Parametric Modeling and Simulation of Orthogonal Milling Process Based Finite Element Method

Jing Sheng[1] and Liping Yao[2]

[1] *Dpt. of Mechanical Engineering, HuBei Automotive Industries Institute, Hubei Shiyan 442002, China*

[2] *Dpt. of Foreign Languages, HuBei Automotive Industries Institute, Hubei Shiyan 442002, China*

Abstract

The key techniques of 2D modeling with MSC.Marc software and the whole modeling procedure of metal oblique cutting process was presented. The rule based on the modeling process was investigated. The finite element simulation of metal machining is a complex process. It is essential to exploit a system to construct a model of simulation so as to obtain simulation data more conveniently and rapidly. This research is significant for the development of parametric modeling. The system's interface, designed using C++ Builder, can access data which includes the geometrical angles and dimensions of tool, the sizes of work, the relative position between tool and work, properties of tool and work, cutting conditions, etc.. The procedure file that is able to model in the MSC.Marc environment automatically is generated by the program. The parametrical modeling of simulation is completed by the system which calls the procedure file. Finally, case studies were performed to study simulation model, interface and simulation. So the parametric modeling is a kind of effective avenue for metal machining process simulation.

Keywords Orthogonal milling machining, Parametric modeling, FEA, Interface design

1 Introduction

The experimentation, analytic and numerical method are frequently applied on the research on the metal cutting process. The disadvantages of experimentation include the high cost and labor-intensive process, and the analytic methods are very difficult to understand and analyze the machining process in detail. Nowadays numerical approaches have been growing acceptance in industries and academia as a method for characterizing machining process [1-10]. It is known that modeling is one of some key techniques, in which geometrical angle and structural parameters of cutting tool are important factors. The modeling procedure, however, is relatively complex and professional. Very little research on parametric modeling in metal machining has been reported.

Numerical simulation will be taken as a tool by consumer, and the parametric modeling is the first problem to be solved because of the practicability. The paper described the general modeling procedure of metal cutting simulation, and presented some key techniques, especially parametric modeling.

2 The Parametric Modeling of Milling Process

2.1 Geometrical Modeling of Milling System

Geometric modeling is very important for the simulation of milling. It directly affects the operation and results of the simulation system. The geometrical model of cutting system is presented in Fig.1. For confirming the milling tool's rotating center conveniently, the origin of the coordinate is placed on the milling tool's rotating center. In Fig.1, Δx represents the transverse distance between the outer circle of the milling tool and the lateral surface of the workpiece, and Δy is the height between the outer circle of the tool and the machining surface of the workpiece.

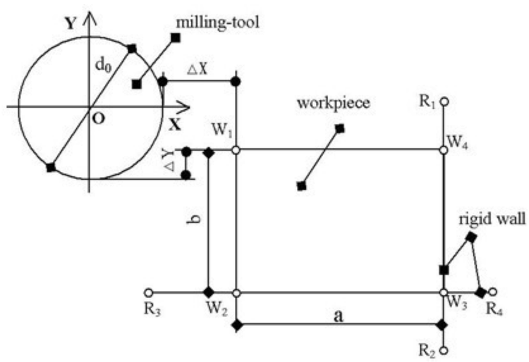

Fig.1 The mode of two-dimension milling

2.2 Geometric Modeling of Milling Tool

Fig.2 shows the polygon line of a milling tool during upmilling. Created the shape of single tooth, the 2-D model of milling tool was derived from duplicating the shape of single tooth along origin O. Computing formulas of the coordinates of the points on a tooth are seen in Table 1.

where θ_1 is the angle between face and back of tooth,θ_2 is the angle of chip flute; while γ, α_{01}, α_{02} represent the rake angle, the first relief angle and the second relief angle respectively. The tooth-spacing angle, the width, the height of teeth and the diameter of cutting tool are denoted by ε, b_{a1}, h and d_0.

The computing formulas of the coordinates of down milling can be obtained by changing the abscissa in the formula into negative number, while keeping the value of ordinate the same.

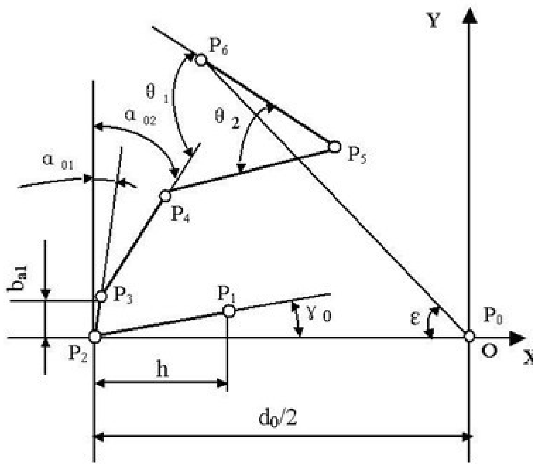

Fig.2 The polygon line of milling tool

Table 1 Computing formulas of the coordinates of the points on a tooth

Point	Coordinates of the points
P_1	$x_1 = -\frac{d_0}{2} + h;\ \ y_1 = h \times tg\gamma_0$
P_2	$x_2 = -\frac{d_0}{2}; y_2 = 0$
P_3	$x_3 = -\frac{d_0}{2} + b_{a1} \times tg\alpha_{01}; y_3 = b_{a1}$
P_4	$x_4 = \frac{y_5 - y_3 + ctg\alpha_{02} \times x_3 - tg(\theta_2 - \varepsilon + \gamma_0) \times x_5}{ctg\alpha_{02} - tg(\theta_2 - \varepsilon + \gamma_0)}$ $y_4 = \frac{y_5 ctg\alpha_{02} - y_3 tg(\theta_2 - \varepsilon + \gamma_0) + tg(\theta_2 - \varepsilon + \gamma_0)(x_3 - x_5) ctg\alpha_{02}}{ctg\alpha_{02} - tg(\theta_2 - \varepsilon + \gamma_0)}$
P_5	$x_5 = -\sqrt{\left(-\frac{d_0}{2} + h\right)^2 + (h \times tg\gamma_0)^2} \times \cos\left(\varepsilon + arctg\frac{h \times tg\gamma_0}{\frac{d_0}{2} - h}\right)$ $y_5 = -\sqrt{\left(-\frac{d_0}{2} + h\right)^2 + (h \times tg\gamma_0)^2} \times \sin\left(\varepsilon + arctg\frac{h \times tg\gamma_0}{\frac{d_0}{2} - h}\right)$
P_6	$x_6 = -\frac{d_0}{2} \times \cos\varepsilon; y_6 = \frac{d_0}{2} \times \sin\varepsilon$

2.3 Geometrical Modeling of Workpiece

The computing formulas of the coordinates of the points on workpiece was derived from Fig.1. The formulas are shown in Table 2.

Table 2 Computing formulas of the coordinates of the points on workpiece

Point	x	y
W_1	$d_0/2 + \Delta x$	$d_0/2 - \Delta y$
W_2	$d_0/2 + \Delta x$	$d_0/2 - \Delta y + b$
W_3	$a + d_0/2 + \Delta x$	$d_0/2 - \Delta y + b$
W_4	$a + d_0/2 + \Delta x$	$d_0/2 - \Delta y$

where a, b are length and height of workpiece respectively.

2.4 Geometrical Modeling of Rigid Walls

Two lines,R_1R_2 and R_3R_4, were used to represent two rigid walls.The two rigid walls are used to restrict the movement of workpiece on x-direction and y-direction. The coordinates of the points on two rigid walls are shown in Table 3.

Table 3 The coordinates of the points on two rigid walls

Point	x	y
R_1	$a + d_0/2 + \Delta x$	$d_0/2 - \Delta y + 1$
R_2	$a + d_0/2 + \Delta x$	$d_0/2 - \Delta y + b - 1$
R_3	$d_0/2 + \Delta x - 1$	$d_0/2 - \Delta y - b$
R_4	$a + d_0/2 + \Delta x + 1$	$d_0/2 - \Delta y - b$

2.5 Material Modeling

It is necessary to configure properties of material. The workpiece material during machining generates elastic-plastic deform under high temperature, large deformation and large deformation rate. Considering the effect of strain hardening, strain-rate hardening, and thermal softening on the stresses, Johnson-Cook's empirical model (see (1)) was adopted. The JC Material law parameters are obtained by SHPB equipment (see Table 4).

$$\bar{\sigma} = [A + B(\bar{\varepsilon})^n]\left[1 + C\ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon_0}}}\right)\right]\left[1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^m\right] \quad (1)$$

where $\bar{\varepsilon}$ is the equivalent plastic strain, $\dot{\bar{\varepsilon}}$ the equivalent plastic strain rate, T the temperature; while A, B, n, C, m and $\dot{\bar{\varepsilon_0}}$ is the parameters determined by a material itself; T_{melt} and T_{room} represent the melting temperature and the room temperature respectively.

Table 4 JC material law parameters

Parameter	A/MPa	B/MPa	n	C	m
Value	626	3614	0.82	0.0268	1

Meshing, configures of contact, boundary conditions, remeshing, analysis conditions, etc. are no longer mentioned here.

2.6 Friction Modeling Between Tool and Chip

There are two explicit areas on the rake surface: slip region and glue region. On the basis of research, constant coefficient friction is applied in slip region and constant friction stress is used in glue one. The friction stress is written as [2].

$$f = \begin{cases} \mu\sigma_n & \sigma_f = \mu\sigma_n \\ k & \sigma_f = k \end{cases} \tag{2}$$

where σ_n is normal stress. μ is friction coefficient and k is shear stress.

2.7 The Criterion of Chip Separation

During the simulation, there are criterions that make the chip separate from workpiece and rake face. They are divided into geometric criterion and physical criterion. The geometric criterion decides the separation through the changes of geometric dimension of deformable body. The physical one is used to identify whether magnitude of physical quantity causes critical value or not.

In fact, chips are separated by setting a minimum force or stress of the nodes as threshold.

2.8 Equation of Heat Conduction

Because the system consists of workpiece, chip and tool generates heat continuously, the first and the second deformation zone of the workpiece go through plastic and elastic deformation. Besides, the rake surface of the tool has severe friction [4-5].

Equation of the heat conduction in unsteady-state temperature field (take variable thermal conductivity into account) is defined as follows:

$$\rho c\frac{\partial T}{\partial t} = K\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + \frac{dK}{dT}\left[\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2\right] - \rho c\left(w_x\frac{\partial T}{\partial x} + w_y\frac{\partial T}{\partial y}\right) + q^* \tag{3}$$

where k represents the thermo conductivity coefficient and T is temperature.ρ is the material density and c is thermal capacity. X and y are Cartesian coordinate system. w_x and w_y represent velocity component of kinetic heat-source in x and y axis respectively. q^* is heat generation rate per unit volume.

$$q^* = W_h \overline{\sigma} \dot{\overline{\varepsilon}} / J \tag{4}$$

where W_h is the ratio that plastic deformation workpiece turn into heat energy. $\bar{\sigma}$ is equivalence stress. $\dot{\bar{\varepsilon}}$ is equivalence strain ratio. J is coefficient of thermal equivalent of workpiece. Because the amount of radiant heat is little, it is ignored.

3 Key Techniques of Parametric Modeling of Simulation of Milling Process

3.1 Interface Design

3.1.1 The Interface Design Between C++ Builder and Database

Exploiting database, database module and database engine provided by C++ Builder or ADO(Active Data Object)were employed to access database. The tables whose type is DBF and frequent BDE engine were used, while parameters about BDE were set, such as path, type and language drive.

3.1.2 The Interface File of Parametric Modeling In MSC.Marc

Governed MSC.Marc software characters, the system's knowledge base rules were established. Thus, procedure files were written using C++ Builder code according to the rule.

Based on the model of the tool and the workpiece, the topology and geometric information of the tool, such as points, line and surface, the procedure of their modeling as well as meshing was written in procedure file line-by-line. Then the modeling of the rigid walls was done, too. While the relative position between tool and workpiece, material model, friction model between tool and chip, properties of tool and workpiece, cutting conditions, the configures about finite element simulation and so on, were written into the file in same way.

Therefore the created procedure file can be operated according to specified manner. So the modeling process becomes easy and rapid. Fig.3 shows the block diagram of modeling process. The structure of procedure file is seen in Fig.4.

3.2 Creating the Parametrical Modeling File

Parametric modeling file (procedure file) can finish the scheduled task in finite element software MSC.Marc to model and simulate the process of milling. So through explanation facility of a process file, the geometric information of cutting system's points and lines can be performed.

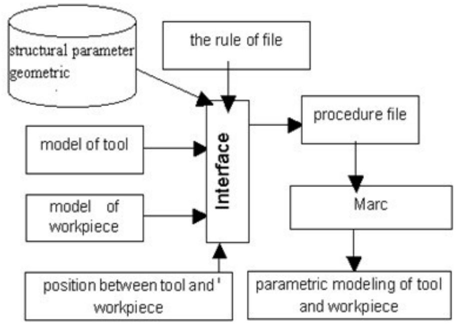

Fig.3 The block diagram of modeling process

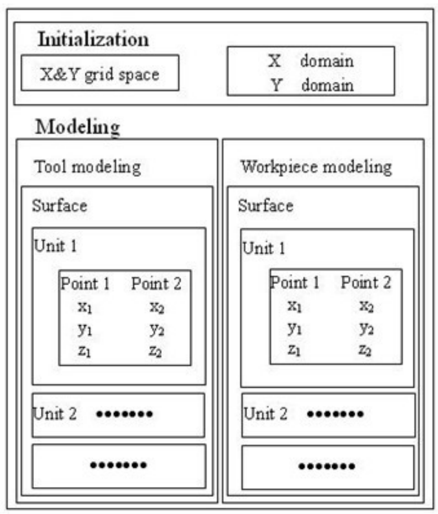

Fig.4 Structure of procedure file

3.3 Parametric Setting of Workpiece and Property of Milling Tool.

Before the simulating of machining process, geometric properties and material property of elements, contact relationship of bodies, mechanics and thermal conductivity between milling tool and workpiece need to be defined and evaluated. Because the dimensions of workpiece, structural sizes and geometrical angles of tool have influence on the number of elements, dynamically meshing workpiece and tool are important. Here element sets were employed to store the workpiece and tool elements respectively. The system implemented the method that setting units invisible or visible instead of calculating the number of elements developed before. By programming, all of configures of the model parameters were carried out automatically.

4 Execution of Example

The user interface of modeling system is presented in Fig.5. The interface has five functions that include file management, adding modeling database, browsing modeling data, parameters of tool and work and contact parameters between tool and work.

In the example, the diameter of tool is 30.2 mm, the height of teeth is 4 mm, and other parameters are given. The model of down milling is shown in Fig.1a and the model of up-milling is shown in Fig.1b.When the amount of feed is 46 mm·min-1,the rotating rate of milling is 275 rpm, and the width of cutting 3 mm, the situations of down milling and up milling are shown in Fig.6 and Fig.7. Fig.8 and Fig.9 show the predicted forces of down milling and upmilling.

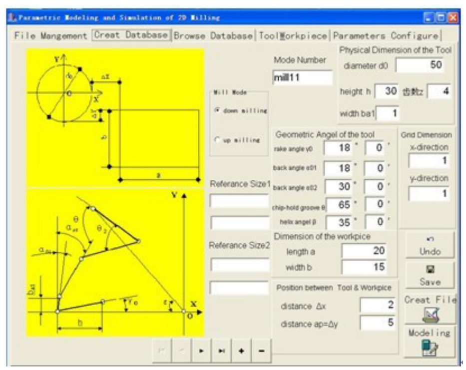

Fig.5 The user interface of modeling system

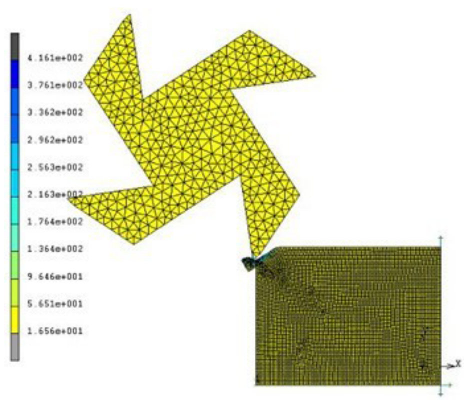

Fig.6 The simulation of down milling

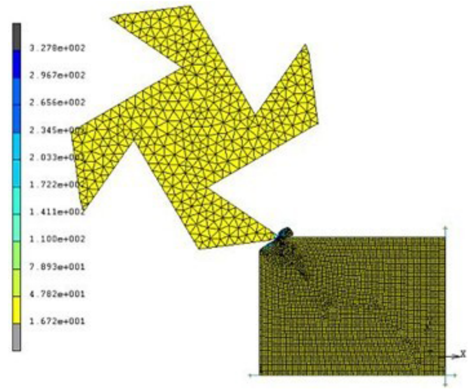

Fig.7 The simulation of up-milling

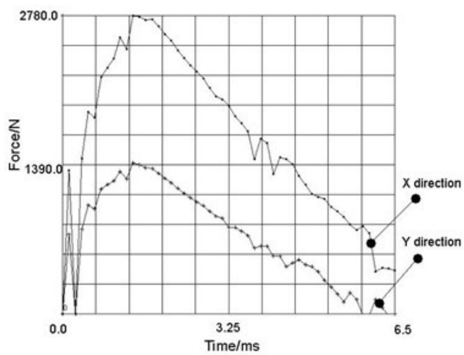

Fig.8 The milling force of down milling

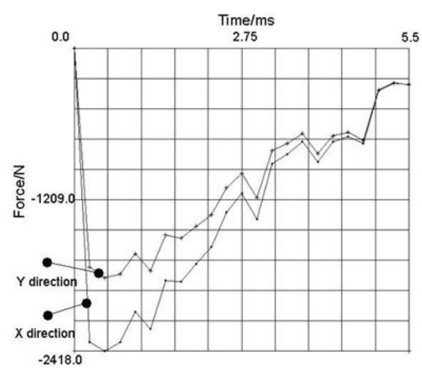

Fig.9 The milling force of up-milling

5 Experimental Verification

For the purpose of verifying the simulation result, a milling experiment was conducted. The milling equipment is XH719 manufactured by QingDao first machine tools factory, and its power is 28 KW. The material of a milling tool is YS2T. The diameter of milling tool with four teeth is d=30.2 mm. The measure equipment is Kistler9237A. Down milling was used.

Cutting conditions were the same as the value used in simulation. The history of cutting force is shown in Fig.10. It is shown that the experimental result agree with the simulation data.

Then orthogonal table was designed to measure cutting temperature(see Table 5). Fig.11 shows experiment value and simulation date.

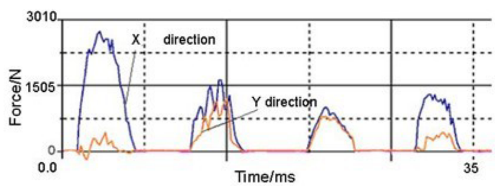

Fig.10 The simulation of cutting force of down milling

Table 5 Orthogonal table

Axial cutting width /mm	Radial cutting width /mm	Amount of feed /mm·min^{-1}	Cutting speed /m·min^{-1}
2.00	5.0	37.5	23.6
2.00	7.1	47.5	29.5
2.00	10.0	60.0	37.3
2.45	5.0	47.5	37.3
2.45	7.1	60.0	23.6
2.45	10.0	37.5	29.5
3.00	5.0	60.0	29.5
3.00	7.1	37.5	37.3
3.00	10.0	47.5	23.6

6 Conclusions

Following the expatiations of the whole process of parametric modeling in MSC.Marc, the paper discussed the key techniques. It has been proven that the ways and means are effective. It is helpful to simulate under different cutting parameters, various dimensions and geometric angles of a tool. Therefore parametric modeling will provide good foundation for creating further cutting databases

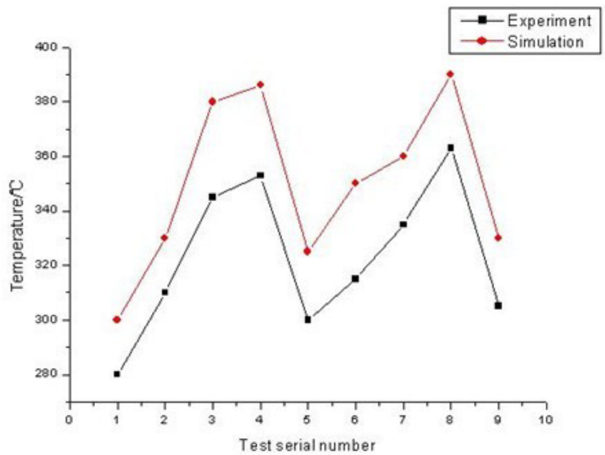

Fig.11 The comparison of cutting temperature

and designing tool.

Acknowledgements
The project is funded by the grants from the Doctor Fundation of HuBei Automotive Industries Institute.

References

[1] Domenico U. (2008), "Finite element simulation of conventional and high speed machining of Ti_6Al_4V alloy", *Journal of Materials Processing Technology,* Vol.196, pp.79-87.

[2] Pantalé, Bacaria J L, Dalverny O, Rakotomalala R, S Caperaa. (2004), "2D and 3D numerical models of metal cutting with damage effects", *Comput. Methods Appl. Mech. Engrg,* Vol.193, pp.4383-4399.

[3] Vernaza-Pena K M, Mason J J, Li M. (2002), "Experimental study of the temperature field generated during orthogonal machining of an aluminum alloy", *Experimental Mechanics,* Vol.42, pp.221-229.

[4] Calamaz M, Coupard D, Girot F. (2008), "A new materialmodel for 2D numerical simulation of serrated chip formation when machining titanium alloy Ti_6Al_4V", *International Journal of Machine Tools & Manufacture,* Vol.48, pp.275-288.

[5] Raviraj Shetty, Laxmikant K R. (2008), "Pai Finite element modeling of stress distribution in the cutting path in machining of discontinuously rein-

forced aluminium composites", *Journal of Engineering and Applied Sciences,* Vol.3, pp.25-31.

[6] Limido J, Espinosa C, Salaun, M. (2007), "SPH method applied to high speed cutting modeling", *International Journal of Mechanical Sciences,* Vol.49, pp.898-908.

[7] Mamalis A G, Horváth M, Branis A S, Manolakos D E. (2001), "Finite element simulation of chip formation in orthogonal metal cutting", *Journal of Materials Processing Technology,* Vol.110, pp.19-27.

[8] Wen Q, Guo Y B, Todd B A. (2006), "An adaptive FEA method to predict surface quality in hard machining", *Journal of Materials Processing Technology,* Vol.173, pp.21-28.

[9] Simoneau A, Elbestawi M A. (2005), "Surface defects during microcutting", *International Journal of Machine Tools & Manufacture,* Vol.10, pp.1-10.

[10] Xie L J, Schmidt J, Schmidt C, Biesinger F. (2005), "2D FEM estimate of tool wear in turning operation", *Wear,* Vol.258, No.10, pp.1479-1490.