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## NUMERICAL-EXPERIMENTAL MODELS FOR ORTHOGONAL CUTTING

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**Abstract.** *The main objective of this work is to present a numerical and experimental procedure to estimate the parameters for the orthogonal cutting process. The mathematical model of the problem is based on the concepts of limit analysis, frictional unilateral contact, Finite Elements Method and techniques of mathematical programming. From the other hand, experimental procedures are carried out by considering different cutting parameters. The calibration of the model is assessing by comparing the numerical and experimental results. The proposed strategy is effective in the estimation of flow configuration, cutting forces and friction stress in the interface between the tool and the chip.*

**Keywords:** *Limit Analysis, Orthogonal Cutting, Experimental Methods*

### 1. INTRODUCTION

The study and simulation of orthogonal cutting aims the determination of cutting forces and it depends of many variables such as material ductility, cutting velocity, cutting depth, friction coefficient at chip-tool interface, tool rake angle among others. Then, the modelling and solution of such process is quite hard. Many models weather analytical or numerical have been developed since mid of 19<sup>th</sup> century until the development of Merchant method in 1940. It is the widespread method in determining cutting forces and found in many machining books (Goover,2010; Armarego,1969).

Nevertheless, the advent of computers and the development of numerical methods enabled the computational simulation of such processes and the addition of variables into the analysis in order to get more accurate results. The greatest difficulty relies on determining the permanent regime configuration. In this paper it can be observed that the straight representation of the chip as in Merchant method does not properly represents the permanent regime configuration.

In this work, it is proposed a numerical method to simulate the orthogonal cutting process considering the prescription of cutting velocity, friction and unilateral conditions at chip-tool interface in order to determine the cutting forces and its behaviour with friction coefficient. Moreover, the study of sliding or adhesion at chip-tool interface allows the study of formation of false cutting edge and, consequently, the formation of the secondary shear zone. The cutting forces and thrust forces are experimentally measured in turning operation by a dynamometer and will be used to compare and calibrate the numerical model.

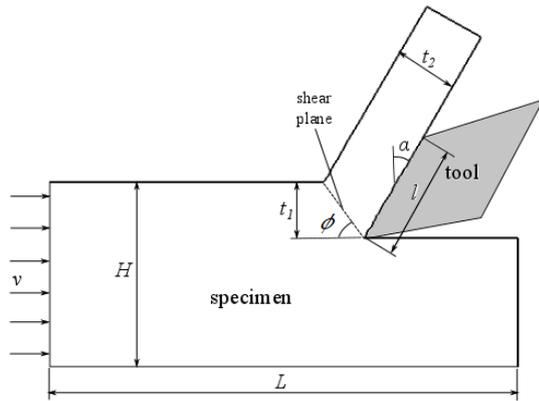
### 2. COMPUTATIONAL PROCEDURE

The specimen is modelled as a deformable body under 2-D plane strain hypothesis and an elastic perfectly-plastic material under prescription of a cutting velocity  $v$  and a stationary rigid tool. The parameters and dimensions applied in the model are defined in the Figure 1.

The specimen is discretized into triangular finite elements, with quadratic interpolation for the velocity field and linear interpolation for the stress field (Zouain,2014; Borges,1996a; Borges,2001b) and solved by limit analysis methodology briefly described in next section (Borges,1996a; Borges,2001b).

It is proposed a geometry adaptation based on Merchant model (Goover,2010; Armarego,1969) and the study of the stream traces obtained from the numerical method develop under finite element and limit analysis methods

(Ebecken,2009; Molinari,2008; Tyan,1992). Then, the chip geometry is approximated by arcs in order to represent the material flux.



parameter	dimension (units)
$H$	5
$L$	12.5
$L/H$	0.25
$t_1/l$	1.2
$\alpha$	$30^\circ$
$\phi$	$\frac{\pi}{4} + \frac{1}{2}(\alpha - \beta)$ (*)

where:  $\mu = \tan \beta$   
 (\*) Merchant equation

Figure 1: Orthogonal cutting

### 3. LIMIT ANALYSIS FORMULATION

Limit analysis method is a direct method and it aims the determination of a collapse power, the admissible stress field  $\mathbf{T}$ , the kinematically velocity field  $\mathbf{v}$ , the rate strain field  $\mathbf{D}$  related with  $\mathbf{v}$  by a deformation operator  $D$  and the plastic multiplier  $\lambda$ . By application of limit analysis theory found in field (Zouain,2014; Borges,1996a; Borges,2001b) and the restrictions associated to unilateral conditions and friction dissipation at chip-tool interface, a limit analysis formulation is developed as seen in (Figueiredo,2015).

### 4. EXPERIMENTAL PROCEDURE

Figure 2 shows the tool holder (Fig. 2a), the insert (Fig. 2b and 2c) and the workpiece holder (Fig. 2d) used in the experiments. A CNC machining center equipped with 9272 Kistler dynamometer and a National Instruments A/D conversion system is used to acquire the cutting forces, namely the cutting force and the feed force.

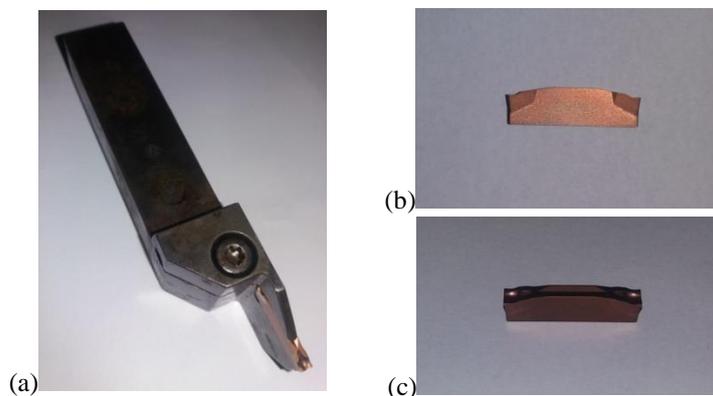




Figure 2: (a) Tool Holder RF-123G20-2020B; (b) and (c) Carbide insert N123G1-0300-0002-CM 1125, (d) workpiece holder.

The experimental data for three replicas for each cutting condition is statically treated using RStudio. The cutting velocity and feed rate are varied while the depth of cut is constant and equal to 3 millimetres.

The cutting parameters were measured in turning operation under cutting parameters as presented in Table 1:

Table 1. Experimental data.

Experiment	Cutting depth (mm)	$F_c$ (N) – Cutting force
1	0,1	537,4
2	0,1	507,5
3	0,1	460,2
4	0,06	353,8
5	0,06	338,6
6	0,8	413,6

## 5. RESULTS AND DISCUSSION

In order to validate the numerical model a preliminary study based on Merchant model is proposed. In this analysis a straight configuration for the chip is considered. Then, based on the velocity field and stream lines, a chip configuration that corresponds to the velocity field is determined.

After this analysis, a numerical model corresponding to experimental set up is implemented and the numerical cutting forces are compared to experimental results.

### 5.1 Preliminary model

An unitary velocity field is prescribed and the specimen is moved against a stationary tool in which unilateral conditions and friction are taken into account. It is considered a controlled contact tool and the contact length  $l$  is supposed known.

On the first run a straight chip is considered. From the post-processing stage, the stream lines are traced and this information is used in order to improve the chip geometry at steady state condition (Figure 3).

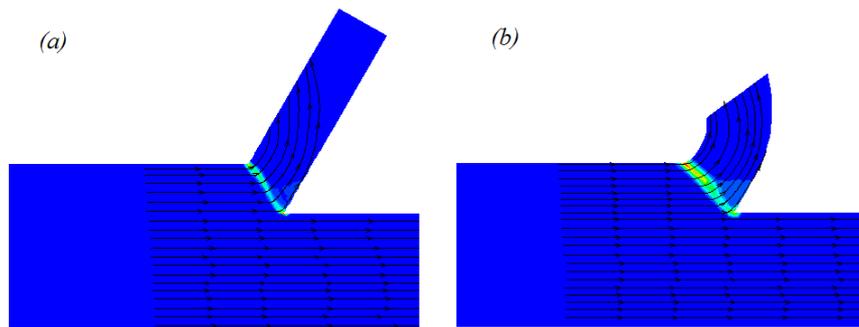


Figure 3: (a) chip at straight configuration (b) chip geometry based on stream lines. Friction coefficient at chip-tool  $\mu=0.2$ .

The proposed method allows the analysis of cutting force  $F_c$  (parameterized by material constant  $k$  and thickness  $w$ ) according to friction coefficient at chip-tool interface (Figure 4). The ratio  $t/l=1.2$ , rack angle  $\alpha=30^\circ$  and the tool tip is sharp.

The influence of friction coefficient at tool-chip interface is evaluated according to Merchant analytical solution and finite element based on Merchant geometry and a solution considering the adapted chip geometry as in Fig. (3.b).

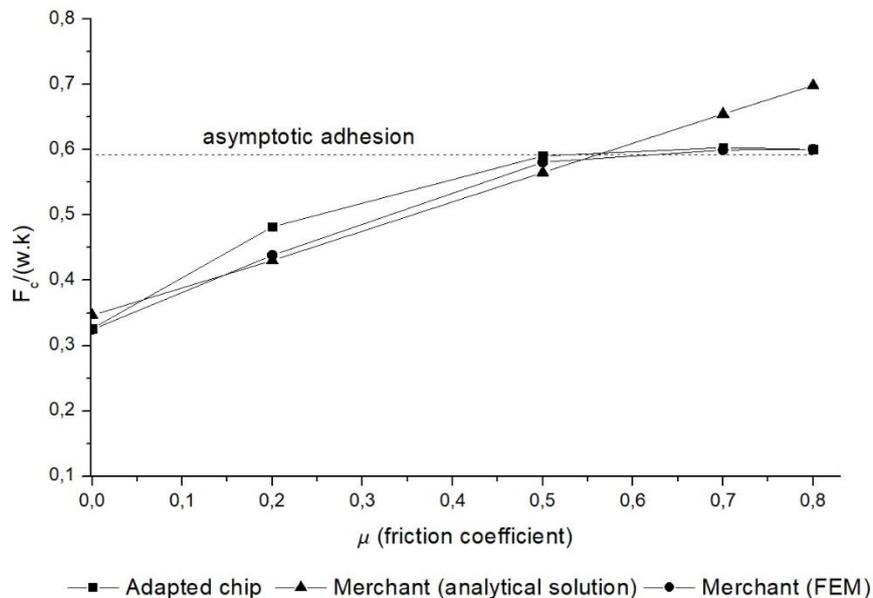


Figure 4: Cutting force and the influence of friction coefficient at chip-tool interface.

The asymptotic adhesion simulates material adhesion along tool contact interface. Besides the frictionless case, these cases constitute limit cases for cutting forces. Friction coefficients higher than 0.5 have no influence on cutting force and the finite element solutions tends to the adhesion asymptotic case. However, this tendency is not reach since analytical solution does not evaluate slipping/adhesion occurrence at tool-chip interface.

## 5.2 Numerical model according to experimental set up

In this case, the contact interface that reproduces the tool geometry is modelled. The frictionless and complete adhesion cases were analysed and compared to experimental cutting forces. Since there is friction at chip-tool interface, the cutting forces are expected to be between the bounds defined by frictionless case and complete adhesion.

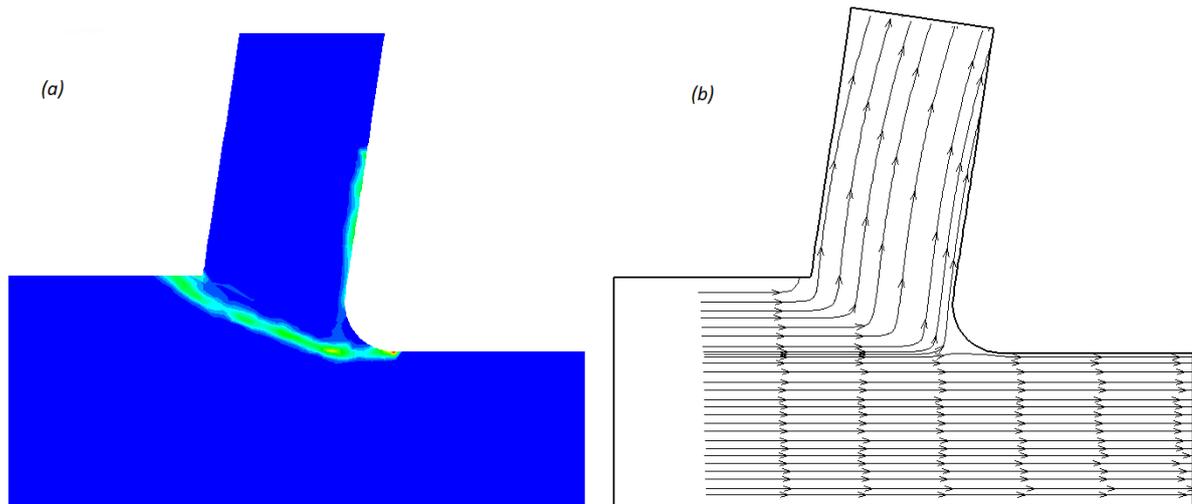


Figure 5: (a) Primary and secondary shear zones for complete adhesion case. (b) material stream traces.

The numerical and experimental cutting forces are compared in table 2 as follows:

Table 2. Numerical and experimental cutting forces.

$t_1$ (mm)	$F_c/(k.w)$ (FEM- $\mu=0$ )	$F_c/(k.w)$ (experimental)	$F_c/(k.w)$ (FEM- adhesion)
0.06	0.5844	0.6447	0.8743
0.08	0.7011	0.7703	1.0640
0.10	0.8159	0.9344	1.2246

## 6. CONCLUSIONS

In this paper it is proposed a numerical-experimental procedure to determine and calibrate the parameters evolved in orthogonal cutting processes. The proposed strategy is effective in the estimation of flow configuration, cutting forces and friction stress in the interface between the tool and the workpiece.

Additionally, it would be possible to study the sensitivity of the process with respect to cutting parameters and the wear in tools. In order to reduce the wear in tools and improve the quality of the final product, the target is to propose a methodology able to control the machining process just in time and adjust the work conditions on time.

In the preliminary model the numerical and analytical solutions were compared in order to validate the proposed model. By fixing the chip-contact length, the influence of friction coefficient on cutting force evaluation was investigated. The frictionless and complete adhesion at chip-tool contact interface constitute bounds for cutting force.

After this step, the geometry of the real tool was considered. The upper and lower bounds for cutting were evaluated and compared to the experimental results. As there is friction at chip-tool interface, the experimental cutting forces are within these bounds as expected.

As future work, one should adjust parameters as friction coefficient and chip-tool contact length in order to adjust the numerical cutting forces and meet the experimental cutting forces.

## 7. ACKNOWLEDGEMENTS

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