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OBTAINING CUTTING FORCES BASED ON JOHNSON-COOK MODEL

Romenigue Igor Melo Araujo Fernandes, romenigue.melo@gmail.com

Rhander Viana, rhanderviana@gmail.com

Lucival Malcher, malcher@unb.br

Danilo dos Santos Oliveira, unbdanilo@gmail.com

Universidade de Brasília Campus-Gama, Área Especial de Indústria Projeção A, CEP: 72444-240, Brasília-DF

Ildeu Lúcio Siqueira – ilsmec@gmail.com

Instituto Federal de Goiás, Rua 75 - Centro, CEP: 74055-110, Goiânia-GO

Abstract. *Simulate a machining process is an important and advanced way to understand the behavior of forces involved in this process without a financial large cost. In this paper, The Johnson-Cook model was used to define thermo-elastic-plastic of workpiece as well as the damage criteria to reach the chip separation during the machining process of AISI 1045. An 3D geometry was modelled using Finite Element Method based on software ABAQUS to simulate a cutting process. The results obtained in this simulation was satisfactory being the difference around of 20% of values attained on physical experiments using a stationary dynamometer.*

Keywords: *Finite Element Method (FEM), Abaqus, Machining Process, Cutting Force, Orthogonal Machining, Johnson-Cook Model*

1. INTRODUCTION

Naming a part that has not gone through the machining process is a difficult task. Without the manufacturing process airplanes, trains and vehicles would certainly not exist. The design of industrial or domestic products would not be possible without a mechanic lathe (Walker, 2000). Such machines improve agility and possibility to design tool with complex geometries with distinguished finishing. Machining process is characterized by the material removal to obtention of shape, dimension or finishing. During this process the removed material is called chip. The chip formation involves many concepts of solid mechanics, heat transfer and physicist. One of these concepts is physical magnitude called cutting force. According to Diniz, Marcondes and Coppini (2000, p. 63), cutting force is the action of workpiece on the tool. Generally, methods for cutting force measurements can be divided into two categories: direct force measurements and indirect force measurements (Scippa *et al.*, 2015). Many factors can influence the cutting force along of manufacture process, such as workpiece material, cutting section area, state of sharpening of tool, tool geometry, tool material, lubrication along machining and cutting velocity (Ferraresi, 1969). Study machining force is important to understand their components behavior. Having this understanding is possible estimate power required to a cut process, avoid tool premature wear, to obtain a machinability scale and collaborate with design and concept of tools and machines (Silva and Machado, 2004).

The global demand to productivity and product quality resulted in advanced research in manufacturing process. Historical Evolution to obtain results to define machining parameters was made by analytical, experimental, mechanistic and numerical methods (Ehmann *et al.*, 1997). Analytical method aims is established a relation of mathematical models between cutting force and workpiece mechanical characteristics. Mechanistic method associate machining process variables and cutting forces. Such association involves geometry characteristics and cutting coefficients obtained by empirical (Gonzalo *et al.*, 2009). The most common form to measure direct forces is through table dynamometers. Typical table dynamometers are made up of piezoelectric sensors which are assembled between two plates (Albrecht *et al.*, 2005). Numerical method consists in solve problems through fundamentals of numerical calculus to attain approximates results. Computational solves are widely needs to solve complex equations by way quick and precise. Finite Element Methods (FEM) is a robust, trustworthy and extensive method used by software of simulation to solve engineering problems. The finite element method started with significant promise of modeling several mechanical applications related to aerospace and civil engineering. One of the most exciting prospects is its application in coupled problems such as fluid-structure interaction, thermomechanical, thermochemical, thermo-chemo-mechanical problems, biomechanics, biomedical engineering, piezoelectric, ferroelectric and electromagnetics (Harish, 2019). The method consists in discretization a specific structure, in other words main divide the structure into a number of small parts. These small parts are called finite elements. Each element has a differential equation generally simple whose solution can be obtained or approximated. The software ABAQUS is a computational tool such use finite element method to solve engineering problems. The program

operations consist in three steps: pre-processing, solution and postprocessing. In pre-processing step, the geometry, properties of material, boundary conditions, loads and type of analyze is defined. That is the main e most important step to aim a satisfactory result. In the solution step occur all calculus to solve matrix of differential equations. Finally, post-processing show results from the previous step. In post-processing is possible extract values and graphs to analyze results of simulation. The exponential development of high-performance computers and increasingly accurate software, computational methods more and more adopted by industry. Such decision result in cost reduction on search and to improvement in productivity process.

The present work aims compare numerical and experimental data relation with cutting forces using the Johnson-Cook method and ALE model to achieve results that can reduce time machining process, increase the life of tools beyond to attenuate human error.

2. MATERIALS AND METHOD

It will be shown below the methodologies and equipments adopted in this present paper.

2.1 Materials adopted on tool and workpiece

To model a tool and workpiece on ABAQUS or any other software of simulation is necessary to know some properties of materials that will compose each part. Mechanical and physical properties values will influence directly on simulation. In the previous studies, tungsten carbide tool was established to be an ideal tool for cutting AISI 1045 (Kalpakjian, 2017). The properties are exhibited in Tab. 1 (Mabrouki and Rigal, 2008). For the workpiece, AISI 1045 was adopted because present an excellent machinability. Their properties are presented in Tab 2. (Wang, 2016).

Table 1. Tungsten Carbide Mechanical Properties

Density	Poisson's Ratio	Elastic Modulus	Thermal Conductivity	Specific Heat
11.900 kg/m^3	0.22	534 GPa	50 $Wm^{-1}C^{-1}$	400 $J/kg \cdot ^\circ C$

Table 2. Material properties for AISI 1045

Density	Young's Modulus	Poisson's Ratio	Shear Modulus	Thermal Conductivity	Specific Heat
7850 kg/m^3	200 GPa	0.29	80 GPa	52 $W/m \cdot ^\circ C$	486 $J/kg \cdot ^\circ C$

2.2 Methodology

To the experiment development with aim to collect cutting force, was adopted some procedures of machining process. The experiment occurred with a constant depth of cut equal to 1 mm and a constant feed rate of 0.094 mm/rot. All process of remove material was realized without cutting fluid. A carbide inserts with no coating whose specification is CNMG 12 04 08 H13A manufactured by Sandvik was utilized on machining process. The tool modeled on software has the same geometry of tool described above. The cutting conditions are shown in Tab. 3. The tool was set following the parameters of cutting edge χ_R , rake angle γ_o and inclination angle λ_s given in Tab. 4.

Table 3. Cutting conditions

	Cutting speed (m/min)	Feed rate (mm/r)	Cutting depth (mm)
1	51.8	0.094	1
2	82.8	0.094	1
3	207.2	0.094	1

Table 4. Parameters of cutting edge

χ_R	γ_o	λ_s
95	-6	-6

2.3 Dynamometer and Lathe

A stationary dynamometer Klistar model 9257B with three channels was used to measure the cutting force during machining process. The dynamometer is widely used on researches and developments because has several features and robust sensors to capture data with high precision. The module is responsible to process information obtained during the machining process in real time.

The stationary dynamometer was mounted on the machine tool's turret head on lathe Nardini Nodus 220 with 5 cv according to manufacturer's manual. The tool was mounted on the dynamometer with a tool holder. In this form, the dynamometer is embedded between the tool and the turret head.

3. NUMERICAL MODELING

In this paper a 3D model was built to simulate a cutting process Fig. 1. Johnson -Cook material model was used to modeling the thermo-elastic-plastic behavior for both materials, Carbide and 1045 Steel. In the simulation, the workpiece is modeled as a deformable plastic material and the tool is modeled as rigid material. The workpiece in this paper is set to be ENCASTRE, in other words, all degrees of freedom are zero. There no rotational and translational displacement. Other way the tool is set to move only in X direction, that is, in cutting direction. The tool is touching the workpiece to attenuate time of processing.

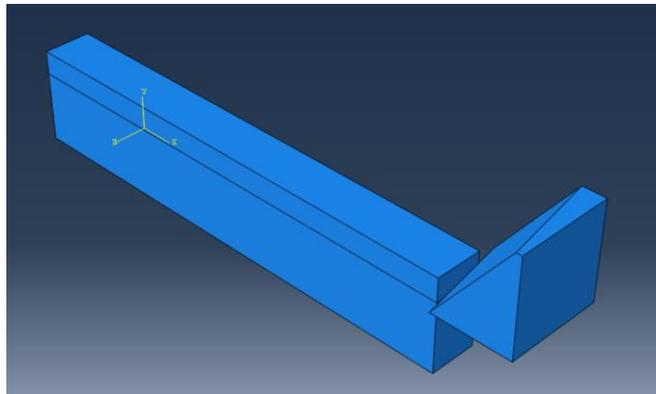


Figure 1. 3D model with workpiece and tool

3.1. The Johnson-Cook Constitutive Model

Johnson and Cook proposed this material model in 1983. This is a phenomenon logical model which is widely used in most computer codes for static and dynamic analysis, such as metal cutting (Dehkharghani, 2016). This model defines the flow stress as function of plastic strain, strain rate and temperature. The J-C model could be described as below in Eq. (1).

$$\sigma = [A + B(\varepsilon)^n] \left[1 + C \ln \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left[1 - \left(\frac{T - T_0}{T_{melt} - T_0} \right)^m \right] \quad (1)$$

The σ is the flow stress and ε , $\dot{\varepsilon}$, $\dot{\varepsilon}_0$ means the effective plastic strain, the effective strain rate and the reference strain rate, respectively. The parameters T , T_{melt} and T_0 are absolute temperature, melting temperature and reference temperature, or room temperature. The material constants are A, B, C, m and n . A is the yield stress of the material under reference conditions, B is the strain hardening constant, n is the strains hardening coefficient, C is the strengthening coefficient of strain rate, and m is the thermal softening coefficient (Murugesan, 2019). Theses constants for AISI 1045 steel are given in Tab. 4 (Vaziri, 2019).

Table 5. Constants for AISI 1045

A (MPa)	B (MPa)	C	n	m
553.1	600.8	0.0134	0.234	1

3.2. Johnson-Cook Damage Model

In finite element analysis, there are two commonly used criteria to separate the chip from the machined surface: a geometrical criterion and an equivalent plastic strain criterion (Ng *et al.*, 1999). The equivalent plastic strains are popular

and effective in modelling chip separation of metal cutting (Mabrouk, 2006). Johnson and Cook proposer that fracture strain typically depends on the stress triaxiality ratio, the strains rate and temperature (Banerjee *et al.*, 2015). The fracture model proposed by Johnson-Cook is given in Eq. (2).

$$\epsilon_f = \left[D_1 + D_2 \exp \left(D_3 \left(\frac{\sigma_m}{\sigma_{eq}} \right) \right) \right] \left[1 + D_4 \ln \left(\frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right) \right] \left[1 + D_5 \left(\frac{T - T_0}{T_{melt} - T_0} \right) \right] \quad (2)$$

Where D_1 to D_5 are the damage model constants, σ_m is the mean stress, and σ_{eq} is the equivalent stress. The damage parameters of AISI 1045 can be seen below in Tab. 5 (Duan *et al.*, 2011):

Table 6. Johnson-Cook damage parameters of AISI 1045

Damage law parameters	AISI 1045 steel
D_1	0.06
D_2	3.31
D_3	-1.96
D_4	0.0018
D_5	0.58

3.3. ARBITRARY LAGRANGIAN-EULARIAN ADAPTATIVE MESHING

The Finite Element Method is necessary to model an effective mesh on workpiece. There are two mathematical formulation for describing motion: Lagrangian and Eularian method. Lagrangian method the mesh moves with the material and the Eularian method the mesh is fixed in space and the material moves with respect to grid (Zatterberg, 2014). The ALE method is a combination of the methods quoted above. It means, the mesh can flow in an arbitrarily specified way. The mesh is essential to obtain the effective chip formation during the simulation. The shear failure at the tool-chip interface is characterized by Zorev's friction model. With Zorev's friction model at the tool-chip interface, the model predicts an accurate direction of chip flow in the chip formation process (Gao *et al.*, 2018). The software ABAQUS/Explicit v6.14 and ALE method will be used to realize the simulation.

4. RESULTS

Analyze cutting force has an important influence on machining processes. The 3D model described previously was submitted to solution step on ABAQUS/Explicit. In the figure 2 and figure 3 is possible to see elements submitted to several forces, like shear and tension stress. The tool slide quickly along the workpiece, removing material. In this moment occur the highest cutting force, beyond heat transfer along the workpiece. The combination of stresses and melting point culminated on chip formation, an expected result due the method adopted in this simulation. The solution step of simulation took over almost 5 hours to generate the post process.

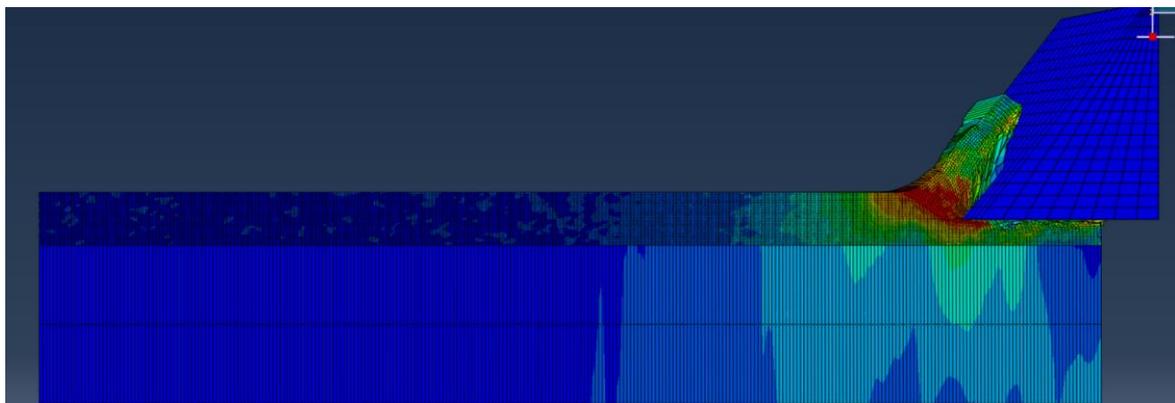


Figure 2. 3D machining process

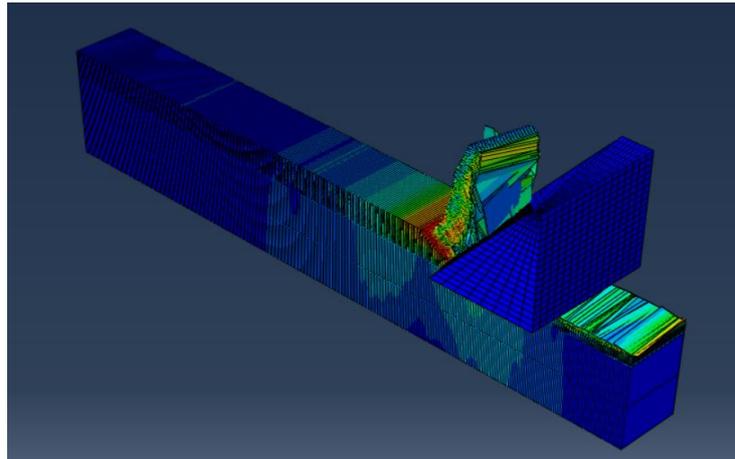


Figure 3. Chip formation

As expected, the tool did not suffer significant deformation. This result is logical because the material that makes up the part is most ductile than the tool material. Thus, the tool designed with a hardened steel is ideal to realize a machining process of AISI 1045 as long as it is within of parameters established in this paper. The mesh can be improved with a better refinement.

The graphs on Fig. 4 compares the values obtained numerically and values attained through stationary dynamometer Kistler. The continuous line describes results collected by sensors of dynamometer and squares describe the force obtained on simulation.

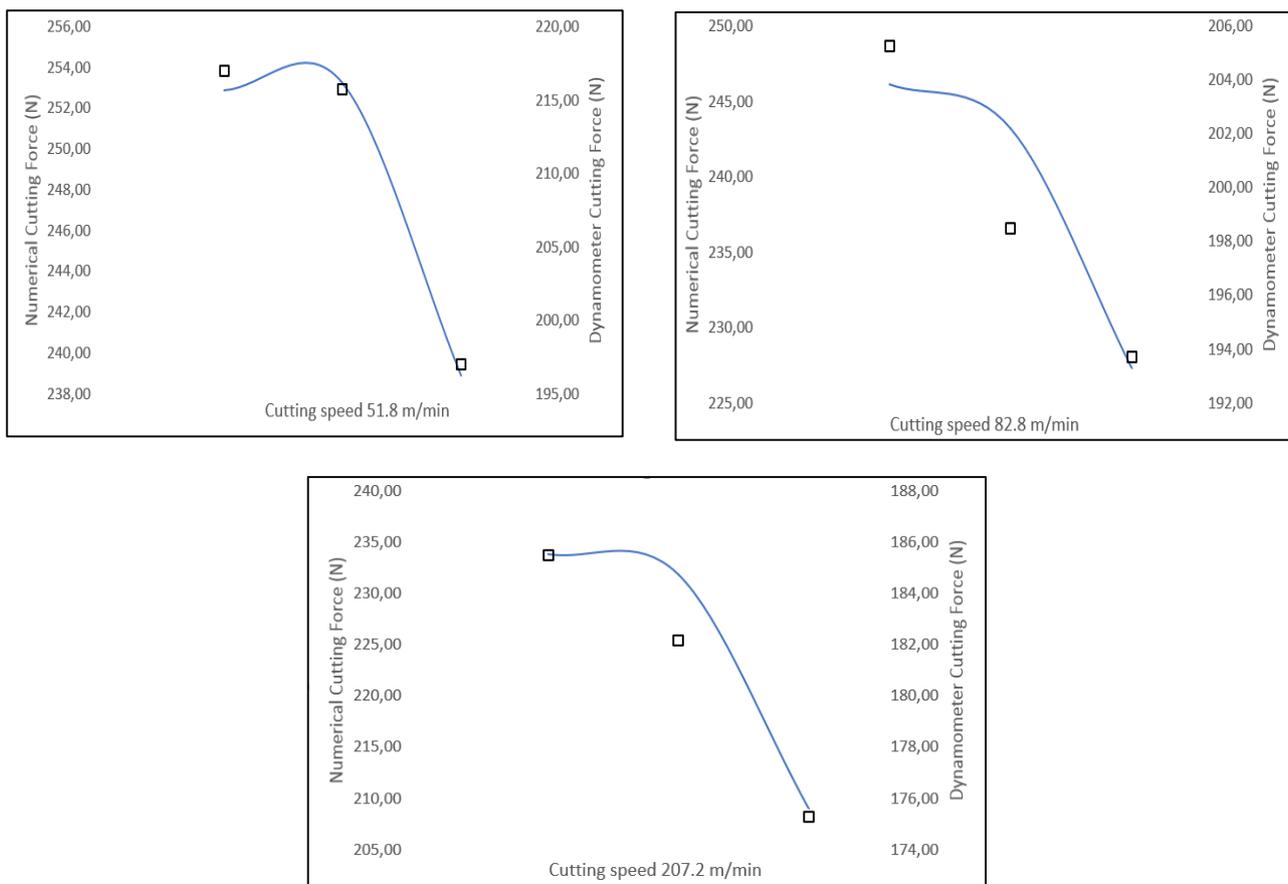


Figure 4. Analyze of cutting force of AISI 1045

The plots of variation of cutting speed helps to validate the theory of machining process. The literature says that cutting force tend to decrease due some phenomena, like temperature and high cutting speed. During the machining process the friction between tool-workpiece and cutting speed raises the temperature. Due the high temperature and speed, the workpiece material becomes more ductile, therefore reduce the cutting force. In graphs above is possible observe this phenomenon. The first one with smallest cutting speed had the higher cutting force while the last one has the higher cutting speed and lowest cutting force. In other words, in machining process the cutting force is totally related with cutting speed and temperature. Is possible to see a proximity of continuous line to squares, that is, numerical and analytical values are close, about 20% of error between them. Boundary conditions and mesh influence directly on results. A better model can minimize the error and improve the accuracy but the solution step of simulation will take longer due necessity of a higher processing.

5. CONCLUSION

All tool has a manual for reference of work prescribed by the manufacturer. Parameters like cutting speed, depth of cut and feed rate affect directly the tool life. Working with a simulation instead a physical experimental is financially viable because can be applied to many other parameters, materials and tools. With numerical data was possible show that higher cutting force occur on the first contact between tool-workpiece. In the cutting force graphs above it is possible to see that numerical simulation is an attractive method and can yield consistent results. There are several factors that may have contributed to the accuracy of the values obtained, such as the mesh chosen and the boundary conditions. The values attained in this simulation is close to value described in bibliography. According to papers, the error between the numerical simulation and the cutting experimental using a dynamometer is close to 20% in a numerical simulation of cutting process.

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