of the graphical entities, as a function of the effective parameters of the cutting process.

Another advantage when working with parametric design is that although relations between parameters can be defined, the graphical entities can be independently positioned with respect to a global coordinate system.

The representation of the cutting edge through a plane and the polar multiplication of this plane around the axis Z, determines the successive positions of the cutting edge at a certain chosen interval (5° for example), along its trajectory taken at one rotation of the tool (Fig. 3). These intervals can be chosen depending on the precision for which the results are to be obtained.

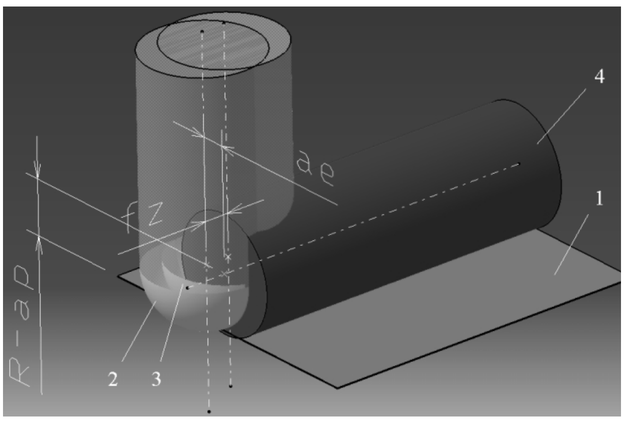

Fig. 2. 3D representation of the solids that generate the undeformed chip.

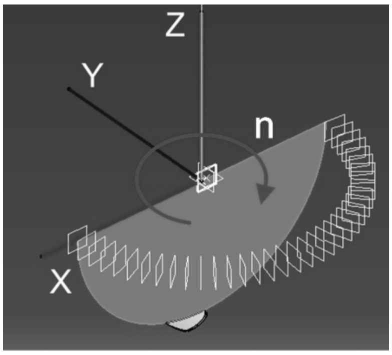

Fig. 3. Successive positions of the cutting edge along its trajectory for a rotation of the tool.

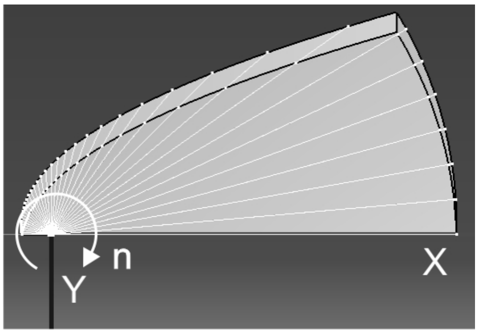

Fig. 4. Intersections with the undeformed chip in different areas along the cutting edge's trajectory.

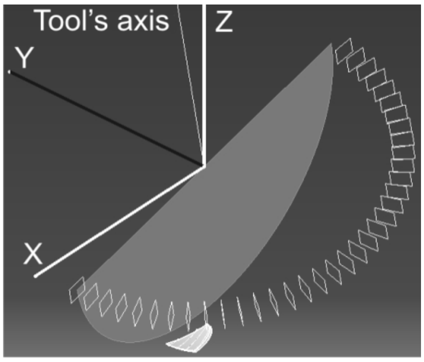

Fig. 5. The position of the cutting edge when inclining the tool differently on each direction.

Intersecting the planes distributed around the axis Z (Fig. 3) with the undeformed chip, result sections of the undeformed chip, placed along the trajectory of the cutting edge for a rotation of the tool (Fig. 4).

The above presented are only valid for the situation when the tool is in a vertical position with respect to the surface to be machined (it has no inclination along one of the tilting directions).

To obtain similar data for the situation when the tool has a certain inclination after one or two directions, the plane that describes the cutting edge needs to be tilted.

Because this plane is a parametric entity, all the other planes that were obtained through polar multiplication will also become inclined with respect to the initial plane. These inclinations are defined with respect to axes X and Y using parameters θ_f and θ_n inclination on the feed direction and inclination on the pick-feed direction respectively.

In Fig. 5, the position of the cutting edge for a tilting angle of 5° on the feed direction (θ_f) and 15° on the pick-feed direction (θ_n) is being presented.

On the intersection operation resulting graphical entities, which represent the undeformed chip's cross sections, measurements can be carried out to obtain data like cross sectional area of the undeformed chip and the contact length of the cutting edge with the undeformed chip.

These measurements can be exported in an Excel file by means of a Visual Basic Macro especially designed for this operation. The data once exported into the Excel file, can be used to raise variation charts and data filter.

Having this model and using the methodology described, it is easy to optimise the cutting conditions along the trajectory of the cuttig edge for a rotation of the tool.

2.2. Cutting force estimation

The maximum area obtained using the graphical model can be correlated with the necessary cutting force for the cutting process by making an analogy with the calculation method proposed by Seco tool manufacturer [13]. They have devised a formula for calculating the cutting force based on the mean chip thickness, as follows:

$$k_c = \frac{1 - 0.01 \cdot \gamma_0}{h_m^{mc}} \cdot k_{c1.1}\,, \tag{5}$$

where:

- γ_0 – the effective tilting angle;
- mc – exponent (table given based on the type of material to be machined);
- $k_{c1.1}$ – the cutting force for a chip having the thickness of 1 mm [N/mm^2] (table given based on the type of material to be machined);
- h_m – mean chip thickness [mm].

The formula for calculating the mean chip thickness is given as follows [13]:

$$h_m = \frac{360 \cdot f_z \cdot a_e}{\pi \cdot D_c \cdot \omega_e} \cdot \sin k\,, \tag{6}$$

where:

- f_z – the feed/tooth [mm/tooth];
- D_c – the tool diameter;
- ω_e – engagement angle;
- k – main lead angle.

This formula, together with the table containing the forces can be found in the tool catalog of other tool producers as well [14], but because for the experiments Seco tools will be used, the correspondence with this data will be made from the tool catalog of this producer.

Within the methodology previously described, the term of "cutting force per mm^2" is used which is not quite correct. According to the International Measurement System force applied on a surface generates pressure and it is measured in [Pa] or [N/m^2]. If it were to analyze the formula (5) one can notice that the resulting measurement unit is not [N/mm^2] used in this context.

Probably this measurement unit is used to underline the force necessary to remove a chip with a surface of 1 mm^2.

Because the surface concept is involved it is highly appropriate to replace the term in relation (5) that includes the mean chip thickness and the tilting angle of the tool with the maximum area of the undeformed chip's cross section. The calculation of the mean chip thickness is being done by taking into consideration f_z, a_e, D_c, sin K and ω_e.

All these parameters can be found in the modeling procedure described above. Moreover, by means of the parametric model, the area/surface on which the force is applied can be extracted directly.

These two terms, $\frac{1-0.01\cdot\gamma_0}{h_m^{mc}}$ and the undeformed chip's cross sectional area, have a common ground: the way the cutting edge enters and leaves the chip as well as the resistance encountered because of the machined material.

It is known that the main leading angle K and the tilting angle γ_0, modify the area of the undeformed chip's cross section and thus the necessary amount of force to remove that chip.

The simulation performed based on the described model takes these parameters into consideration when it generates the sections of the undeformed chip. If the result is multiplied by the specific cutting force, the necessary quantity of effort to remove that chip is obtained:

$$k_c = A_{sa\max}\cdot k_{c1.1}\,, \quad (7)$$

where $A_{sa\max}$ – the maximum area of the cross sections of the undeformed chip.

Practically, taking into account the maximum area of these sections, the maximum necessary cutting force can be estimated being equivalent with the necessary force needed when the cutting edge arrives at the biggest area of the chip that is being removed.

On this hypothesis it is recommended to use the maximum area of the cross sections of the undeformed chip for calculating the necessary cutting force necessary to remove a certain amount of material. The formula for calculating the mean chip thickness is no longer needed if it is to use the parametric model described.

3. CASE STUDY

The results of this parametric graphical model are the way the cutting edge enters and exits the chip, the volume of the undeformed chip, the variation of the cross sectional area of the chip along the cutting edge's trajectory at a rotation of the tool, the contact angle of the cutting edge with the workpiece material as well as the theoretical contact length of the cutting edge with the undeformed chip. These data obtained from the model will be correlated in this case study with the cutting force according to relation (7).

Because some machine tools do not allow big inclinations of the tool with respect to the surface to be machined and because some pieces have a complex configuration that do not allow big tilting angles cause of the risk of collisions, this study will take into account tilting angles between 0° and 20°.

According to the tools acquired, the study will be performed for a surface finish operation with a ball nose end mill having $D = 2R = 14$ mm, $z = 2$ teeth and the cutting regime $f_z = 0.1$mm/tooth, $a_p= 0.3$ mm, $a_e = 0.3$ mm. The cutting speed to be used is $V = 250$ m/min and it will dictate the necessary rotation when the effective cutting diameter will be measured.

For this study there will be two chosen situations, for annealed C45 workipece material, situated at opposite extremities in what regards the cutting conditions i.e. the contact length of the cutting edge with the tool:

- the cutting edge enters the chip in the area of big thickness and at a small contact length;
- the cutting edge enters the chip in the area of big thickness and at a long contact length.

It was chosen that the cutting edge should enter the chip in the area of big thickness, similar to the classical situation of climb milling, because of the technical recommendations for this type of milling.

The purpose of the study is to highlight the differences between the two situations similar from the cutting regime point of view but different from the cutting conditions point of view.

3.1. The cutting edge enters the chip in the area of big thickness and at a small contact length

Based on the proposed model it was identified that the negative inclination of the tool on the feed direction (θ_f) allows the cutting edge to enter the chip in the region where the thickness is big and having a small contact length with the chip.

This negative inclination on the feed direction combined with the positive inclination on the pick-feed direction (θ_n) creates a small contact length of the cutting edge with the undeformed chip.

The variation of the cross sectional area of the undeformed chip for this case is presented in Fig. 6.

It can be easily noticed that the cutting edge engagement angle is inversely proportional with the inclination value. The more the tool is being tilted, the less the tool stays in contact with the workpiece. This way the same amount of material is being machined but on a shorter engagement of the cutting edge than when machining with the tool in a vertical position.

The variation of the contact length on the cutting edge with the chip, according to the cases presented in Fig. 6, is illustrated in Fig. 7.

Concluding the analysis for this case, the following inclination has been chosen: −20°(θ_f) with 5°(θ_n). The maximum area of the cross section for this case was measured to be $A_{sa\max} = 0.00811$ mm^2 and the contact length of the tool with the undeformed chip $l_c = 1.277$ mm.

The cutting force necessary for machining annealed C45 material (the type of material to be used for experimental validation of the model) based on relation 7 becomes:

$$k_c = 0.00811\cdot 1500 = 12.165\ \text{N}\,, \quad (8)$$

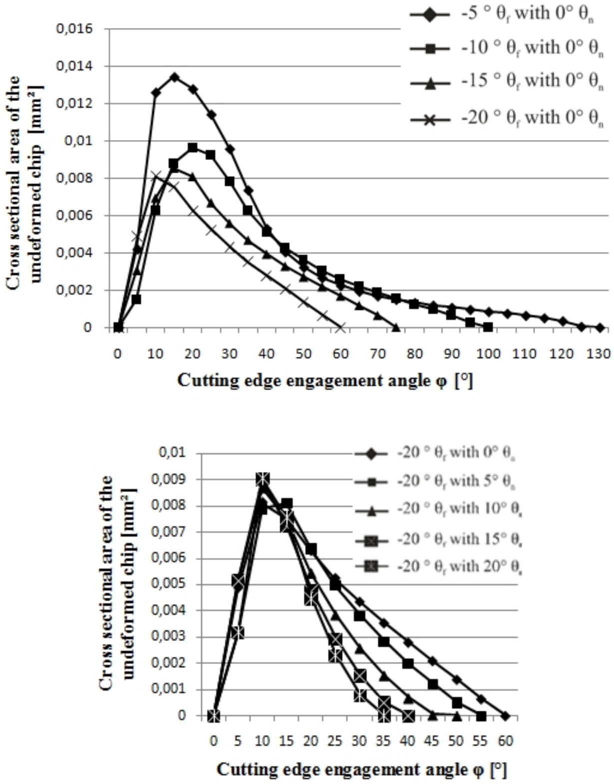

Fig. 6. Variation of cross sectional area of undeformed chip.

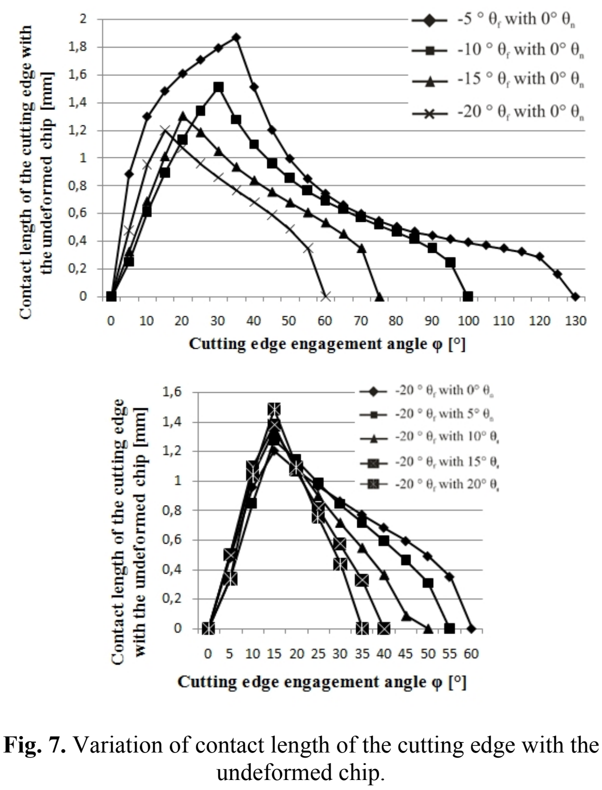

Fig. 7. Variation of contact length of the cutting edge with the undeformed chip.

where $k_{c1.1} = 1500 \dfrac{\text{N}}{\text{mm}^2}$ for C45 [13].

This case was considered to be the optimum choice for this type of material because, as one might see in Fig. 8, the cutting edge enters the chip at a big thickness and on a short contact length.

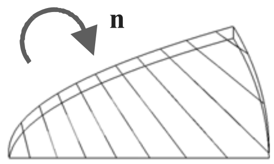

Fig. 8. Succesive positions of the cutting edge along it's trajectory for one rotation of the tool.

The effective cutting diameter for this case was measured to be D_{ef}= 6.82mm.

3.2. The cutting edge enters the chip in the area of big thickness and at a long contact length

It was identified that the positive inclination on the pick-feed direction (θ_n) combined with the positive inclination on the feed direction (θ_f) of the tool allows the cutting edge to enter the chip in the region where the thickness is big and with a long contact length with the chip. This case is considered to be inappropriate for this type of working material (C45). This hypothesis will be confirmed or infirmed by experimental data.

The variation of the cross sectional area of the undeformed chip for this case is presented in Fig. 9.

The variation of the contact length of the cutting edge with the chip, according to this case is illustrated in Fig. 10.

Concluding the analysis for this case, the following inclination has been chosen: 0°(θ_f) with 10°(θ_n).

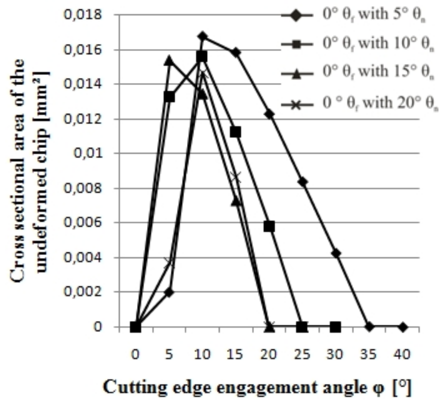

Fig. 9. Variation of cross sectional area of undeformed chip.

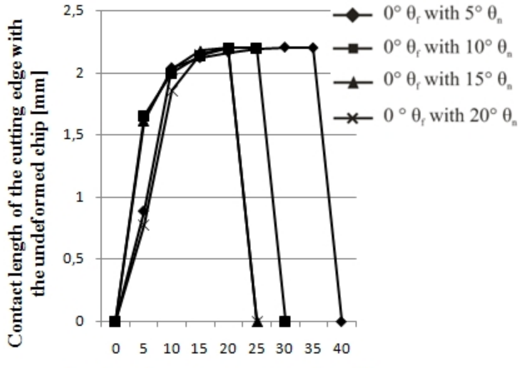

Fig. 10. Variation of contact length of the cutting edge with the undeformed chip.

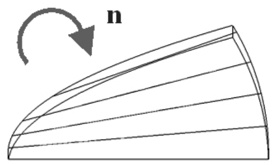

Fig. 11. Successive positions of the cutting edge along it's trajectory for one rotation of the tool.

The maximum area of the cross section for this case was measured to be $A_{sa\max} = 0.0156$ mm^2 and the contact length of the tool with the undeformed chip $l_c = 2.022$ mm.

The cutting force necessary for machining annealed C45 material (the type of material to be used for experimental validation of the model) based on relation (7) becomes:

$$k_c = 0.0156 \cdot 1500 = 23.4 \text{ N}, \quad (9)$$

where $k_{c1.1} = 1500 \frac{\text{N}}{\text{mm}^2}$ for C45 [13].

This case was considered to be the worst choice for this type of material because, as one might see in Fig. 11, the cutting edge enters the chip at a big thickness and on a long contact length.

Similar values of the cutting force were measured by [15], to be more specific 50–225 N for $a_e = 0.2$ mm, $a_p = 0.5$ mm, $f_z = 0.2$ mm/tooth, inclination of 45° (three axis milling) and cutter radius $R = 4$ mm, when milling Inconel 718 of hardness 44 HRC. For a maximum cross sectional area $A_{sa\max} = 0.004$ mm^2, the authors of the paper [16] have estimated a cutting force of 40 N for $a_e = 0.5$ mm, $a_p = 0.5$ mm, $f_z = 0.05$ mm/tooth, inclination of 45° and tool radius $R = 5$ mm, without mentioning the type of material for which the force was calculated.

The effective cutting diameter for this case was measured to be $D_{ef} = 6.32$mm which is smaller than in the first case. This means a bigger rotational speed in order to maintain the same cutting speed as in the first case.

4. CONCLUSIONS

The model described in this paper is only applicable when machining with ball nose end mills with straight cutting edge, $z = 2$ teeth and a rake angle $\gamma = 0°$.

The maximum cross sectional area of the undeformed chip might be used for cutting force estimation.

For the same undeformed chip the cutting force may vary according to the inclination of the tool. This fact probably influences the level of vibrations, noise and tool life.

It is recommended to test these two situations under industrial conditions in order to confirm or to infirm the validity of the proposed parametric model and the two hypotheses.

The behavior of the cutting tool when using cutting fluids is important for this situation, because of the different thermal conditions on the cutting edge and consequently because of thermal fatigue.

ACKNOWLEDGEMENTS: The current paper is part of a research project financed by CNCSIS (National University Research Council) Romania, Project title: *Contributions to the metal cutting tribosystem*, Project code: RU-PNII-TD36/2008, Project manager: Eng. Vlad Diciuc.

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