ADVANCES IN MANUFACTURING SCIENCE AND TECHNOLOGY
Vol. 39, No. 4, 2015
DOI: 10.2478/amst-2015-0020

EFFECT OF TOOL MODEL ON RESULT OF FINITE ELEMENT SIMULATION OF HIGH SPEED MACHINING (HSM)

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Summary

The finite element method has been extensively used for the simulation of manufacturing processes and especially machining. In this paper, finite element models of high speed machining are presented. More specifically, orthogonal and oblique cutting models are presented, where the geometrical and material properties of the cutting tool are investigated. Orthogonal models pertain to the simulation of cutting with three different CBN tool types. Chip formation, cutting forces and temperatures are compared for each model, at the same cutting conditions. Additionally, 3D models are presented, where the back rake angle of the cutting tool is varied. From the results it may be concluded that 3D models provide more realistic results but they are computationally more demanding than 2D models. Finite element modelling of high speed machining can provide data for the process that would be either difficult or in some cases even impossible to obtain through extensive experimental work.

Keywords: cutting tool modelling; orthogonal cutting; 3D simulation; cutting forces; cutting temperature

Analiza oddziaływania modelu narzędzia na symulację numeryczną MES procesu skrawania z dużą prędkością (HSM)

Streszczenie

W artykule określono oddziaływanie geometrii narzędzia na wyniki symulacji numerycznej skrawania z dużą prędkością. Przeprowadzono symulacje numeryczną dla skrawania ortogonalnego 2D, dla trzech modeli narzędzi z CBN o różnej geometrii. Porównano podział modeli numerycznych narzędzi na elementy skończone oraz przedstawiono analizę procesu kształtowania wióra, wartości składowych siły skrawania, temperaturę w strefie skrawania oraz odkształcenie plastyczne w warstwie wierzchniej dla wybranych ich geometrii. Przeprowadzono również proces symulacji dla modelu skośnego 3D dla różnych wartości kąta pochylenia krawędzi skrawającej. Wyniki symulacji pozwoliły stwierdzić, że zastosowanie modeli 3D lepiej odzwierciedla rzeczywisty proces. Stawia jednak większe wymagania w zakresie obliczeń niż przy użyciu modeli 2D. Symulacja MES obróbki z dużą prędkością pozwoliła uzyskać wyniki, które mogą być trudne lub w niektórych przypadkach niemożliwe do uzyskania w ramach badań eksperymentalnych.

Słowa kluczowe: modelowanie narzędzi skrawających, skrawanie ortogonalne, symulacja 3D, siły skrawania, temperatura skrawania

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1. Introduction

High Speed Machining (HSM) is of special interest to the industry and the academia due to the advantages it exhibits in comparison to the same machining processes performed at lower speeds. Original research on high speed machining combined three objectives, namely the technological breakthrough in machining specific kinds of materials such as aluminium and titanium, the improvement of the final product quality and mainly its surface characteristics and the achievement of higher productivity [1]. The first of the objectives is related to the areas of application of HSM and especially the aerospace and automotive industry, where advanced materials such as aluminium alloys, titanium alloys, steels and superalloys are incorporated into the final products. The second objective is a constant pursue in machining and its combination with increased material removal rates is ideal. The third objective aims at drastically increasing productivity and quality without increasing production costs [2]. These are realized through the use of suitable cutting tools, machine tools' stiffness and damping capacity, toolholders and workholders, special spindles, fast feed drives and the level of automation implemented in the machine tools.

HSM special characteristics are indeed related to high material removal rates, which are a function of the cutting speed as well as the undeformed chip cross-section; HSM leads to higher productivity, especially in the case of light metal alloys. Besides the increase in the material removal rate, an increase in surface quality is achieved with HSM, thus making these processes suitable for precision machining. The excellent surface finish reported in HSM operations, further reduces machining time and cost as it makes subsequent finishing operations such as grinding redundant. Furthermore, as experimental work has shown, cutting forces reduce by 10-15% as the speed is increased to high values [3, 4]. Force reduction is attributed to the reduced strength of the workpiece material at elevated temperatures appearing in the process due to the minimization of cutting fluids as a common practice in high speed metal cutting [5, 6]. Although process temperatures are higher, this has little or no effect on the workpiece since the heat is transported away by the chips, making the machining of workpieces with critical heat influence possible [7]. Other explanations for the force reduction are either a decrease in friction or the tendency of many materials to produce segmented chip at high cutting speeds; this saw-toothed chip is considered to be energetically favourable resulting in lower cutting forces. On the other hand, it results in increased chip velocity, chip-tool friction and temperatures at the rake face of the tool that consequently provoke significant wear and tool life reduction. However, tool life can be prolonged by optimizing cutting parameters, cutting conditions and machining strategy [8]. In any case, lower loads simplify part fixture design and allow for the machining of thin-walled sections, a common geometry of workpieces in the aerospace industry and automotive industry. The aforementioned advantages have placed HSM in a high position in modern production engineering with constantly growing industrial interest.

The boundary between conventional machining and HSM depends on factors such as the workpiece material and the process. Most commonly, definitions of HSM make use of cutting speeds pertaining to turning, separately for ferrous and non-ferrous materials; the limit above which an operation is characterized as HSM for some non-ferrous materials can be higher at about one order of magnitude to that of alloyed steel. However, the highest cutting speeds can be achieved for non-ferrous materials that exhibit good machinability, such as aluminium, but they are limited by the attained cutting speeds of the machine tools. On the other hand, machining speeds of materials with poor machinability, such as titanium, are limited by the available cutting tools. Furthermore, operations such as turning, milling and grinding are more suitable for performing HSM than other operations. Thus, definitions that account only for cutting speed or only one cutting operation or wide material groups tend to have a lot of exceptions and to soon be outdated due to the ongoing research regarding machine tools and cutting tools for HSM.

Considering the above, a global definition of HSM operations is rather difficult to be provided since a number of factors need to be accounted for; cutting speed, spindle speed, feed, the cutting operation, workpiece material, cutting tool and cutting forces are the features included in some definitions [4, 9, 10]. A definition by Tlusty [11] states that HSM refers to processes with cutting speed or spindle rotational speed substantially higher than some years before or also than the still common and general practice. The definition, even though is very general, avoids to give a spectrum of speeds or a lower value above which a machining process is characterized as HSM and can be applied to various materials and processes.

Nevertheless, the phenomena taking place and the complexity of chip formation at high speeds call for the application of sophisticated methods for the analysis of HSM. The use of modelling and especially the Finite Element Method (FEM), a numerical simulation technique extensively used for the analysis and the prediction of the cutting performance of machining in general [12], can be used for the case of HSM. The already published results pertain to chip morphology, cutting forces and temperatures among other characteristics [13, 14], with varying cutting conditions.

However, there are only few works dedicated to the modelling of cutting tools. In the next paragraph we present a review on the published works pertaining to FEM modelling of HSM. Furthermore, some works on the modelling of cutting tools are mentioned and we explain the methodology used for the suggested models. First, we present 2D orthogonal models of HSM with three different tools. The first tool is simple in concept, with edge radius and negative rake angle. However, two more cutting tools, from a known tool making company are tested. They are incorporated into the model with careful modelling of their geometry and material properties. Additionally, 3D FEM models of oblique cutting are presented. We investigate the influence of the positioning of the tool on the chip formation. From the models we can deduct useful conclusions regarding various parameters that are connected to tool performance and wear. The models can be used in the future not only for the prediction of various machining parameters but also for optimisation by knowing a priori the outcome of the process.

2. Finite element modelling

FEM modelling used for the analysis and the prediction of the cutting performance of HSM has a background of about two decades. Simulations usually pertain to orthogonal machining while simulations of 3D nature are quite rare. The models of the relevant literature deal mainly with features such as chip morphology, cutting forces and temperatures. Most of the relative work examines turning but milling is considered as well. Among the advantages of the method is that it can provide several difficult-to-measure data on variables such as temperatures, plastic strains, strain rates, and stresses and models can be correlated to surface integrity and tool wear [15, 16].

Marusich and Ortiz [17] were among the first to provide models of HSM and simulate the segmented chip formation. Özel and Altan [18] proposed a finite element model with a variable coefficient of friction so that the dynamic cutting situation is considered. Bäker [19] proposed an orthogonal machining model that implements a generic flow stress law in order to simulate the cutting force reduction and the chip formation. Hortig and Svendsen [20] investigated the dependence of element size and orientation on chip formation, also using adaptive mesh refinement. Machining of aluminium alloys under high speeds is the main objective of a work presented by Davim et al. [21]. Iqbal, Mativenga and Sheikh [22] provide FEM models based on variable Coulomb and hybrid sticking-sliding friction models. Finally, Duan et al. [23] as well as Tang et al. [24] utilize the Johnson-Cook material model and fracture criterion for modelling the HSM of hardened steel.

In most FEM machining analyses performed, cutting tool is considered as a rigid body, although exceptions exist [25-28]. In the case of a rigid tool, no deformation takes place; however, thermal analysis for the determination of the temperatures, especially in the tool tip, can be carried out. Cutting tool materials and their properties play an important role. For example in hard cutting, cutting tools are made of specialized materials, such as cubic boron nitrite (CBN), that are ideal for machining iron-based materials at the severe cutting conditions associated with this process [5]; they possess exquisite properties, even at elevated temperatures, allowing for their application at high cutting speeds. The combination of hard turning and high speed machining is proved to be very advantageous since a great reduction in processing time can be achieved. If cutting tool coatings are also modelled, they are modelled as elastic materials and only heat transfer and elastic material properties are needed [13]. Nieslony et al. [29] presented a paper with constitutive material models which consider the appropriate mechanical thermo-physical properties of both workpiece and tool materials, including thin layered coatings. The geometrical properties of cutting tools are also the topic of several investigations, pertaining to FEM simulations that consider detailed representation of cutting tools in micromachining [30, 31], machining with accurate representation of the tool micro-geometry [32] and modelling of various types of cutting tools [33].

The models provided in the following paragraphs are 2D and 3D models of orthogonal and oblique cutting where several features of the cutting tools are investigated. The models are developed with Third Wave AdvantEdge software, which integrates special features appropriate for machining simulation. The program menus are properly designed so that model preparation time is minimized. Furthermore, it possesses a wide database of workpiece and tool materials commonly used in cutting operations, offering all the required data for effective material modeling. AdvantEdge is a Lagrangian, explicit, dynamic code which can perform coupled thermo-mechanical transient analysis. The program applies adaptive meshing and continuous remeshing for chip and workpiece, allowing for accurate results. The models presented in this paper were validated with experimental and numerical results [5, 13, 14] and proved to provide reliable results for both 2D and 3D modeling schemes. In the presented work each model is used to exhibit tool modeling features and the models are compared to each other. Next paragraph is divided into two parts. In the first part we present orthogonal models of HSM with CBN tools. These tools, due to their sensitivity in mechanical loads, are used with negative rake angles and in forms like the ones presented in Fig. 1 (a)-(c). The tool of Fig. 1 (a) is a honed tool usually employed in finishing operations with a tool edge radius of 0.02 mm, rake and clearance angle of –5 and 5°, respectively; we have used this tool in previous publications and it is also used here for comparison with the other CBN tools [5]. The other two cutting tools are existing tools from Sandvik. The realistic representation of the tools in the models is performed through the program used for the analysis. In Figure 1 (b), a chamfered or T-land tool CNGA120408T(KR) for roughing and in Fig. 1 (c) a chip breaker tool DCMT11T304-UM, are shown. In the presented models, we set the depth of cut at 1 mm, cutting speed at 300 m/min, feed at 0.05 mm/rev and for workpiece material tool steel AISI H-13.

In the second part, we present oblique cutting models with an uncoated cemented carbide tool of edge radius of 0.05 mm, rake and clearance angle of 12 and 5°, respectively, for the processing of AISI 1020 steel workpiece 1 mm wide, at 130 m/min and for feed of 0,2 mm/rev. In Fig. 2 we present the initial configuration of the workpiece and the tool; we examined the cases where three different inclination angles, namely 10, 20 and 30°, are applied to the model.

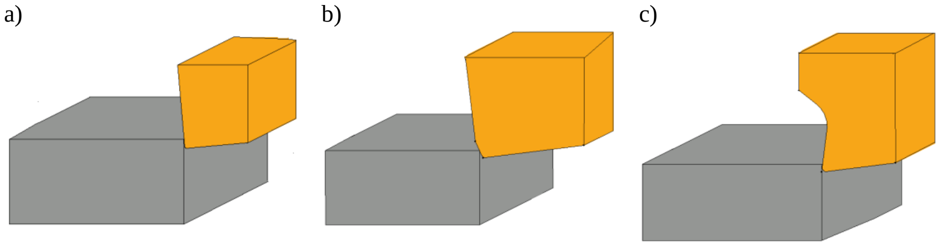


Fig. 1. Models of CBN cutting tools: a) negative, b) negative chamfered, c) positive

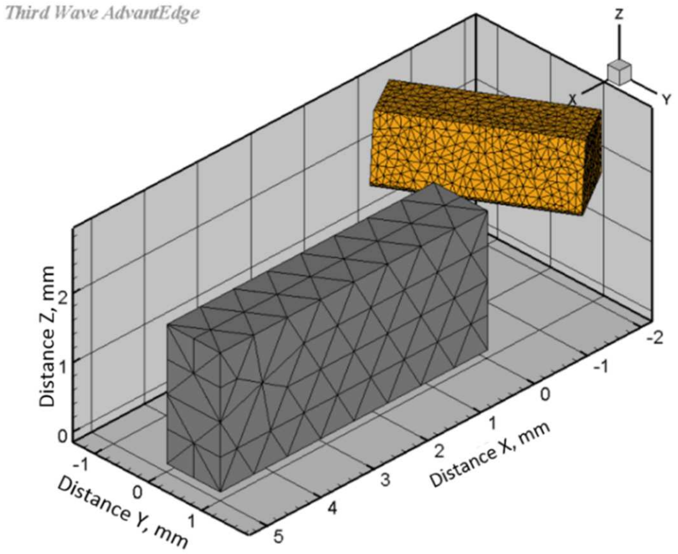


Fig. 2. 3D Oblique cutting model

3. Results

3.1. Orthogonal cutting models

The initial model configuration and discretization for the three different tools can be seen in Fig. 3 (a)-(c). Note that the depth of cut is perpendicular to the plane shown in the figures. In Fig. 4 (a)-(c), the formation of chip, for the same time step, for the three tools, is depicted. In Figures 3 and 4, the continuous meshing and the adaptive re-meshing procedures can be observed. Note, that in Fig. 3 the mesh is denser near the tool tip, where deformation is about to take place, while in Fig. 4 new elements are created in the shear zone where the strain rate is expected to be high. Note, also, that the mesh density in the chip, especially in its inner and outer surfaces, is also high because of the deformation of the material in this area; finer mesh can follow the curve of the curling material more closely and, furthermore, provide more accurate results.

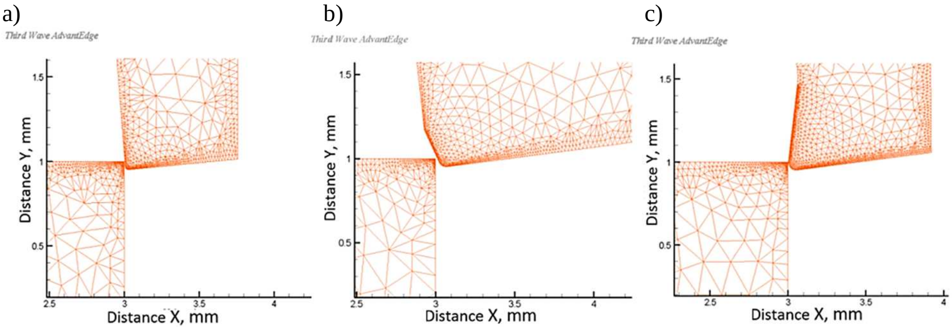


Fig. 3. Tool – workpiece geometrical configuration with mesh models for tool geometry: a) negative, b) negative chamfered, c) positive

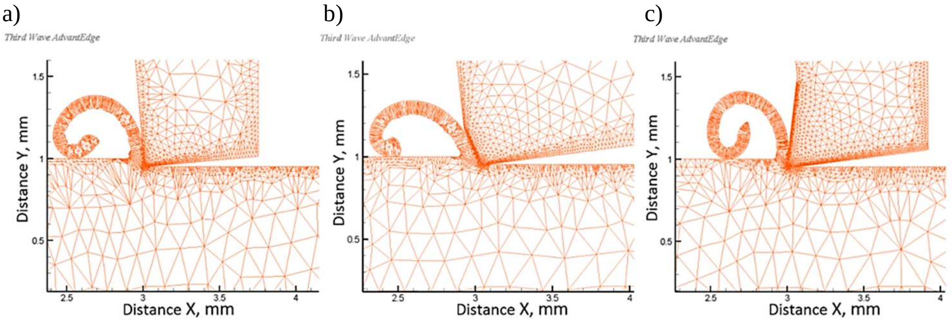


Fig. 4. Mesh of workpiece, chip and tool for 1.96 mm cutting distance for tool geometry: a) negative, b) negative chamfered, c) positive

In Figure 5 cutting forces for the three cutting tools are given. In the first tool, thrust force is higher than cutting force while the opposite can be observed in the other two tools. Comparing all cases, higher forces are noted in the second tool.

In Figure 6 (a)-(c), the temperatures in the tool and workpiece can be observed. We found that the higher temperatures are near the tool tip and towards the rake face, as expected, indicating the wear region of the tool. The knowledge of the maximum temperature and distribution of the temperature fields in the rake face of the tool is of great interest because high temperatures in CBN tools are connected to wear mechanisms that reduce tool life. With the numerical results provided by the model it is possible to minimize unwanted effects and choose suitable cutting conditions for the optimization of the process. The values of the temperatures were 721, 807 and 619 ^{o}C for the three tools. Fig. 7 (a)-(b) shows the exit of the tool from the workpiece and the formation of a burr. In the same

Figures, the plastic strain on the chip is shown. In Figures 4, 6 and 7, the formation of chip is shown and it is different for the three tools. From Figure 7, we see that burr is also different in every case, with burr of the first tool being the most protruding. Plastic strain is quite intense on the outer surface of the chip produced from the first tool. The second chip exhibits intense plastic strain in all of its volume, due to the contact with the tip of the tool that creates an active negative rake angle greater than the rake angle of the tool. Due to the longer contact length between tool and chip, this tool also exhibits the higher temperatures. The third chip is forming a spiral, due to contact with a tool with edge radius bigger than the first tool and positive rake angle. The edge radius of the third tool may perform burnishing of the machined surface and produce better results in connection to surface quality of the workpiece. Note, also, that it is possible, besides the results presented here, to extract from the proposed model predictions for values that it would be very laborious or even impossible to obtain otherwise.

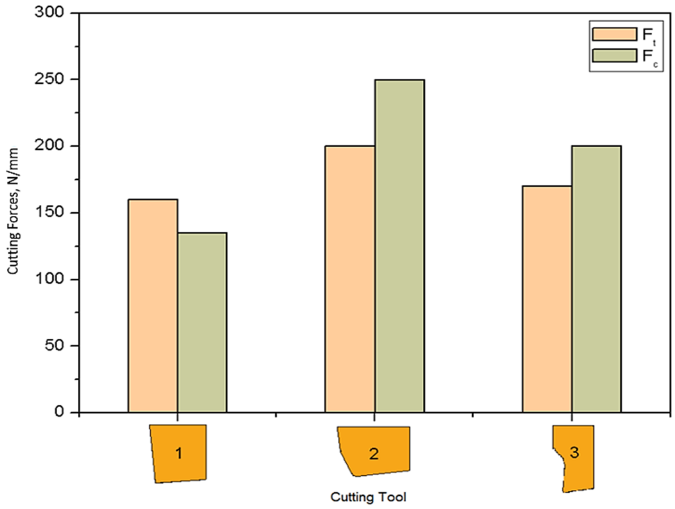


Fig. 5. Cutting and thrust force

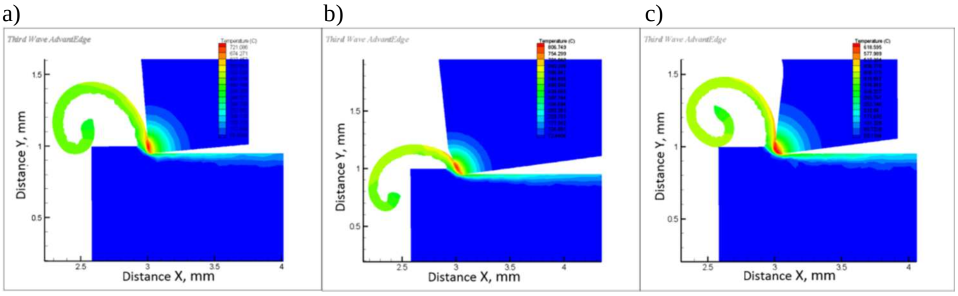


Fig. 6. Temperature on tool, chip and workpiece for tool geometry:
a) negative, b) negative chamfered, c) positive

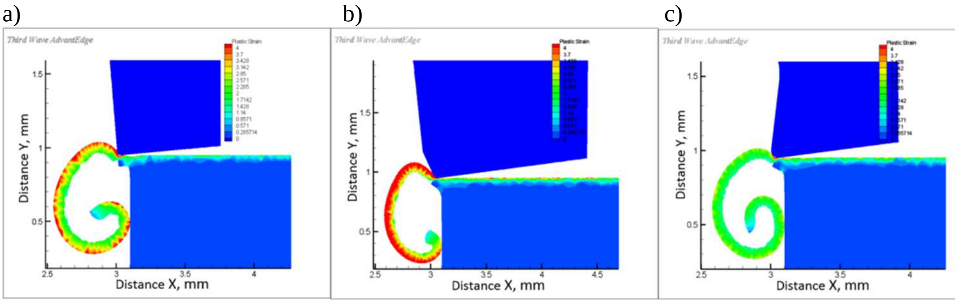


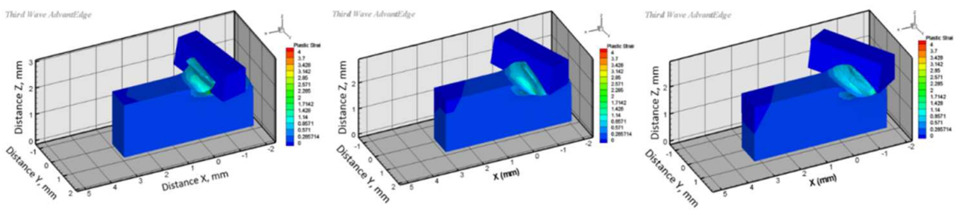
Fig. 7. Plastic strain on the chip and burr formation for tool geometry:
a) negative, b) negative chamfered, c) positive

3.2. Oblique cutting models

The models presented so far are more popular in the modelling of cutting operations since they are relatively simple and they can offer acceptable accuracy. Nevertheless, orthogonal machining is an ideal representation of cutting, where the chip deforms in a plane. In reality, chip deformation takes place in all three dimensions. We present oblique cutting models, which are of 3D nature, hereafter. We constructed three different models, with three different back rake angles in order to observe how this affects the performance of the cutting tools.

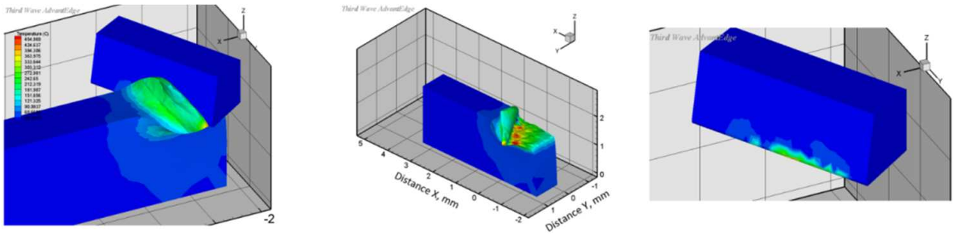
Figure 8 shows the chip formation for three different inclination angles of the tool. The deflection of the chip to the third dimension and the more realistic representation of the chip formation are quite obvious. The oblique cutting models can provide, as in the case of 2D modelling, much useful data. In Fig. 9 (a) the temperature fields in the workpiece, the chip and the tool can be observed. With increasing back rake angle, cutting forces and temperatures also increase. In the same figure, the position of the cutting tool, relative to the workpiece, can also be seen, explaining the form of the chip created. The curling of the chip can be better observed in Fig. 9 (b), where a rear view of the workpiece in the same time step can be seen. Additionally, in the same figure, the cutting tool is omitted so that the temperatures at the location where cutting takes place can be observed. Figure 9 (c) shows the areas of the tool that are thermally loaded.

The 2D and 3D models cannot be directly compared as they present many differences. However, it is worth noticing that more elements are required in the analysis of oblique cutting in comparison to orthogonal cutting, with computational time being approximately 10 times more; the computational time required for a 3D model on a moderate PC is over 100 hours. Furthermore, single shear plane models have been criticized over the years and experimental data do not always correlate well with theory results. Astakhov summarized the major inherent drawbacks of the single shear plane model [34]. Nevertheless, even though 3D models provide more information being more realistic and regarded as more sound than 2D models, they are less practical and thus less popular.



a) b) c)

Fig. 8. Chip formation for tool back rake angle: a) 10°, b) 20°, c) 30°



a) b) c)

Fig. 9. Temperatures on: a) chip, b) workpiece, c) tool, for 30° angle

4. Discussion

In the present paper orthogonal models of HSM with three different types of CBN tools and oblique models, with the finite element method are discussed. The main findings of the analysis are connected to cutting forces, temperatures on the chip and the workpiece, chip morphology, burr formation and many other parameters that can be calculated from the models. The results may be summarized as:

- A commercial finite element code was used for the analysis. The software offers the ability to construct a FEM model quickly and make use of the databases already incorporated. As a drawback of the software we mention the inability of the user to intervene to the material and friction modelling to be used in the analysis.
- Orthogonal cutting models exhibit that chamfered tools present higher cutting forces and temperatures, due to their shape. They are more compact but are likely to present more rapid wear. On the other hand, the third tool is more likely to produce a better surface quality of the workpiece.
- 3D models need more time and computational power but offer more realistic results than 2D models.
- The proposed models can provide theoretical and practical benefits and they can be used for the investigation of special features of high speed machining and for the theoretical analysis of the process.

Finally, with the aid of the numerical results provided, it is possible to increase tool life and optimize cutting conditions without performing laborious and time-consuming experiments.

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Received in November 2015