Vol. 38, No. 2 (2016) 214-220

Tribology in Industry

www.tribology.fink.rs

RESEARCH

Friction in Orthogonal Cutting Finite Elements Models with Large Negative Rake Angle

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Keywords:

Machining
Finite elements
Simulation
Large negative rake angle
Friction coefficient

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A B S T R A C T

In this paper, orthogonal cutting finite elements models are built for the investigation of the impact of large negative rake angles on the friction coefficient in the tool-chip interface in machining. The simulation results give an insight on the mechanism of chip formation in processes with large negative active rake angle, such as machining with chamfered tools, grinding and micromachining. For the present analysis, cutting conditions resembling the qualitative and quantitative characteristics of the aforementioned processes were selected. More specifically, tool rake angles varying from -10o to -55o and Coulomb friction with constant friction coefficient were considered. The results indicate that friction coefficient is greatly affected by the negative tool rake angle, exhibiting values well above 1 for the high extreme of the examined rake angle spectrum.

1. INTRODUCTION

Modelling, used as a procedure for the representation of a system, phenomenon, or process over time, is commonly used in engineering [1-4] and more specifically in manufacturing [5-10]. The Finite Elements Modelling (FEM) in particular, has been employed for the simulation of machining problems for over four decades [11]. In the early 1970s some pioneering works on machining modelling with the Finite Element Method begun to find their way in scientific journals. Over the years and with the increase of computer power as well as the existence of commercial FEM software, this method has proved to be the favourite modelling tool for researchers of the field. This is established by the vast number of publications on this subject as well as the modelling novelties introduced and used, even by the fact that software dedicated solely for the purpose of modelling machining operations exist. Finite element models are used today for gaining knowledge on fundamental aspect of material removing mechanisms but more importantly for their ability to predict important parameters such as cutting forces, temperatures, stresses etc. essential for the prediction of the process outcome, the quality of the final product and in a timely and inexpensive way. The requirements for performing such a task are many; theoretical background, manufacturing experience, accurate data and knowledge on modelling are supplies for building a model and interpreting its results. The advances in computer technology and the use of commercial FEM software have made it possible for researchers to develop powerful models that produce reliable results in acceptable computational time and cost.

Among the various subjects of investigation in machining modelling and simulation with FEM, tool-chip friction is one of the most important and simultaneously difficult problems to be addressed [12]. At the same time, friction parameters are difficult to be experimentally measured. Although methods like pin-on disc friction test are available for the determination of friction characteristics, in cutting operations, matters are perplexed due to phenomena taking place at the tool-chip contact area. In this area, severe contact conditions between the tool and the chip are observed, especially for turning operations that the interaction between those two elements is long. Researchers have turned to modelling as an alternative method for the study of the characteristics of chip formation and the friction conditions encountered in the secondary deformation zone, at chip and tool rake face interaction area.

Furthermore, a lot of machining models with tools possessing either positive or negative rake angle exist; in single-point tools machining, tool rake angles range usually between small positive to small negative values. However, in certain special cases of machining, very large negative rake angles are involved in the procedure. Such cases pertain to machining with worn or chamfered tools, grinding and micromachining. In the aforementioned cases the actual or the acting rake angle may take large negative values, significantly altering friction conditions in the tool-chip interface. Nevertheless, only a few studies refer to machining with large rake angles, especially greater than -40^{o} in the relevant literature [13-15]. In this paper, an orthogonal cutting FEM model is proposed for the determination of friction in the tool-chip region, when cutting with large negative rake angles, as the research in this area is still limited. The results of the numerical analysis are compared to experimental data of processes with similar cutting conditions and useful conclusions are drawn from the analysis.

2. FINITE ELEMENTS MODELS

2.1 Numerical parameters

The finite elements software MSC MARC was used to conduct a coupled thermo-mechanical analysis of the machining process. The proposed finite elements model was a 2D modified orthogonal cutting model. Plane strain conditions were assumed to reduce the problem dimensionality of the modelled cutting process, as it was considered that plastic flow is constrained within the specific cutting plane. Using the assumed plane strain conditions, only a constant thickness value was required to represent the third dimension of the workpiece and the cutting tool in this simplified model. The proposed model is a Lagrangian one; chip formation requires no separation criterion. However, when a predefined threshold value of tool penetration occurred, re-meshing was applied. With the aforementioned technique, chip formation was performed smoothly and no large distortions of the original mesh were allowed. Additionally, the tool was assumed rigid and therefore it was represented by curves with the appropriate rake and clearance angles, rather than a closed deformable body. Thus a simplified approach was adopted. The cutting edge was finally modelled by a fillet curve with a suitable radius of curvature, taking into consideration the minimum chip thickness requirements. Fixed boundary conditions were imposed on the bottom and left sides of the workpiece to prevent rigid body motion. Finally, tool-chip interaction was modelled using the appropriate contact pair between them, with a Coulomb friction model applied to the contact surface.

Commonly, finite elements models of machining assume that it is a case of classical friction situation following Coulomb's law; frictional sliding force is proportional to the applied normal load. The ratio of these two is the coefficient of friction, which is constant in all the contact length between chip and tool. A similar model was used and validated in a previous work [12] and was also employed for the analysis presented in the next paragraphs. The relation between frictional stresses and normal stresses may be expressed as:

$$\tau = \mu \cdot \sigma \tag{1}$$

Furthermore, friction coefficient is associated to cutting and thrust forces, F_c and F_t, respectively, where γ is the rake angle, through the equation:

$$\mu = \frac{F_t + F_c \tan\gamma}{F_c - F_t \tan\gamma} \tag{2}$$

Cutting and thrust forces can be experimentally measured or numerically calculated.

2.2 Model configuration

For the determination of the friction coefficient a model with the modelling characteristics described in the previous section was built. Then, the geometrical parameters and cutting conditions of orthogonal cutting experiments described in [13] were incorporated into the model. The experiments pertain to the face turning of a steel tube with various large negative rake angles. This configuration was selected as it creates orthogonal cutting conditions ideal for use with the proposed model. A schematic representation of the experimental setup can be seen in Fig. 1.

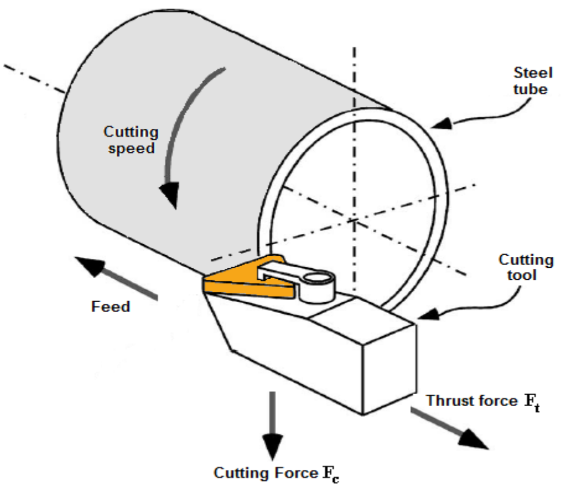

Fig. 1. Experimental setup for orthogonal cutting

An initial value of the friction coefficient of 0.5 was adopted and after a number of trials, by adjusting properly the friction coefficient value, its exact value was determined by matching the cutting and thrust forces from the experimental data to the calculated ones.

The dimensions of the workpiece were 4 mm by 0.5 mm and due to the plain strain conditions and thickness value of 0.15 mm was defined in the z-direction. Clearance angle was taken equal to 25° with five different rake angles, i.e. -10°, -25°, -35°, -45° and -55°, see Fig. 2.

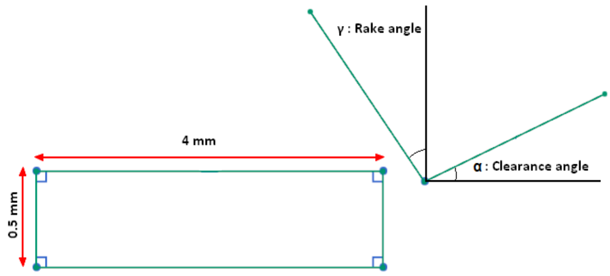

Fig. 2. Geometrical characteristics of the model

In Fig. 3 the model setups for three different rake angles, namely -10°, -35° and -55° are depicted.

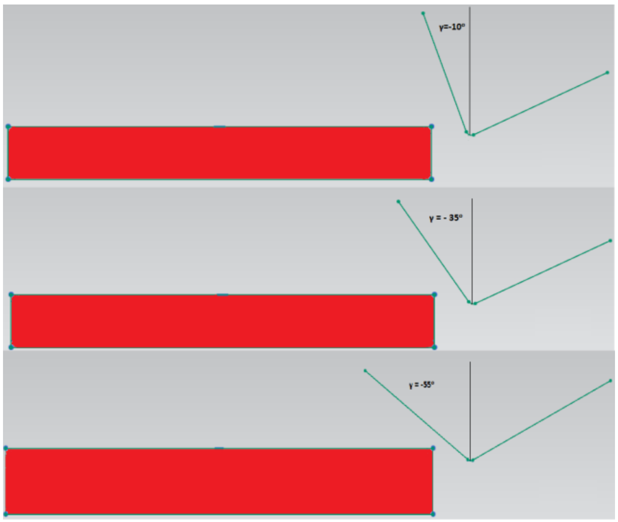

Fig. 3. Model setup for three different rake angles

A constant speed of 180 m/min was assigned to the cutting tool and its movement was linear along the -x direction. An undeformed chip thickness of 0.01 mm was applied to all the simulations. An adaptive mesh refinement technique was employed and an initial coarse mesh of 5,000 elements was consecutively refined after the re-meshing criteria were met. The maximum allowed number of elements was set to 50,000 after a mesh independence study. Quadrilateral, 4-noded finite elements with a modification so as to facilitate the re-meshing technique were employed as is depicted in Fig. 4.

The workpiece was modelled as a deformable, elastic-plastic isotropic hardening model material with a Von Mises yield criterion and its exact material properties were extracted from the software's materials database. Material properties such as thermal conductivity, specific heat and thermal expansion were considered temperature dependent.

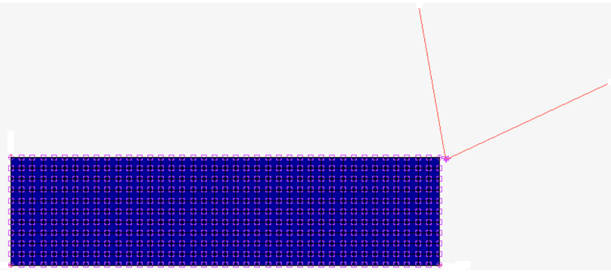

Fig. 4. Initial mesh configuration

Machining processes and consequently their numerical simulations are inherently time-dependent. Thus, the choice of the proper time-step to assure the stability of the solving process, the convergence of the results and the reduction of the unnecessary computational cost is strongly required. Thus, a constant time step of 0.1 μs was chosen. Furthermore, termination criteria were generally employed in simulations to stop the simulation after the cutting tool has moved for a given length or maximum time duration was reached. In the current study, simulations carried on for a total cutting length of 3.81 mm.

3. RESULTS AND DISCUSSION

Although contact conditions in the tool-chip interface are complicated, a simplistic approach where simulations incorporate Coulomb friction condition with constant friction coefficient is commonly assumed.

Astakhov [16] argues that for a friction coefficient with value greater than 0.577 no relative motion between the chip and the rake face of the tool can occur. However, experimental results and theoretical works have produced friction coefficient values well beyond this limiting value. Zorev [17] states friction coefficient in the range of 0.6 to 1.8, Kronenberg [18] gives values between 0.77 and 1.46 and Armarego and Brown [19] cite values up to 2.0; more examples can be found in the work of Astakhov and Outeiro [20].

The evaluation of friction models has been the topic of a number of publications. An ALE model was used by Arrazola and Özel [21] to measure the influence of friction models on several parameters. They tested Coulomb and sticking–sliding friction and compared the results of the simulations to experimental results. The results of the two friction schemes indicated small discrepancies. On the stick-slip model implementation it was concluded that a major disadvantage is the uncertainty of the limiting shear stress value.

In the work by Filice et al. [22], five different friction models were analyzed, namely models with constant shear friction on the chip-tool interface, constant Coulomb friction on the chip-tool interface, constant shear friction in sticking region and Coulomb friction in sliding region, stick-slip conditions and variable shear friction on chip-tool interface. The investigators concluded that mechanical result, e.g. forces and contact length, are practically insensitive to friction models, as long as the "correct" friction coefficient is applied, while on the other hand, friction modelling greatly affects thermal results. It should be noted that several papers presume frictionless contact in the chip-tool interface.

In Fig. 5, the chip formation for rake angle -10^{o}, for three different time steps can be seen. This rake angle is not unusual for cutting tools and the chip is formed in an anticipated way. In the same figure, the equivalent Von Mises stress on the workpiece and the chip can be seen.

In Fig. 6, chip formed under the cutting tool with a rake angle of -35^{o} is depicted. The chip in this latter case presents a thicker deformed chip thickness, which is at the same time shorter. Cutting forces are quite higher in this case in comparison to the ones presented for -10^{o} rake angle.

From Figs 5 and 6, the re-meshing procedure applied to the proposed models can also be observed, for the primary and secondary deformation zones. The mesh although distorted, is finer and denser around the tool, in comparison to the mesh shown in Fig. 4. The same can be observed for the created chip, as this is an area where large deformations of the workpiece material and thus of the corresponding mesh are present.

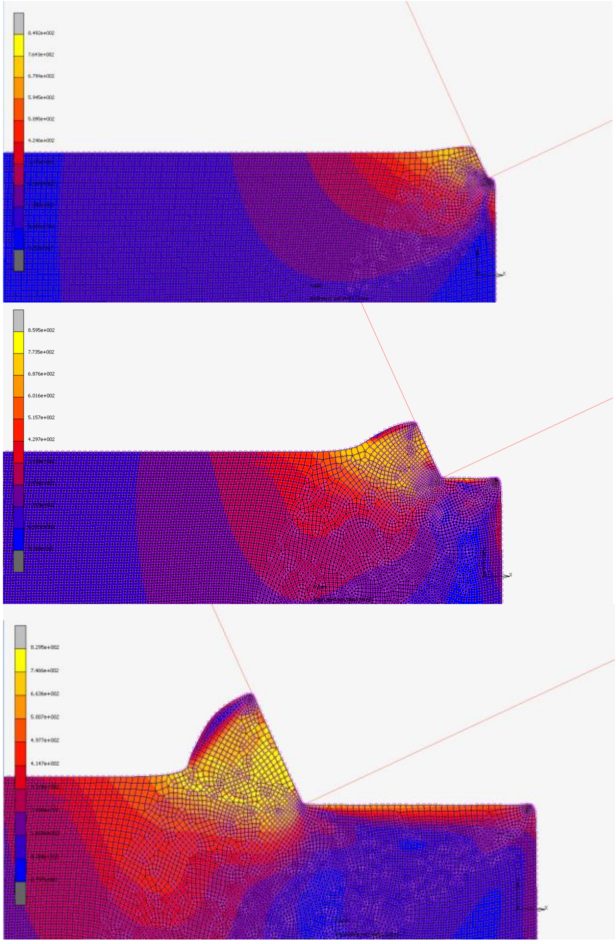

Fig. 5. Chip formation for rake angle -10º for cutting speed 180 m/min and undeformed chip thickness 0.01 mm.

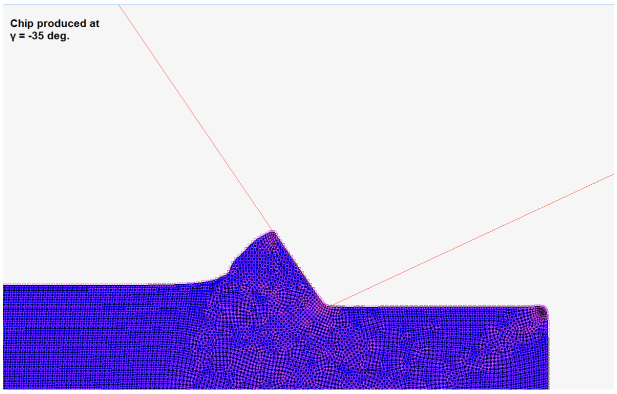

Fig. 6. Chip formation for rake angle -35º for cutting speed 180 m/min and undeformed chip thickness 0.01 mm.

The increase in cutting forces for an increase in tool rake angle for very large values was also reported by Komanduri [13], in his experiments. Furthermore, in machining with single point tools, the cutting force is about double the thrust force. However, the results of the analysis presented, indicate that the thrust force is higher than the cutting force. This is also reported in the work of Komanduri [13] who resembles cutting with large negative angles to the material removal mechanism taking place in grinding. He explains his claim based on the rubbing grain hypothesis introduced by Hahn [20], presenting an analogy between material removal in grinding and milling.

The friction coefficient attained by the procedure described in section 2.2, is tabulated in Table 1. Friction coefficient values are exceeding 1 and increase for larger negative rake angles, reaching the value of 2 for -55º rake angle.

Table 1. Variation of friction coefficient with rake angle.

Rake Angle	Friction coefficient
-10º	1.35
-25º	1.65
-35º	1.80
-45º	1.90
-55º	2.00

In Fig. 7, friction coefficient μ versus rake angle γ is presented, showing an almost linear increase in friction coefficient for increasing the value of rake angle.

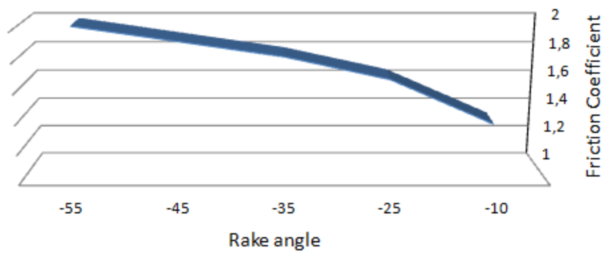

Fig. 7. Effect of tool rake angle on friction coefficient.

4. CONCLUSION

The finite elements method was used for the construction of a model that evaluates the friction conditions with increasing negative rake angles in machining. The model was based on the orthogonal machining theory and it can produce valuable results on the friction conditions and chip formation mechanisms of processes that involve large and very large negative rake angles as acting rake angles.

Similar numerical works are limited in the relevant literature.

The proposed model incorporates constant Coulomb friction on the chip-tool interface. Five different models, with five different negative rake angles, i.e. -10^{o}, -25^{o}, -35^{o}, -45^{o} and -55^{o}, were considered. Then the model was run several times for each rake angle with different friction coefficients until the cutting forces matched the cutting forces of similar experimental results.

It is notable that for the conditions analysed with the presented simulations, thrust forces appear to be higher than cutting forces; this is unusual for machining with single-point tools. It can, however, be explained and relevant analyses exist. Furthermore, the results of the analysis show that large negative rake angles have an influence on the friction coefficient, which increases with larger negative rake angles. Finally, it can be noted that the chip formation is also influenced by large negative rake angles.

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