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# Parametric Modeling of Orthogonal Cutting and Numerical Simulation

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**Abstract:** Modeling of Finite Element Method (FEM) of metal machining is complex. Parametric modeling in the modeling system applied has a vital and practical significance for more convenient and rapid simulation for a consumer. Therefore, the whole modeling procedure of the metal cutting process with Marc is presented in this study. Some key techniques of orthogonal cutting modeling are further discussed, e.g., focusing on the rule to create a procedure file that is able to generate a FEM model automatically, as well as the system's interface, designed using $C^{++}$ Builder. The file accesses data with the help of a mechanism,which include the geometrical angles and dimensions of a tool, the sizes of a workpiece, the relative position between a tool and a workpiece, their properties and cutting conditions, etc. Furthermore, several cases studies are performed to analyze simulation models, an interface and simulation results. And the experimental results are compared with the simulated ones for the cutting force and temperature that demonstrated the effectiveness of the proposed parametric modeling for the metal machining process simulation.

**Key words:** Orthogonal machining, parametric modeling, FEM interface design

## INTRODUCTION

For the purpose of improving the competitive ability, increasing efficiency and reducing costs are accepted by manufacturing industries. By analyzing metal machining mechanics, process parameters can be adjusted correctly to carry out high efficiency cutting. Thus it is required to get an understanding of the process.

Experimentation, analysis and the numerical method are frequently applied to the researches on the metal cutting process. The disadvantages of experimentation include the high cost and labor-intensity of the process and analytic method is very difficult for qualitative and quantitative analysis (Pantale *et al*., 2004; Yen *et al*., 2004; Kumar *et al*., 2012; Liu *et al*., 2012).

So far, the investigations about turning and milling simulation have been conducted. At the same time, if one among parameters of some properties is changed in a kind of machining condition, the simulation model needs to be reconstructed. In addition, more calculating and preprocessing before modeling have to be done, so it is difficult to make process simulation become a practical tool for a consumer.

It is known that the modeling procedure is relatively complex. However, very little research on parametric modeling has been reported. In order to solve the problems mentioned above, taking parametric modeling as an idea, the whole modeling procedure is described in detail as follows.

With the aim to simulate the turning process quickly, a finite element model is set up automatically with the help of the parametric idea.

The objective of this study is to investigate a coupled thermo-mechanical finite element model to simulate an orthogonal cutting process, with a particular emphasis on the parametric modeling of the cutting tool and work. The steady-state and plane strain cutting condition will be considered. The simulative and experimental temperatures and forces field are obtained in different cutting parameters. Part of the simulative results obtained from simulation will be compared with the experimental data.

## FEM MODEL FOR ORTHOGONAL CUTTING ANALYSIS

Figure 1 shows a finite element model of orthogonal cutting.

**Modeling of the cutting tool and work piece:** Based on the physical model and characteristics of FEA computer software, B-rep (Boundary representation) was introduced. This method can express two kinds of information: Geometrical data and topological information (Fig. 2). Geometrical data reflect the size and position of the object and topological information describes the relative position. The computational model of a cutting tool and a workpiece in a rectangular coordinate is

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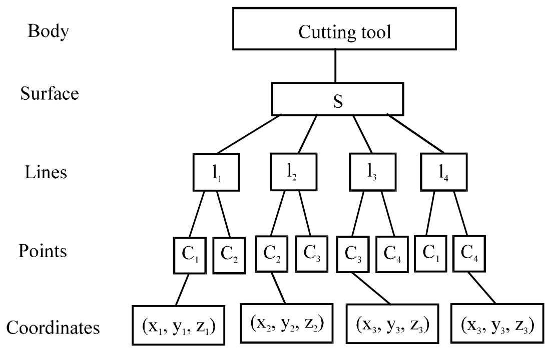


Fig. 1: Finite element model of orthogonal cutting

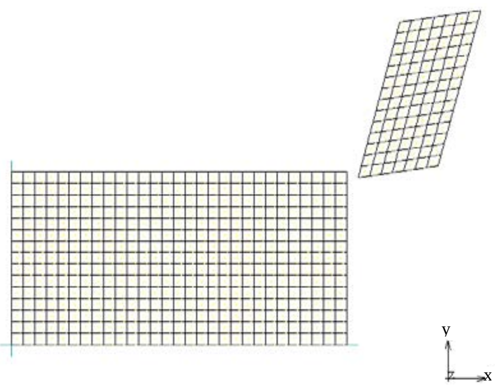


Fig. 2: The topological structure of a cutter

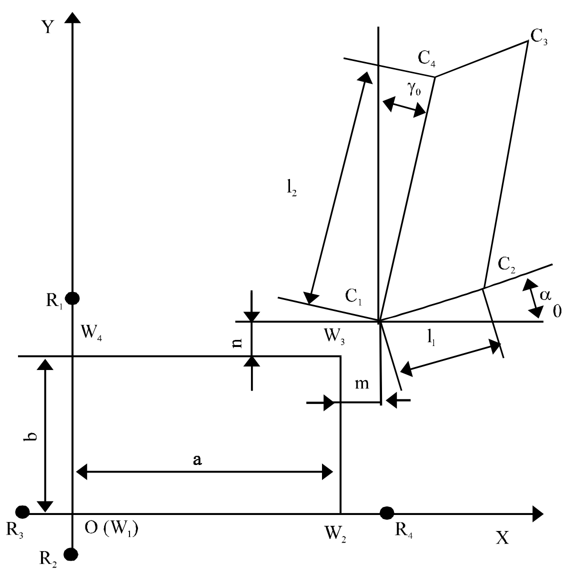


Fig. 3: The construction of model of a cutting tool and a workpiece in a rectangular coordinate system

presented in Fig. 3. By deduction, the coordinates of the model of a cutting tool and a workpiece are seen in Table 1 and 2, in which x stands for the horizontal ordinate of a certain point and y stands for ordinate.

Table 1: The computational coordinates of model of a cutting tool and a workpiece

| Point | x | Y |
|---|---|---|
| $W_1$ | 0.0 | 0.0 |
| $W_2$ | a | 0.0 |
| $W_3$ | a | b |
| $W_4$ | 0.0 | b |
| $C_1$ | a+m | b+n |
| $C_2$ | $a+m+l_1\times\cos\alpha_0$ | $b+n+l_1\times\sin\alpha_0$ |
| $C_3$ | $a+m+l_1\times\cos\alpha_0+l_2\times\sin\gamma_0$ | $b+n+l_1\times\sin\alpha_0+l_2\times\cos\gamma$ |
| $C_4$ | $a+m+l_1\times\sin\gamma_0$ | $b+n+l_2\cos\gamma_0$ |

$W_1$, $W_2$, $W_3$ and $W_4$ are the workpiece vertex, and $C_1$, $C_2$, $C_3$ and $C_4$ are the tool vertex. a, b is the length and height of a workpiece, respectively, m and n is the dimension of relative position between a tool and a workpiece, $l_1$ and $l_2$ are the length of every edge of the cutting-tool and $\gamma_0$ is rake angle and $\alpha_0$ is flank angle of the cutter

Table 2: The computational formulas of the endpoints of two rigid walls

| Point | x | Y |
|---|---|---|
| $R_1$ | 0.0 | b+l |
| $R_2$ | 0.0 | -1.0 |
| $R_3$ | -1.0 | 0.0 |
| $R_4$ | a+n | 0.0 |

$R_1$, $R_2$, $R_3$ and $R_4$ are the endpoints on the rigid walls

**Modeling of the rigid walls:** Two lines ($R_1R_2$ and $R_3R_4$) are used for rigid walls to restrict the displacement of a workpiece in x and y direction. The computing formulas of key coordinates of the rigid walls are seen in Table 2.

**Material model :** The workpiece material to be simulated is a two-phase deposited stainless steel which Poisson ratio is 0.18 and density is 7.8×103 kg $m^{-3}$.

The workpiece material was modeled as elastic-plastic, with isotropic hardening and flow stress defined as the function of strain, strain rate and stress temperature. The original form of the Johnson-Cook material law is used for the simulations. This relationship is frequently adopted for dynamic problems. The dynamic compressive properties of the test material have been studied by means of a split Hopkinson pressure bar at high strain rates and at 25,300 and 500°C (Fig. 4). The yield limitation is defined by following expression (Kabaldin *et al*., 2012):

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

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 $\dot{\bar{\varepsilon}}$ are the parameters determined by a material itself; Tmelt and Troom represent the melting temperature and the room temperature, respectively. The following are the materials used in the experiment: A is 626 Mpa, B is 3614 Mpa, q is 0.82, C is 0.0268 and p is 1.


Fig. 4(a-b): Experimental equipment for Split Hopkinson Pressure Bar to obtain material data

**Friction model 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 the slip region and constant friction stress is used in the glue region (Smaoui *et al*., 2011). The friction model of the transitional region is expressed as:

$$\sigma_f \le -\mu\sigma_n \frac{2}{\pi}\arctan\left(\frac{v_r}{r_{V_{cnst}}}\right) \quad (2)$$

where, $\sigma_f$ is the frictional stress, $\sigma_n$ the normal stress, $\mu$ the coefficient of sliding friction, $v_r$ the opposite slip velocity of contact point and $v_{rcnst}$ the critical relative speed between contact bodies while there is relative motion.

**The criterion of chip separation:** Geometric criterion and physical criterion are combined in simulation to make the chip separate from the workpiece and the rake face (Crichigno Filho, 2012).

**Equation of heat conduction:** Because the system which includes the workpiece, the chip and the tool, generates

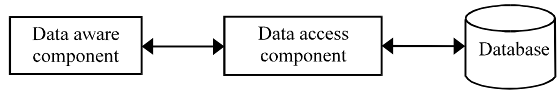


Fig. 5: The block diagram interaction between advanced computer language and database

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. The equation of the heat conduction in 2D unsteady-state temperature field is described using the following relationship (Kabaldin *et al*., 2012):

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

where, $\lambda$ represents the thermo conductivity coefficient, t is the time, $\rho$ is the material density and c is thermal capacity, $w_x$ and $w_y$ are the velocity component of kinematic heat-source in x and y axis respectively. q* denote heat generation rate per unit volume:

$$q^* = \frac{W_h \bar{\sigma}\dot{\bar{\varepsilon}}}{J} \quad (4)$$

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

The finite element model used for the plane-strain orthogonal metal cutting simulation is based on the updated Lagrangian formulation as provided by the MSC. Marc code. Since the cutting width is at least five times greater than the depth of cut during real metal cutting processes, the chip is produced under nearly plane-strain conditions. The vertical displacement of the nodes, Y, at the lower boundary of the workpiece and the horizontal displacement of the nodes, X, at the left boundary, are zero. The task restricted the displacement is accomplished by a rigid wall.

## KEY TECHNIQUES OF PARAMETRIC MODELING

### The interface design of parametric modeling

**The interface design between C$^{++}$ Builder and database:** The Interaction design between advanced computer language and database is seen in Fig. 5, in which the operation process of data is expressed. The system exploited with C++Builder advanced language, accesses the data by BDE (Borland Database Engine) engine. An example is expressed as follow:

```
Void __fast call TForm1::Button1Click (T Object *Sender)
{Table1->Database Name= "Cutting_ tool";
Table1->Table Name= "b1_3";
Table1->Active=true£»}
```

**Interface file of parametric modeling in MSC. Marc:** The entity models for the cutting tool and workpiece and the rule to create a procedure file were built. Then the topological information and the geometrical information (including point, line and surface) are calculated out and written to the right place in the process documentation. And the mesh of the cutting tool and the workpiece can be automatically generated, simultaneously. Thus, the final process documentations are opened via the format specified by the finite elements software to access and the whole modeling process is completed. The procedure above mentioned is controlled by an explanation facility (Rai and Xirouchakis, 2009).

The procedure file generated can be operated according to a specified format. So the modeling process becomes easy. Figure 6 shows the block diagram of the modeling process. The structure of a procedure file is seen in Fig. 7. All the modeling parameters are accessed in several correlative databases by the BDE engine concurrently. Part of the interface file is shown as follows:

```
{••••••;s_file=tblPath->FieldByName("path1")->AsString.
Trim(FileName)+s_file+".proc";
FILE *outf; outf=fopen(s_file.c_str(Path1),"w+");
fprintf(outf,"%s\n"," MSC.Marc Mentat (32bit)");
••••••;
*material_value is otropic:youngs_modulus
109000.0 0.3 0.000000008
*material_option is otropic:plasticity:elastic_plastic
*material_type plasticity
*material_option plasticity:method:johnson_cook
*material_value plasticity:johnson_cook_a
593.0 580.0 0.133 0.023 ••••••;}
```

**Interface of entering finite element environment for modeling:** With the help of an interface, a customer can finish the modeling of a machining process in MSC. Marc environment by a function that calls a modeling file conveniently in Windows operating system. Part of an interface file is shown below:

```
{••••••;s_Procname=tblZjiao->FieldByName("bh")->AsString+".proc";
ProcPath=tblPath->FieldByName("path1")-AsString;
c_Procname=ProcPath+s_Procname;
ShellExecute(Handle,"open",c_Procname.c_str(blank),NULL,NULL,SW_
SHOWMAXIMIZED); }
```

**Creating the parametrical modeling file:** The geometric information of cutting condition can be performanced by

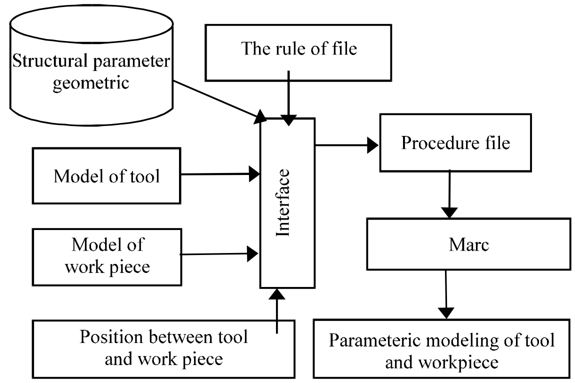


Fig. 6: The function of each module and the relationship between them during modeling process

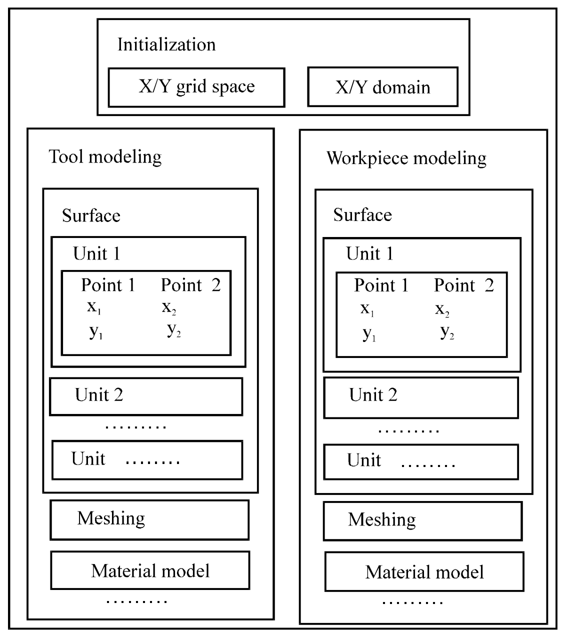


Fig. 7: The hierarchical structure of a modeling procedure file

process file's translation machine. The process file is shown below:

```
{••••••;*material_value is otropic:youngs_modulus
109000.0 0.3 0.000000008
*material_option is otropic:plasticity:elastic_plastic
*material_type plasticity
*material_option plasticity:method:johnson_cook
*material_value plasticity:johnson_cook_a
593.0 580.0 0.133 0.023 ••••••;}
```

Parametric modeling files (process file) can finish the scheduled task to model and simulate the machining procedure in finite element software MSC. Marc.

**Parametric setting of workpiece and milling cutter's property:** Before simulation of cutting process, geometric properties and material property of elements, contact relationship of bodies, mechanics and thermal conductivity between cutter and workpiece need to be defined and evaluated. But the number of elements is influenced by the size of work, structural sizes and geometrical angles of tool, so dynamic meshing of workpiece and tool are a key problem.

Element sets are used technically to stored the elements information of a workpiece and a tool separately by setting of a function which can make units invisible or visible rather than calculating the number of elements before Oluwajobi and Chen (2011).

Parametric method was conducted in the study. And development platform was carried out to construct a geometrical model and a further finite element model. The whole modeling procedure was automatically finished by rule-based reasoning and object-oriented method.

## EXECUTION OF EXAMPLE

The interface for modeling is seen in Fig. 8. A customer is able to fulfill the whole modeling procedure for cutting in MSC.Marc software by this interface. The model that the system generates is shown in Fig. 1.

In order to verify the simulation model, an experiment was employed, using a turning lathe of C630 and cutting tool with material of YW1. The cutter is with rake angle of 4°, relief angle of 10°, inclination angle of 0° and angle of declination 90°. Four groups of cutting parameters in Table 3 were adopted in the simulation and experiment. The cutting speed was 339 mm g $sec^{-1}$. Figure 9 shows the result of the simulation.

To contrast simulation and experimentation, a comparison of the cutting forces and a comparison of the cutting temperature are seen in Fig. 10. The two main

Table 3: The cutting depths and amount of feeds in four group of cutting parameters for experiment and simulation

| Serial No. | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Cutting depth (mm) | 0.30 | 0.35 | 0.40 | 0.46 |
| Amount of feed ($mm{\cdot}rev^{-1}$) | 0.26 | 0.30 | 0.36 | 0.45 |

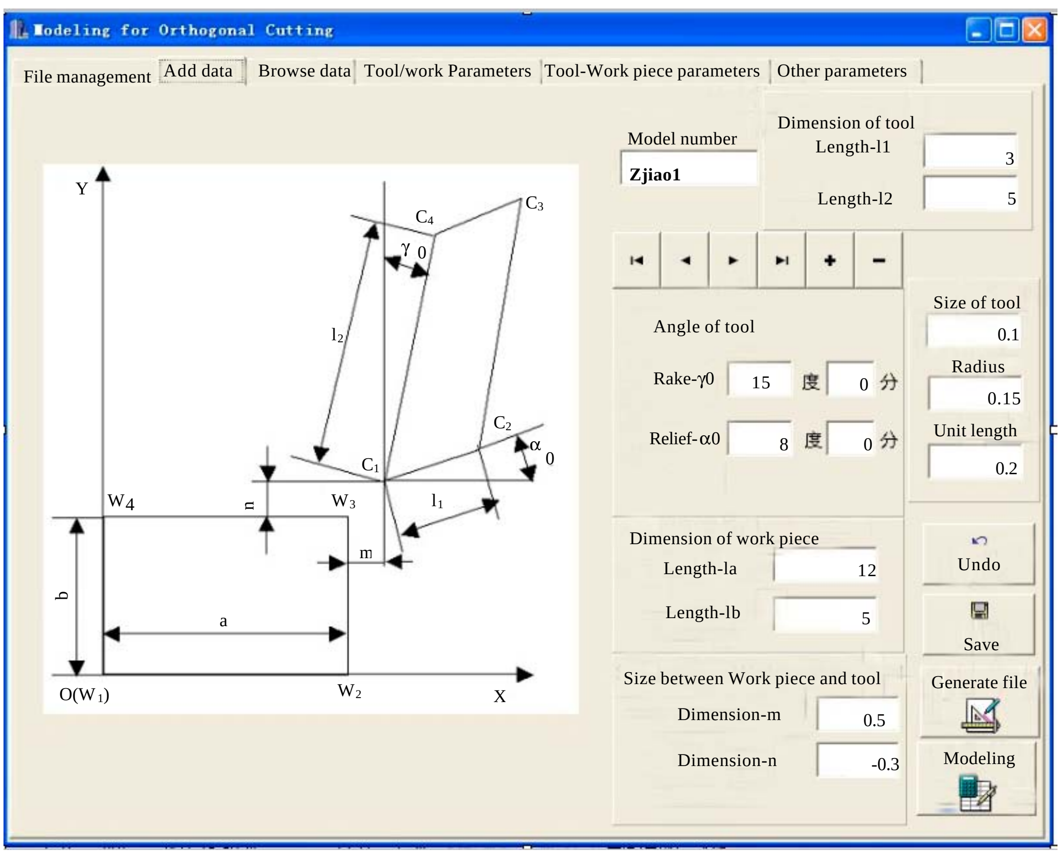


Fig. 8: A customer interface to construct a model of a workpice and a cutting tool

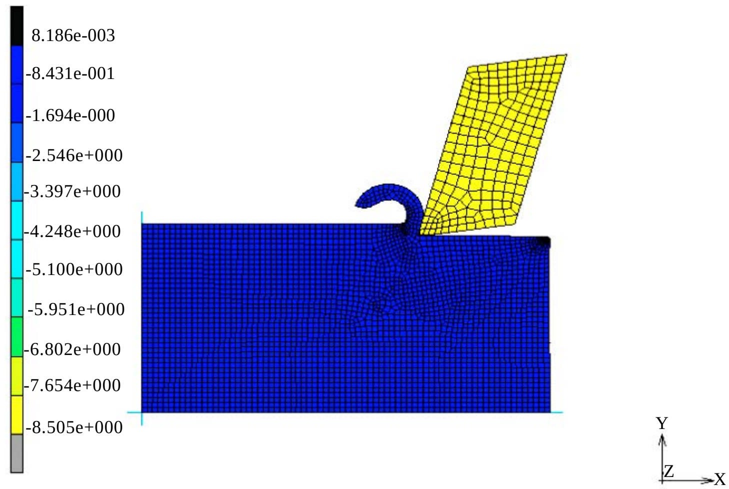


Fig. 9: The cutting force of simulation at a depth of cut of 0.30 mm and a cutting speed of 0.26 mm $rev^{-1}$

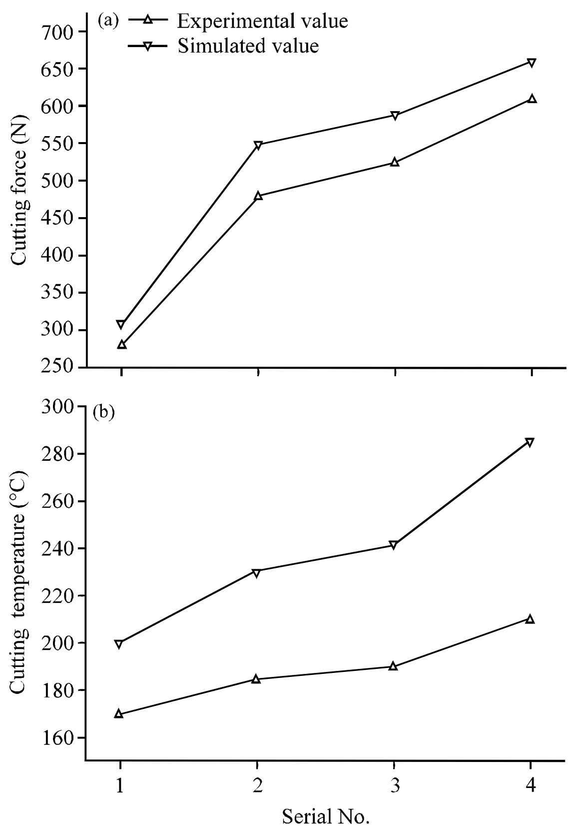


Fig. 10(a-b): Comparisons of experiment and simulation of both cutting forces and cutting temperatures values and in the four sets of condition, (a) Comparison of experiment and simulation of cutting force in the four sets of condition (b) Comparison of experiment and simulation of cutting temperature values in the four sets of condition

reasons for error between the simulation and the experimentation are that the tool is treated as a wedge angle and that the material flow stress model is not accurate enough (Wu and Jia, 2013).

It is proven for examples running that the time to model has been reduced greatly. So operator can model and simulate conveniently under a processing condition.

## CONCLUSION

By analyzing the simulation procedure of the machining process, the steps of parametric modeling were defined. Based on the features of MSC. Marc software and the formats of a process file, the interfaces between the database, MSC. Marc and advanced language, were developed. An explanation facility was also exploited (Liu *et al*., 2013). The modeling file was generated automatically after a consumer constructed a simulation model through the interface and could be run to generate a simulation model rapidly. An example shows the modeling procedure and results of the simulation. It can be concluded that parametric modeling is an effective tool. Output data of the simulation, such as forces, stress, strain, displacements and temperatures, should be considered in the future.

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