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EXPERIMENTAL AND SIMULATION ANALYSIS OF VERTICAL SURFACE GRINDING PROCESS IN PREDICTION OF FORCES

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Abstract. This article describes the experimental and simulation analysis of vertical surface grinding process. The grinding experimental under different conditions such as cutting speed, workpiece speed and depth of cut (vs, vw e ap). The prediction simulation of grinding forces involved in the process has been evaluated by finite element model (FEM). Reduced contact points between abrasive grain and workpiece in the dry condition were used in both the experimental test and the simulation. The objective is to determine the forces per grain and estimate the forces of conventional Al_2O_3 straight cup wheels in industrial operations. The material investigated has no specific data regarding numerical simulation, this material is mold and die steel produced by Villares metals called N2711M. The results showed the behavior of two forces orthogonal to each other that are directly related to chip formation and give an idea of the energy involved in the process. The effects of deformation in relation to the passage of grains over the surface provide information about the behavior of the investigated material in relation to surface quality aspects presented through the images extracted from scanning electron microscopy observations. The results indicates that there is a good agreement between the experimental and simulated results, as the coefficients of the constitutive law model of the material were determined. The most influential parameters on the force results are the cutting speed and depth of cut. The feed demonstrated how the passage of abrasive grains deforms the surface of the workpiece, resulting in a good method for tribological analysis of the contact between abrasive and workpiece. In the future, the expectation is to develop grinding wheels with orientation in the distribution of abrasive grains to reduce costs in their manufacturing, improving the material removal rate of the workpiece, and the produce finished surfaces with lower energy consumption.

Keywords: prediction force, vertical surface grinding, simulation, element finite method

1. INTRODUCTION

An important practical problem is to evaluate the force in grinding processes. Through the forces it is possible to estimate the grinding power and in association with grinding ratio, also referred to as the G-ratio, get the performance of grinding wheels.

The effect of grain shape and orientation has been found single-grit tests, mainly for superabrasives, such as diamond and CBN, cubic boron nitride, (Matsuo *et al*., 1989; Ruttimann *et al*., 2013). These tests are an important tool for understanding grinding processes, however, are often expensive and not feasible. Computational simulations can be a great assistance in the study of material machining, as stated by Özel (2006). Simulation models based on the finite element method (FEM) have the potential to provide additional predictions of tool wear and fracture, as well as the integrity of machined surfaces (residual stresses, microhardness, and microstructure). However, the accuracy of a finite element model is determined by its ability to describe and predict the constitutive behavior of the material. Therefore, it is necessary to study the dynamic deformation behavior of materials under rapid impact loads to develop an accurate model of material behavior (Chen, 2023). Currently, a model that has been widely incorporated into commercial finite element software is the Johnson-Cook model, which is used to simulate the flow behavior of various materials under specific loading conditions (Liu, 2021).

The Johnson-Cook (J-C) model considers strain hardening, thermal softening effects, and material strain rate when subjected to high loads. Additionally, by using five material-specific constants, the model can predict the mass flow behavior under high stresses, high strain rates, and high temperatures (Chen, 2023 citing Johnson, 1983). Through the modified J-C model, various parameters in the machining of LA103Z Mg–Li alloy were compared between real values and simulation results, resulting in a relative error of 8.83% for the cutting force between the measured and simulated values (Chen, 2023).

Explicit dynamics is a numerical analysis method used to simulate dynamic events, such as collisions, impacts, and explosions. In this method, the equations of motion are explicitly solved in time, and the simulation is performed in very small-time steps. The explicit dynamics method can also be applied to simulate machining processes, such as grinding. The objective of the simulation is to predict the system's behavior during the machining process, including cutting forces, temperature, residual stress, and burr formation, (ANSYS, 2021).

2. EXPERIMEMTAL METHOD

Using a ROMI Discovery 760 machining center, 11 kW, with a rotational speed ranging from 10 to 10,000 rpm, a flat face grinding process was performed. The cutting parameters are described in Table 1. It was used a cutting tool A151/4AR60O5V, manufactured by CARBURUNDUM, made of pink aluminum oxide and compliant with ISO 525 standards. This tool has a limited number of abrasive grains that come into contact with the workpiece. In this study, it was observed that the grains in contact with the workpiece during grinding ranged from 6 to 8. Taking an average of 7 grains, the arithmetic mean of the forces distributed on each abrasive was calculated to simplify the analysis and achieve convergence of the simulated model. An aluminum fixture, designed according to ABNT 1100 commercial standards, was used to hold the tool. The fixture which is similar to a straight cup wheel with an outer diameter of 76.2 mm. Another mounted point was added at 180 degrees from the first one, positioned 0.5 mm above the surface to be machined, to ensure system balance. Figure 1 shows a frontal view of the assembly system comprising the holder, tool, and workpiece used in the experimental test to replicate the frontal grinding process, (Fernandes, 2015).
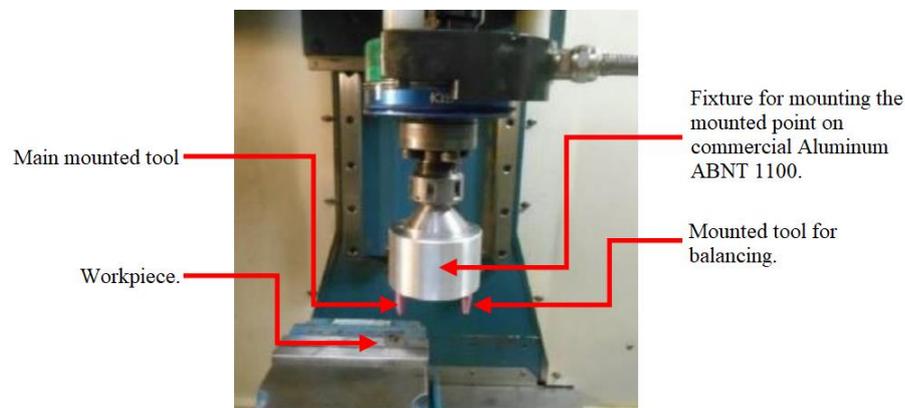

Figure 1. An overview of the assembly system for the holder-tool-workpiece.

The workpiece selected for machining is made of ABNT N2711M steel (44 HRC), which is widely used in extrusion dies, injection molds for plastics, and blow molds. This material was chosen for its characteristics, such as good machinability and uniform hardness. The dimensions of the analyzed workpiece are 40 mm x 20 mm x 4 mm.

Table 1. Parameters used in the experimental test.

Parameters	Value
Wheel velocity, m/s	25
Depth of cut, m	5_x10^{-6}
Workpiece velocity, m/min	250

3. FINITE ELEMENT METHOD

Finite element analysis is a powerful and versatile numerical technique for solving engineering problems in which the mathematical equations describing the physical behavior of the system are too complex for an analytical solution, (Logan, 2007). With the FEM cutting simulation, it is possible to estimate the values of process variables that are not measurable or that are very difficult to measure by experiment, (Yen, 2004).

3.1. Model Formulation

In continuum-based FEM modeling of cutting, there are two types of analysis in which can be described: Eulerian and Lagrangian. In a Lagrangian analysis, the computational grid deforms with the material whereas in a Eulerian analysis it is fixed in space, (Özel, 2006). In this study, the Lagragian model was used.

3.2. Material Model

Material model: Johnson-Cook, this material model was developed in the 80s for studying impacts, penetrations, and explosives. It was considered appropriate to use it in conditions like the presented study, in which involves problems of rapid deformations and large strains, such as simulations of machining processes (Johnson, 1983). The Johnson-Cook (J-C) model is a constitutive equation that takes into account the influence of temperature and strain rate on flow stress, primarily focusing on the strain strengthening at room temperature. This model is widely utilized to describe the material's behavior under high strain rates and elevated temperatures, (Chen, 2023). The J–C model defines the yield stress Y as shown in the following equation (1).

$$Y=[A+B\varepsilon^n][1+Cln\varepsilon^*][1-T^m] \qquad\qquad (1)$$

Where:
ε= effective plastic strain
ε^*= normalized effective plastic strain rate
T= homologous temperature = (T-Troom)/(Tmelt -Troom)
The five material constants are A, B, C, n and m.

In this study, the J-C constants of the 4340 steel were used, as starting point because it is similar to N2711M steel. The yield stress of the material was defined as 1.002 GPa, (Montalvão, 2014), a linear approximation of the hardness constant was made.

3.3. Tool and Workpiece Geometry

A grinding wheel has a multiple of geometrically undefined cutting points (tools) which are irregularly distributed on its working surface, which are presented to the workpiece at random orientations and positions. Consequently, there is significant variation in the cutting geometry from point to point, (Malkin, 2008). Abrasive particles in bonded abrasive products (grinding wheels) are blocky crystals that roughly resemble a sphere with many sharp edges, as represented in the figure 2, (Shaw, 1996).
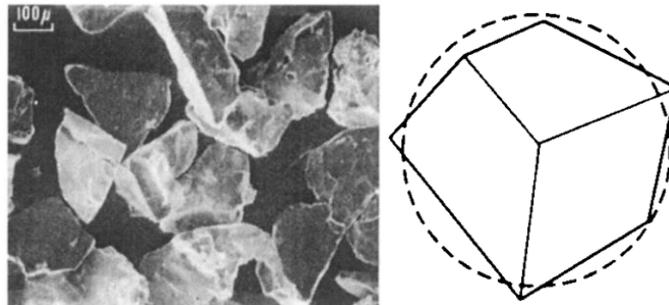

Figure 2. Al_2O_3 particles and similarity between a blocky abrasive particle inserted in a spherical volume.

The grain dimensions were determined according to the FEPA classification for mesh size 60, where the average grain diameter is 253 μm. The grain shapes were classified into four types: conical shape, spherical shape, circular tabular shape, and rectangular pyramid shape, (Lee et al., 2012). In this study, rectangular pyramid shape and circular tabular shape were used. Since the object of analysis is the workpiece, the height of the simulated grain geometry was defined to be approximately 3 times the cutting penetration depth (ap).

The geometry of the workpiece was defined as a parallelepiped with dimensions of 65x65x100 micrometers. To achieve the objective of this study, which is to analyze the impact forces caused by the contact of the abrasive grain with the workpiece, the geometry of the workpiece was reduced to decrease computational costs in the simulations.

3.4. Contour Condition

Boundary conditions are of two general types. The more common type is homogeneous boundary conditions, which apply to locations that are completely restricted from any movement. Nonhomogeneous boundary conditions, on the other hand, are employed when finite nonzero values of displacement are specified, such as when defining the settling of a support, (Logan, 2007). Parameters that closely resembled the experimental grinding process were used. The workpiece was fixed by a support attached to its lower face, and the displacement of the abrasive grain was limited in the X and Y

directions to simulate the tool's clamping in the machine. The velocity set for the computational simulations was 25 m/s, and the depth of cut of the abrasive grain on the workpiece was 5 micrometers.

Özel, (2006) identified that the cutting force in finite element simulations is highly dependent on the added coefficient of friction. In this study, the coefficient of friction was varied from 0 to determine the optimal condition at 0.2 and 0.05.

3.5. Mesh Control

To determine the mesh used in the simulations, a mesh refinement process was employed until additional refinements did not yield significant variations in the force results, as shown in Table 1. The mesh element size was set to 5 micrometers to better observe the stress distribution during the cutting process.

Table 2. Parameters for model mesh convergence.

Mesh (µm)	Nodes	Elements	Force (N)
10	779	619	0.4385
8	1621	1302	0.9573
5	5345	4519	0.1473
3	22103	19771	0.1653
2	70280	65119	0.12509

With defined mesh parameters and boundary conditions, simulations were initiated to determine the Johnson-Cook model constants that best represented the experimentally obtained cutting forces, as shown in figure 3.
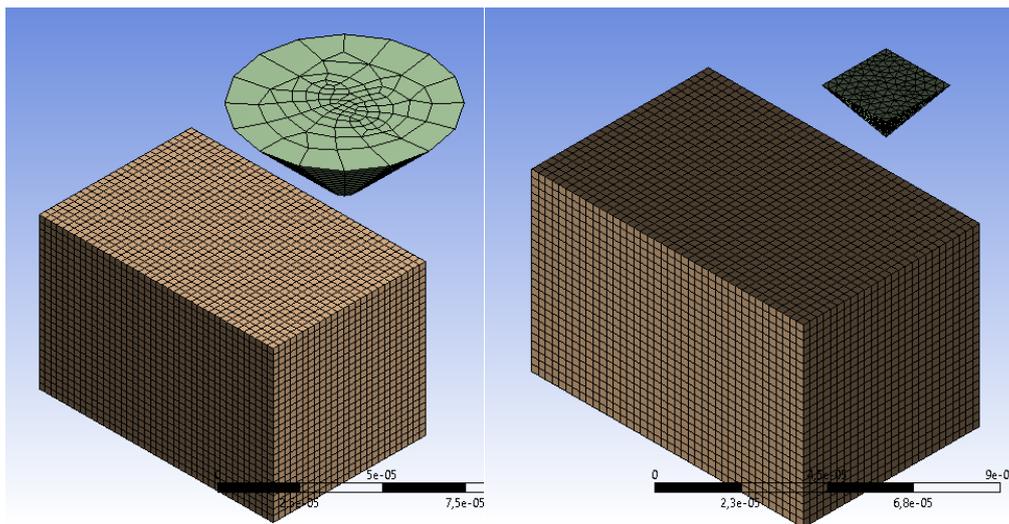

Figure 3. Mesh and grain shape used in this study.

4. RESULTS AND DISCUSSION

Initially, the "Hardening constant" parameter was increased up to a value of 1.5 GPa until it no longer showed a significant increment in force results. Then, the "strain rate constant" parameter was increased up to a value of 2, which stabilized the tangential force at 1.05 N and the normal force at 0.94 N. The parameters "thermal softening exponent," "Melting temperature," and "Reference strain rate" did not show significant variations in force results for this experiment. After 30 variations the constants of the Johnson-Cook model, the values that best matched the forces obtained during the simulation and the forces measured experimentally using a dynamometer were determined. The values for the J-C constants are presented in Table 3.

Table 3. Constants of the Johnson-Cook material model that presented the best approximation.

Initial Yield Stress (GPa)	Hardening Constant (GPa)	Hardening Exponent	Strain Rate Constant	Thermal Softening Exponent	Melting Temperature (C)	Reference Strain Rate (/sec)
1.7	1.1	0.5	0.2	1.03	1519.9	1

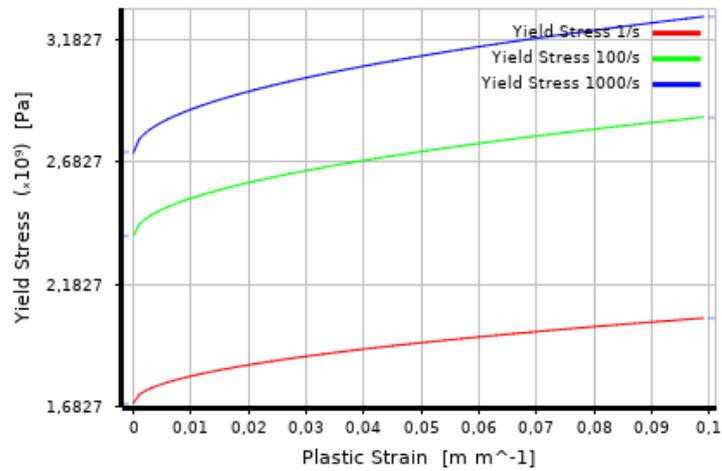The stress-strain graph with the defined J-C constants is shown in Figure 4.

Figure 4. Johnson-Cook Strength, ANSYS 2021.

With this finalized model, it was possible to observe the equivalent Von-Mises stress in the workpiece for the pyramidal geometry, as shown in Figure 5, and for the conical geometry, with a truncated vertex, as shown in Figure 6.
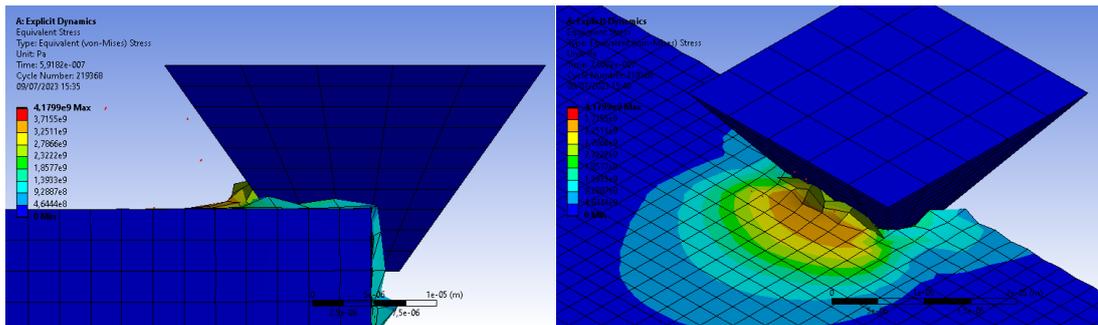

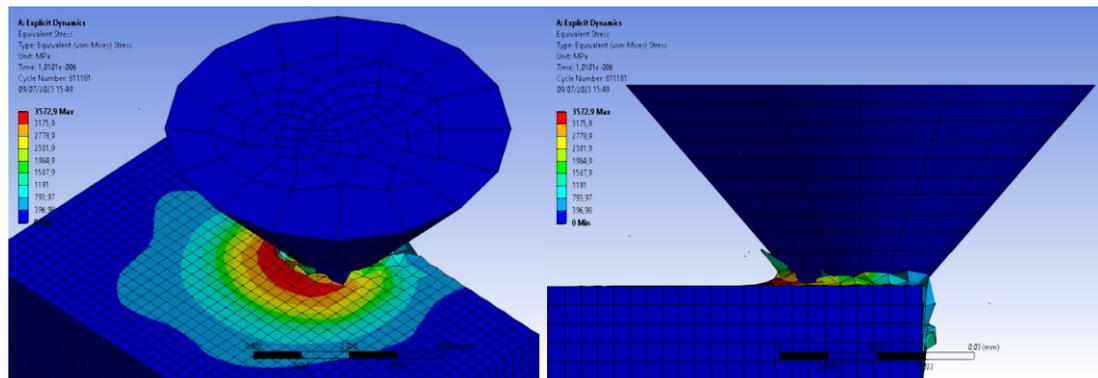Figure 5. stress equivalent Von-Mises rectangular pyramid shape.

Figure 6. Stress equivalent Von-Mises conical shape with a truncated vertex.

The results for the forces applied to the workpiece during the abrasive grain passage with a velocity of 25 m/s and a cutting depth of 5 micrometers are shown in figure 7.
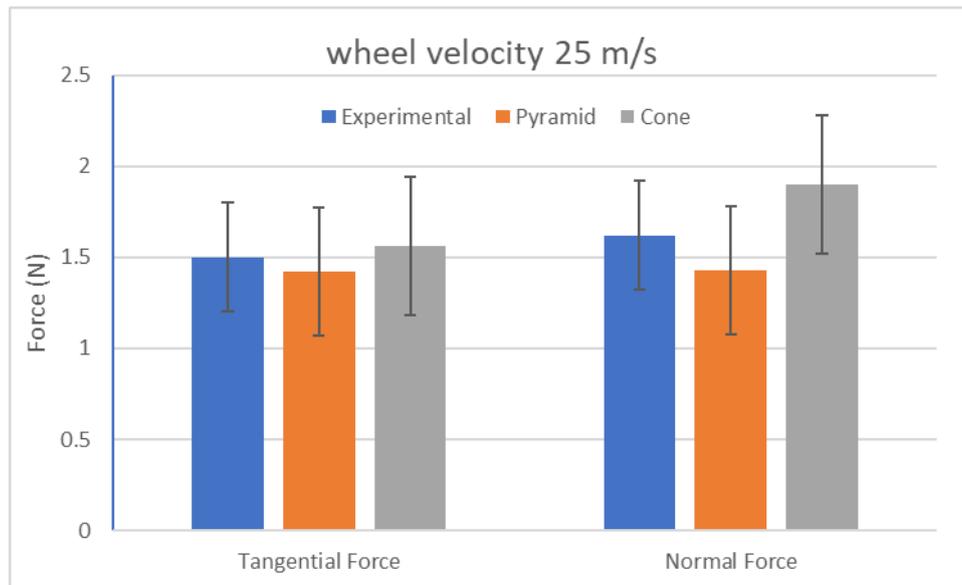
Figure 7. Comparison of the forces obtained in this study.

The simulated process forces were scaled up with the same factor of the experimental arrangement as adopted by other researchers (Rüttimann, et al, 2013; Axinte, et al, 2013). According to the theory, the normal force has 3 to 4 times the value of the tangential force (Malkin, et al. 2008), but it was not noticed in this experiment. A possible cause for such result can be attributed to the reduced cutting depth that led to a ductile-regime grinding (Bifano, et al, 1991).

The simulate tangential and normal force agreed with the experimental measured forces. The simulated normal force, represented by Fy, had relative error of 14.3% for pyramidal morphology and 35.7 % by conical morphology. However, as noted the dispersion around 0.3N of the experimental results demonstrate that simulation results have a correlation. The simulated tangential force, represented by Fz, had relative error of 6.6% for pyramidal morphology and 6.0 % by conical morphology.

5. CONCLUSIONS

In order to support the development of the grinding process date simulation, can be summarized as follows:

The profiles of the abrasive grain replicate the envelope geometry of the grit.
The simulate tangential and normal force agreed with the experimental measured forces in view of the dispersion of the experimental results.
This work is a pioneer in the search of the coefficients that make up the Johnson-Cook equation for N2711M steel.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE

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