Main Cutting Force and Cutting Temperature Affected by the Tool Rake Angle Based on Orthogonal Cutting Model

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ABSTRACT

A 2-dimensional elasto-plastic finite element model of metal oblique cutting was developed with a DEFORM 2D. An automatic remesh technique was used to remesh the distortion mesh; a couple of numerical simulations have been developed on the metal oblique cutting process with different tool rake angles, some conclusions was obtained according to the simulation results: the variational rule of cutting force and the temperature distribution of tool-workpiece. Theory foundations are provided to the selection of tool geometry and to improve the surface quality of workpiece.

KEYWORDS

Rake angle; Finite element model; Numerical simulation; Main cutting force; Cutting Temperature

INTRODUCTION

Cutting process not only involves the elasticity, plasticity, fracture mechanics, and thermodynamics, tribology, etc., and quality are effected by cutting tool shape, chip flow, temperature distribution, heat flow and tool wear and other [1], However, it is difficult to quantify the cutting mechanism analysis and research by using conventional analytical methods.

The rapid development of computer technology makes use of numerical simulation methods to study the relationship between the cutting process and the various parameters possible. In recent years, the finite element method in the cutting process showed that finite element simulation of cutting processes and chip formation

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of the cutting mechanism for understanding, improve cutting quality is helpful. Bushing part machining process was simulated. Figure 1. is a guide sleeve part drawing.

![Figure 1. Guide sleeve parts.](image)

**CUTTING THEORY**

**Workpiece Material Model**

The first deformation zone in the elastic deformation is negligible, workpiece material model can be simplified to incompressible elastic - viscoplastic materials. This method has been used and validated by Shih et al [2]. Taking into account nonlinear problems material flow yield stress of the workpiece material should be described by the Von Mise criteria, namely: "When the material in a plastic state, equivalent stress is always a constant value" expressed by the formula [3] for:

\[
\bar{\sigma} = \sigma_s
\]

(1)

Which is

\[
(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\sigma_s^2
\]

(2)

Which \( \bar{\sigma} \) is equivalent stress, \( \sigma_s \) the yield stress of the material, \( \sigma_i \) as the first principal stress \( i = 1, 2, 3 \)

Suppose shear zone of plastic deformation can be completely converted into heat, the plastic deformation of the heat generation rate \( \dot{Q} \) can be expressed by Norton-Hoff rule as the shear flow stress \( k \), strain rate \( \dot{\varepsilon} \), efficiency \( \eta \), and function of deformation strain rate sensitivity exponent \( m \), as follows formula :

\[
\dot{Q} = \eta k \sqrt{3\dot{\varepsilon}^m}
\]

(3)

Dimensional orthogonal metal cutting simulation problems can be viewed as a plane strain state, the main cutting force and direction of tool movement is the same force. In order to obtain the cutting force, cutting force it can be considered as the force in the direction of movement of the components of the tool between a rake face and chip and flank and the machined surface stress. The degree of deformation of metal cutting \( \Lambda_{ha} \) can be expressed as the ratio of chip thickness \( h_{ch} \) and cutting layer
thickness $h_p$ or represented as $\Lambda_{hl}$ by layer cutting length $l_c$ than cutting chip length $l_{ch}$, such as formula 2-4, 2-5 [2]:

$$\Lambda_{ha} = \frac{h_{ch}}{h_p}$$  \hspace{1cm} (4)

$$\Lambda_{hl} = \frac{l_c}{l_{ch}}$$  \hspace{1cm} (5)

Since the workpiece width changes very little when the cutting layer was cut into a chip, according to the volume of the same principle, it is clear [4]:

$$\Lambda_{ha} = \Lambda_{hl} = \Lambda_h$$  \hspace{1cm} (6)

**CUTTING HEAT**

When the two-dimensional cutting was simulated, heat conduction equation is[1]:

$$\lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + Q = C_\rho \left( u_x \frac{\partial T}{\partial x} + u_y \frac{\partial T}{\partial y} \right)$$  \hspace{1cm} (7)

Where $T = T(x, y)$ is the temperature distribution; $\lambda$ is thermal conductivity; $C_\rho$ specific heat; $Q$ is the heat generation rate per unit volume, it can be calculated by the equivalent stress and equivalent strain rate [1]:

$$Q = \bar{\sigma} \bar{\varepsilon} / J$$  \hspace{1cm} (8)

Where: $\bar{\sigma}$ is the equivalent stress, $\bar{\varepsilon}$ equivalent strain rate, $J$ for the mechanical equivalent of heat.

**FINITE ELEMENT SIMULATION OF MACHINING**

The actual turning is three-dimensional, but the main cutting force and temperature field simulation required to obtain can be obtained under the two-dimensional, and the use DEFORM 2D software can save a lot of computing time, improve work efficiency, so the DEFORM 2D simulation software was selected.

**Cutting Parameters**

Cutting parameters used are shown in Table 1., simulation parameters as shown in Table 2.

**TABLE 1. CUTTING CONDITIONS.**

| Cutting speed (mm/s) | 1500 |
|----------------------|------|
| Cutting depth (mm)   | 0.141|
| Feed amount (mm/r)   | 0.1  |
| Tool main angle (°)  | 45   |
| Tool clearance angle (°) | 6    |

NOTE: THE TOOL - WORKPIECE CONTACT FRICTION WAS SIMPLIFIED, AND COULOMB FRICTION MODEL HAS BEEN CHOSEN [5];
Establish Finite Element Model of Two-dimensional Cutting

GEOMETRIC MODEL TRANSFORMED INTO FINITE ELEMENT MESH MODEL

In the tool, for example, the cutting geometry Geometric model established in the CAD software was shown in Figure 2., it was saved as iges format then imported finite element software to do mesh; where in the workpiece is a quadrilateral mesh, the total number of units 1200 one; the tool triangular mesh, the total number of units to 178, the tip of the refined mesh. Furthermore, since the two-dimensional plane strain belonging to the cutting model, therefore you need to specify the grid thickness of 1mm. The resulting two-dimensional finite element mesh cutting model shown in Figure 3-6. In the tool, for example, the establishment of cutting geometry in the CAD software shown in Figure 2., saved as iges format import finite element meshing software was made; wherein the workpiece is a quadrilateral mesh, the total number of units 1200 one; the tool triangular mesh, the total number of units to 178, the tip of the refined mesh. Furthermore, since the two-dimensional plane strain belonging to the cutting model, therefore you need to specify the grid thickness of 1mm. The resulting two-dimensional finite element mesh cutting model was shown in Figure 3.

| TABLE 2. ANALOG PARAMETER SETTINGS. |
|--------------------------------------|
| Coefficient of friction (Coulomb friction model) | 0.4 |
| Convective heat transfer coefficient (N/(sec-mm·°C)) | 0.02 |
| Thermal conductivity (W/(m·K)) | 45 |
| Ambient temperature (°C) | 20 |
| tool cutting distance of Single simulation (mm) | 10 |

PARAMETER SETTINGS OF MATERIAL PROPERTIES

Workpiece material is 45 steel, Carbide tool steel YT15.
CUTTING SIMULATION RESULTS ANALYSIS

Analysis of The Main Cutting Force

Main cutting force alone extract $\gamma = 10^\circ$ with the cutting distance variation graph was shown in Figure 4.,

$$\text{FIGURE 4. } X = 10^\circ \text{ CUTTING FORCE CHANGE PATTERN WITH THE CUTTING DISTANCE.}$$

Cutting force increases linearly from zero 397.7966N about to steady state, then cutting force keeping volatility (maximum relative error: 3.6%) in the value up and down within a small range. In the initial stage of cutting, cutting power consumption was mainly used against the elastic deformation of the workpiece, while gradually increasing the contact area between the knife cuttings, so the main cutting force rise; when cutting up to a steady state, due to cutting heat, soften the workpiece itself, decreased cutting force, and maintain a relatively stable value. This theory is consistent to the cutting line with cutting rules, visible simulation is successful. The average cutting force of each front corner simulation obtained under Table 3., when $\gamma = -15^\circ$, the cutting force of up to 457.2163N. decreases with the increase of plastic deformation on the one hand so that the cutting rake surface layer is extruded, i.e. the decrease of formula (6); on the other hand to reduce the frictional resistance of the chips flowing through the rake face, thus cutting force reduction.

| Rake angle $\gamma$ | -15° | -10° | -5°  | 0°   | 5°   | 10°  | 15°  |
|---------------------|------|------|------|------|------|------|------|
| Analog values (N)   | 457.3| 444.3| 428.4| 413.2| 409.0| 397.8| 403.8|
| theoretical values (N) | 505.7| 485.5| 465.3| 445.1| 424.8| 404.6| 384.4|
| Absolute error (N) | 48.4 | 41.2 | 36.9 | 31.9 | 15.8 | 6.8  | 19.4 |
| Relative error (%)  | 9.6  | 8.5  | 7.9  | 7.2  | 3.7  | 1.7  | 5.0  |

TABLE 3. IS THE THEORETICAL VALUE CALCULATED BY THE MAIN CUTTING FORCE EQUATION (9)[6].

$$F_z = 9.81 \times 60^n F_z a_p^{F_z} f^{F_z} v^{F_z} k_{F_z}$$

(9)

Where: $a_p$ is cutting depth, $f$ is the amount of feed, $k_{F_z}$ for the first angle correction coefficient, $v$ is the feed rate. Constant Coefficient $C_{F_z} = 270$, $\chi_{F_z} = 1.0$, $\gamma_{F_z} = 0.75$, $n_{F_z} = -0.15$. Known by the equation (9), in the other conditions
remain unchanged, the main cutting force varies with changes in $k_{FZ}$; Known by the table 4., FZ is increased with increasing rake angle trend.

### Table 4. Correction Coefficient Table of Front Angle [7].

| Appellation | Tool Material | Correction Coefficient |
|-------------|---------------|------------------------|
| -15         | 1.25          |                        |
| -10         | 1.20          |                        |
| -5          | 1.15          |                        |
| 0           | 1.10          |                        |
| 5           | 1.05          |                        |
| 10          | 1.00          |                        |
| 15          | 0.95          |                        |
| 20          | 0.90          |                        |

Figure 5. is chart of the comparison between the main cutting force simulation and theoretical values in a different angle, which show the results with the theoretical results agree well with the simulation, the simulation can be considered a success.

**Figure 5. The Comparison Between the Main Cutting Force Simulation and Theoretical Values in a Different Angle.**

### Cutting Temperature

Temperature of the workpiece, chip and tool internal distribution during the first 800 steps was shown in figure 6.&7. As can be seen from Figure 6.

**Figure 6. The Temperature Distribution of the Workpiece and the Chip of the First 800 Steps.**

maximum temperature concentrated in the area of local deformation near the blade and blade at, because there is plastic deformation and friction relatively concentrated
areas. In step 800 the maximum temperature of the workpiece reaches 736 °C. From Figure 6. it can also be seen under the surface of the workpiece has been added also has a high temperature, which causes the workpiece residual deformation and residual stress.

![Figure 7](image)

**Figure 7. Tool temperature distribution of the first 800 steps.**

The curve of the maximum temperature of the tool and the workpiece with the front corner. in the first 800 step was shown in Figure 8. The maximum temperature of the workpiece surface decreases with γ value, which is due to the γ value is increased, deformation of the small cutting, cutting heat produced less, thus reducing the surface temperature of the workpiece; for the tool, since the tool and result in increase in chip rake angle the contact area is reduced, namely by means of the tool chip away heat is greatly reduced, the tool surface cooling conditions deteriorate, but the rake face temperature increased.

![Figure 8](image)

**Figure 8. Toolworkpiece first800 steps at the highest temperature with the rake angle curve.**

**CONCLUSIONS**

Metal cutting model of plane strain state using finite element analysis software were analyzed. Cutting force, cutting temperature and the effects of stress and strain affected by rake angle changes were predicted, that the following conclusions can be draw draught:

1. With the rake angle γ gradually increased from -15° 10°, the main cutting force is gradually reduced, and in the range of -15° ~ 0°, the impact of changes to the main cutting force rake angle than at 0° ~ 10° interval affect large; increases in 10° ~ 15° main cutting force, near the main cutting force in 10° minimum.

2. With the increase of rake angle, the surface temperature drops slightly, a slight increase in the surface temperature of the tool, and the tool - the maximum
temperature of the workpiece contact does not appear in the rake face of the tool tip but crumbs knife contact nearby.

(3) Due to the finite element model for cutting conditions, such as: factors workpiece, tool material, cutting speed, depth, etc. can all be changed. So the model can be used as a general model to study the effect of other parameters on the cutting tool material and cutting process.

(4) for the formation of the local chip machining with high-temperature, high-speed molding characteristics, the local temperature is bound to affect various performance parameters of the material, thus affecting the cutting process of the workpiece.

REFERENCES

1. Fang Gang, Zeng Pan. Advances in numerical simulation technology for cutting process [J]. Advance in Mechanics, 2001, 31(3): 394-404
2. Shaw MC. Metal Cutting PriciPles. Oxford: Clarendon Press, 1984: 18 -- 27.
3. Budak E., Altintas Y., Armorego E.I.A. Prediction of milling force coefficients from orthogonal cutting data [J]. ASME Journal of Manufacture Science and Engineering, 1996, 118: 216-224.
4. [4] Wang Hongjun, Turning simulation based on DEFORM software [J]. Digital Manufacturing Industry. 2002: 9: 57-59.
5. [5]Xie Feng, Zhao Ji-wen, Numerical Simulation of Two-dimensional Metal Cutting Process [J] Journal of System Simulation, 2004, 16(7): 1412-1416.
6. [6] S. Ratchev, S. Liu, W. Huang, et al. An advanced FEA based force induced error compensation strategy in milling [J]. International Journal of Machine Tools and Manufacture. 2006, 46(5): 542-551.
7. [7]Weifang Chen, JianbinXue, Deformation prediction and error compensation in multilayer milling processes for thin-walled parts [J] International Journal of Machine Tools & Manufacture 49 (2009) 859–864.
8. [8]Mohammadpour M., Razfar M.R., Jalili Saffar R. Numerical investigating the effect of machining parameters on residual stresses in orthogonal cutting. Simul Model Pract Th. 2010. 18: 378-389.
9. [9]Saurabh Agrawal, Suhas S. Joshi. Analytical modelling of residual stresses in orthogonal machining of AISI4340 steel. Journal of Manufacturing Processes. 2013.15(1): 167-179.
10. [10]Borja C., Virginia G.N., Oscar G., Ana A., Carmen S. Influences of turning parameters in surface residual stresses in AISI 4340 steel. Int J Adv Manuf Technol. 2011. 53: 911-919.