

PREDICTION OF THREE DIMENSIONAL MILLING FORCES BASED ON FINITE ELEMENT METHOD FOR UP MILLING PROCESS OF TITANIUM ALLOY (TI-6AL-4V)

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Abstract—The model of milling force is mainly proposed to predict and analyze the cutting process based on finite element method in this paper. Firstly, Milling Finite Element model is given based on orthogonal cutting principle, and then the influence laws of cutting parameters on chip formation are analyzed by using different simulation parameters. In addition, the three-dimensional milling forces are obtained from finite element models. Finally, the values of milling force by the milling experiment are also compared and analyzed with the simulation values to verify the feasibility and reasonability. It can be shown that milling forces match well between simulation and experiment results, which can provide many good basic data and analysis methods to optimize the machining parameters, reduce tool wear, and improve the workpiece surface roughness and adapt to the programming strategy of high speed machining.

Index Terms—Milling Force, Simulation, Chip Formation, Finite Element Method.

I. INTRODUCTION

At present, traditional processing methods almost depended on experience and processing standards. But with the rapid advancement of scientific technology, the goal of manufacturing technology produces parts correctly in the shortest time, in the lowest cost, and in the most effective way. Since the product complexities are increasing and the competitive product life cycle times are reduced, the most effective method is to develop a set of virtual simulation systems for machining process [1, 2]. It leads to the necessity that finite element method replaces physical machining process to analyze and optimize cutting parameters.

In cutting process, the relationship between inputs (cutting parameters, tool geometry and material properties, workpiece geometry and material properties, etc.) and out-puts (cutting force, cutting temperature, cutting vibration, surface equality, etc.) can be obtained based on the change of processing conditions, so the processing scheme can be modified and machining parameters can be optimized depending on the simulation results [3, 4]. With the rapid development of computer technology, finite element simulation has been developed to study the mechanics of machining, optimization of cutting parameters, cutting tool design, and so forth. The ultimate goal is mainly to eliminate expensive and time consuming experimental modeling approaches in favor of simulation models that are capable of producing realistic results at practical cutting conditions in process design [5–7]. In addition, Finite Element Method permits obtaining the relation between cutting forces and chip thickness for different cutting speed and feed rates. The influences of some important parameters include the cutting edge radius, rake angle, clearance angle, depth of cut, and cutting velocity [8–10].

There are some literature researches on this finite

Element method in cutting process. Aurich and Bil [11] have presented a 3D coupled finite element model for the simulation of segmented chip formation in metal cutting. the generation of segmentation is achieved by element erase with respect to damage or by modification of material low stress data. Ozel et al. [12] have proposed that the modified material models with strain softening effect are developed to simulate chip formation with finite element analysis and investigate temperature fields for coated inserts. Predicted forces and tool wear contours are compared with experiments. Bouzakis et al. [13] have presented an integrated procedure for simulating the complicated chip formation. The developed finite element method model capabilities have been demonstrated in terms of chip low and morphology in cutting of spur gears as well as in the four possible cutting variations of helical gears. Yen et al. [14] have studied estimation of tool wear in orthogonal cutting using the finite element analysis. Based on temperatures and stresses on the tool face predicted by the finite element analysis simulation, tool wear maybe estimated with acceptable accuracy using an empirical wear model. Therefore, it is feasible and rational that finite element method can be instead of traditional experimental method by the comparisons of milling force in simulation and experiment conditions.

II. FINITE ELEMENT METHOD OF MILLING OPERATIONS

The aim of this work is the investigation of milling forces of milling operations. Milling operations are very common in several industrial sectors, like aeronautic, medical, race, etc. The prediction of the performances of cutting process and the influence of the process parameters on the product quality is important for tool and process design. The Finite Element Method (FEM), applied to machining, is able

to predict the cutting forces, stresses and temperatures of the process. These physical quantities are useful to design the cutting tool and determine the best cutting parameters.

The increasing productivity challenge together to the increasing cost pressures and changing environmental awareness has led manufacturing industry to give critical considerations to the strategy of machining and the use of conventional coolant in machining process. For materials, it is difficult to cut, like nickel based alloys and titanium alloys, the adoption of high speed milling strategy is limited to the milling tool capability. It is crucial to know the mechanical and thermal load acting on the insert changing cutting parameters. The finite element method turns out to be suitable to know the milling tool condition, in term of stresses, temperatures and chip morphology.

The objective of this research is to provide a powerful analysis tool to design and optimize the cutting process. Different materials have been used in milling operation. The idea is to be a support for high value added machining operations, like hard to cutting materials and green cutting.

The general problem is referred to the prediction of the interaction between workpiece and tool during machining. This interaction is very complex, because several physical phenomena are concerned, from micro to macro scale. The workpiece and the tool are in contact due to the relative movement, to determine cutting speed, depth of cut, feed rate and cooling fluid. During the operation the wear of insert causes a modification of its geometry, and then the interaction tool-workpiece changes.

III. MODELING OF ORTHOGONAL CUTTING BASED ON FINITE ELEMENT

In orthogonal cutting, the material is removed by a cutting edge that is perpendicular to the direction of relative tool-workpiece motion. The orthogonal cutting resembles a shaping process with a straight tool and a metal chip is sheared away from the workpiece. As the edge of tool penetrates into the workpiece, the material ahead of tool is sheared over the primary shear zone to form a chip. The chip partially deforms and moves along the rake face of the tool, which is called the secondary deformation zone. The friction area, where the flank of tool rubs the newly machined surface, is called the tertiary zone [1]. The chip leaves the tool, losing contact with the rake face of the tool, and the length of contact zone depends on the cutting speed, tool geometry, and material properties.

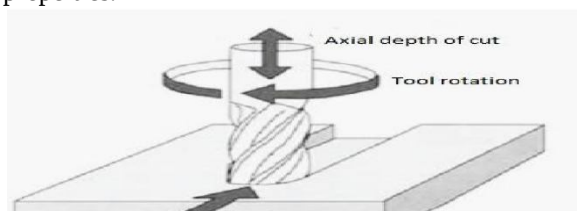


Figure 1. Orthogonal cutting configuration

In orthogonal milling, the cutting is assumed to be uniform along the cutting edge; therefore it is a plane strain deformation process without side spreading of the material. Hence, the cutting forces are exerted in the directions of velocity and uncut chip thickness, which are called feed forces and tangential forces [1, 4]. The orthogonal cutting configuration is shown in Figure (1).

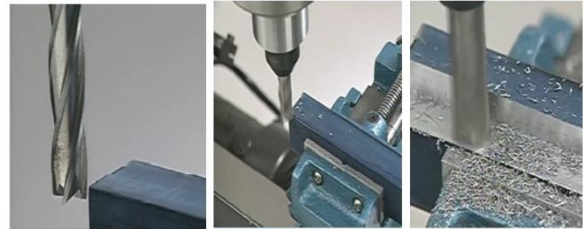


Figure 2. Chip formation process in different steps



Figure 3. Comparison of chip formation between experiment and simulation

The FE orthogonal cutting model was created by using the 3D DEFORM software with Lagrangian formulation, which means material is attached to the mesh, with periodic re-meshing to avoid severe element distortion. The cutting process requires a coupled thermo-mechanical analysis, because mechanical work is converted into heat, causing thermal strains and influencing the material properties [14]. The tool is assumed to be rigid and workpiece material is taken as isotropic, elastic-viscoplastic in the model.

The Johnson-Cook (JC) material model is widely used for analysis of material low stress, especially for those materials of which their flow stress is highly influenced by temperature and strain rate; the influence of strain, strain rate, and temperature on the low stress is defined by three multiplicative yet distinctive terms [13–14].

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

where σ is the equivalent low stress, ε is the equivalent plastic strain, $\dot{\varepsilon}$ is the equivalent plastic strain rate, $\dot{\varepsilon}_0$ is the reference equivalent plastic strain, T is the workpiece temperature, T_m is the material melting temperature, T_r is the room temperature, and other letters are related to workpiece material from experiment measure.

For the continuous chip, the relation between cutting force F and τ shear stress in the shear plane (shear and for the serrated chip formation) can be

obtained instable mechanical equilibrium [1, 14].

$$F = \tau \cdot b \omega \frac{\cos(\beta - \omega)}{\cos(\phi + \beta - \omega) \cdot \sin \phi} \quad (2)$$

Where b is the uncut chip thickness, ϕ shear angle, ω the cutting width, and β the tool-chip friction angle. It can be seen equation (1) that the cutting force is approximately in proportion to the shear stress in the shear band.

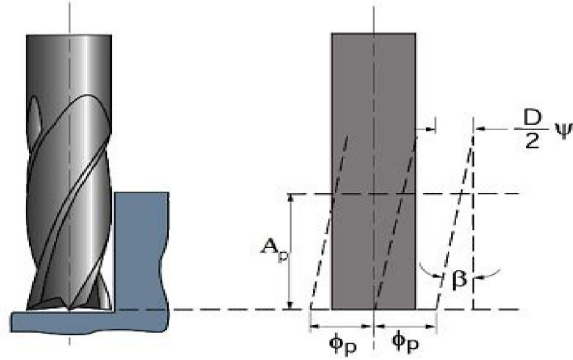


Figure 4. Geometry of a helical end mill

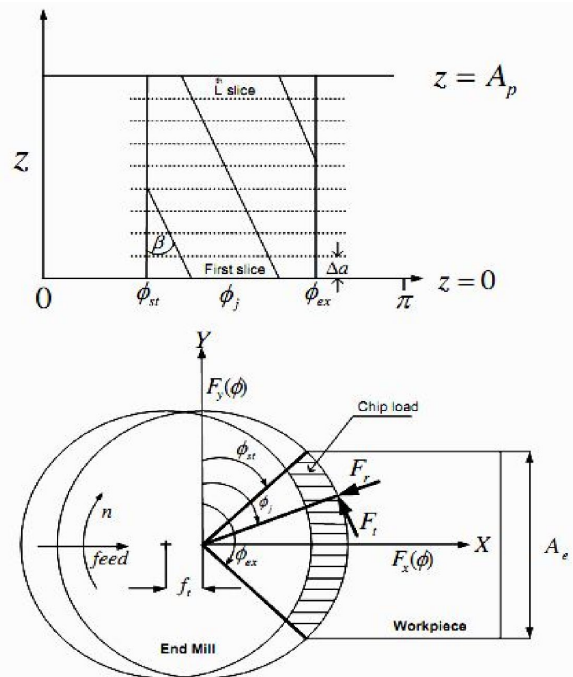


Figure 5. Chip formation phenomenon in milling operation

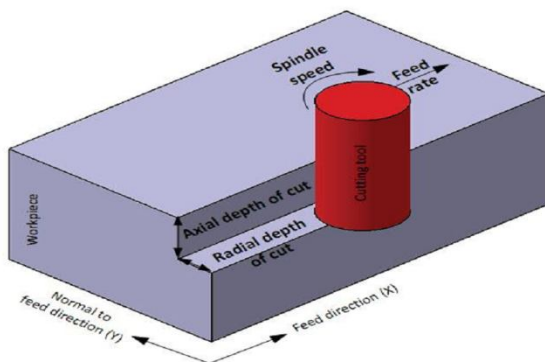


Figure 6. Definition of cutting conditions

IV. COMPARISON OF MILLING FORCES BETWEEN SIMULATION AND EXPERIMENT

A. Simulation of Chip Formation and Milling Forces

The FE chip formation model was created by using updated Lagrangian formulation, in which the material is attached to the mesh, with periodic remeshing to avoid severe element distortion. Three-dimensional simulation is conducted by Design Environment for Forming (DEFORM) software on the aspects of mesh generation and material removal, so that it is better to realize the chip separation. With the dynamic adaptation grid technology which avoids the mesh distortion and improves the accuracy of the solving, the simulation results can be more reliable by the Lagrangian method[16]. The chip formation is shown in different steps in Figure 2. Because the formation of chip is the result of the deformation of workpiece material Titanium alloy (Ti-6Al-4V), it does not need to have a chip separation criterion. The comparison of chip formation between simulation and experiment is shown in Figure 3.

Three-dimensional milling forces are simulated based on chip formation in different cutting parameters. Titanium alloy Ti-6Al-4V is used as workpiece material. The cutting condition is up milling half immersion angle for spindle speed 501.275rpm, diameter 19.05mm, feed rate 100.25mm/min, number of flute 4 flutes, axial depth of cut 5.08 mm/rev, helix angle 30 degree, and cutting forces are shown in Figure 8. It can be noticed that load predictions can be measured in milling process, and then the average values are calculated and obtained based on these data.

B. Analytical Modeling of Milling Force

For the analytical modeling of the milling forces the axial depth of cut and immersion angle is divided into small intervals (Δa) and ($\Delta \phi$) respectively. The bottom edge of one flute is assigned as the reference immersion angle ϕ , flute $j = 0$ (the reference flute) is aligned at $\phi = 0$.

Where $j = 0, 1, 2, \dots, (N-1)$. The instantaneous angle of immersion ϕ is measured in clockwise direction measured from the normal to feed Y direction. The bottom end points of the remaining flutes are at angles

$$\phi_j(0) = \phi + j\phi_p \quad (3)$$

Where $\phi_p = 2\pi/N$ is the pitch angle. At an axial depth of cut z , the lag angle is given by $\psi = k_\beta z$ where $k_\beta = 2 \tan \beta / D$. The immersion angle for flute j at axial depth of cut z is calculated by:

$$\phi_j(z) = \phi + j\phi_p - k_\beta z \quad (4)$$

If $\phi_{st} \leq \phi_j \leq \phi_{ex}$, then the tangential ($dF_{t,j}$), radial ($dF_{r,j}$) and axial ($dF_{a,j}$) cutting forces on the differential element along the cutting edge with height Δa and

uncut chip area ($\Delta a h_j(\phi_j(z))$) are expressed as:

$$\begin{aligned} dF_{t,j}(\phi, z) &= [K_{tc} h_j(\phi_j(z)) + K_{te}] \Delta a \\ dF_{r,j}(\phi, z) &= [K_{rc} h_j(\phi_j(z)) + K_{re}] \Delta a \\ dF_{a,j}(\phi, z) &= [K_{ac} h_j(\phi_j(z)) + K_{ae}] \Delta a \end{aligned} \quad (5)$$

Where K_{tc} , K_{rc} and K_{ac} are the cutting force coefficients contributed by shearing action and K_{te} , K_{re} and K_{ae} are the edge force coefficients in tangential, radial and axial directions respectively ϕ_{st} and ϕ_{ex} are the start and exit angles for the cutting zone respectively. In milling the chip thickness is a periodic function of the varying immersion angle ϕ . Due to the assumption of a circular tooth path, the chip thickness associated with the j^{th} flute is approximated as:

$$h_j(\phi, z) = f_t \sin(\phi_j(z)) \quad (6)$$

Where f_t denotes the feed rate in mm/rev-flute. The elemental milling forces on flute j in the feed (X), normal to feed (Y) and axial (Z) directions are calculated by resolving the differential cutting forces using Equation 7:

$$\begin{aligned} dF_{x,j}(\phi_j(z)) &= -dF_{t,j} \cos \phi_j(z) - dF_{r,j} \sin \phi_j(z) \\ dF_{y,j}(\phi_j(z)) &= dF_{t,j} \sin \phi_j(z) - dF_{r,j} \cos \phi_j(z) \\ dF_{z,j}(\phi_j(z)) &= dF_{a,j} \end{aligned} \quad (7)$$

Substituting the differential forces Equation (5) and the chip thickness Equation (6) into Equation 7 leads to:

$$\begin{aligned} dF_{x,j}(\phi_j(z)) &= \frac{f_t}{2} [-K_{tc} \sin 2\phi_j(z) - K_{rc} (1 - \cos 2\phi_j(z))] dz \\ &+ [-K_{te} \cos \phi_j(z) - K_{re} \sin \phi_j(z)] dz \\ dF_{y,j}(\phi_j(z)) &= \frac{f_t}{2} [K_{tc} (1 - \cos 2\phi_j(z)) - K_{rc} \sin 2\phi_j(z)] dz \\ &+ [K_{te} \sin \phi_j(z) - K_{re} \cos \phi_j(z)] dz \\ dF_{z,j}(\phi_j(z)) &= [K_{ac} f_t \sin \phi_j(z) + K_{ae}] dz \end{aligned} \quad (8)$$

The total cutting force for the j^{th} flute is calculated by integrating the differential cutting forces along the cutting zone of the j^{th} flute:

$$F_w(\phi_j(z)) = \int_{z_{j,1}}^{z_{j,2}} dF_w(\phi_j(z)) dz, w = x, y, z \quad (9)$$

Where $z_{j,1}(\phi_j(z))$ and $z_{j,2}(\phi_j(z))$ are the lower and upper axial engagement limits of the cutting zone of the flute j . The total instantaneous force on the cutter at immersion angle ϕ is summed up from the differential cutting forces from all slices and all flutes and is given by Equation 10:

$$F_x(\phi) = \sum_{j=0}^{N-1} F_{x,j}, F_y(\phi) = \sum_{j=0}^{N-1} F_{y,j}, F_z(\phi) = \sum_{j=0}^{N-1} F_{z,j} \quad (10)$$

The resultant of cutting forces acting on the milling cutter is expressed as

$$F(\phi) = \sqrt{F_x(\phi)^2 + F_y(\phi)^2 + F_z(\phi)^2} \quad (11)$$

The accuracy of the model depends on the selected integration intervals, Δa and $(\Delta \phi)$.

C. Milling Forces Analysis and Validation

Milling experiments should be carried out to verify the currency of the values got from the finite element simulation. The milling test was conducted in vertical milling machining Vcenter 85W(BT-40), the specifications for Vcenter 85W(BT-40) are X axis travel 850 mm, Y axis travel 600 mm, Z axis travel 560 mm, spindle speed 8000 rpm, spindle motor 5.5 KW, machine dimension are X length 2450 mm, Y length 2400 mm, Z height 2965 mm, machine weight 5700 kg and cutting tool used in milling test was 19.05 mm diameter end mill equipped with four flutes and a tool holder [1].

For measuring the cutting forces in, and direction, the Kistler dynamometer is mounted on the machining center. In the up and down milling, cooling method is dry cutting. In order to compare the milling forces between simulation and experiment, the cutting condition and experimental results of cutting forces are shown in Figures 8 and 9.

It can be noticed that cutting forces are small when the cutting parameter is small; at the same time, cutting efficiency is very low, which is not in the reasonable range and cannot meet the needs of actual production. With the increase of depth of cut and feed, cutting efficiency and the cutting force gradually increase.

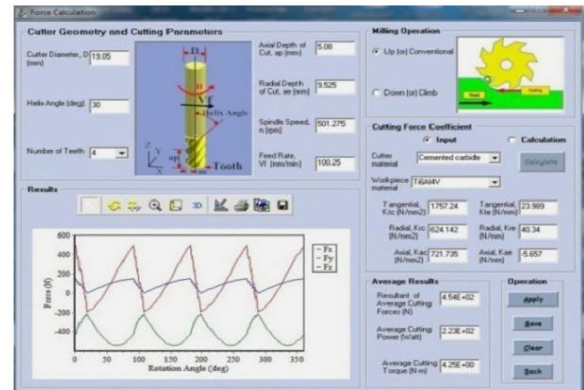


Figure 7. Cutter geometry and cutting parameters

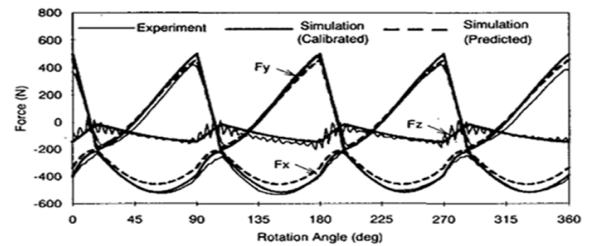


Figure 8. Cutting force in x,y,z direction from experiment

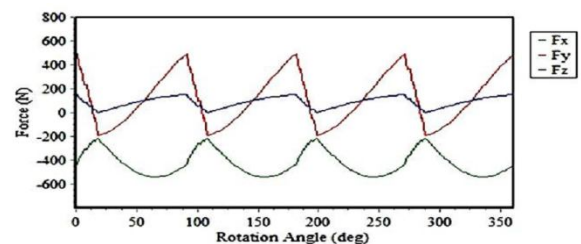


Figure 9. Cutting force in x,y,z direction from simulation

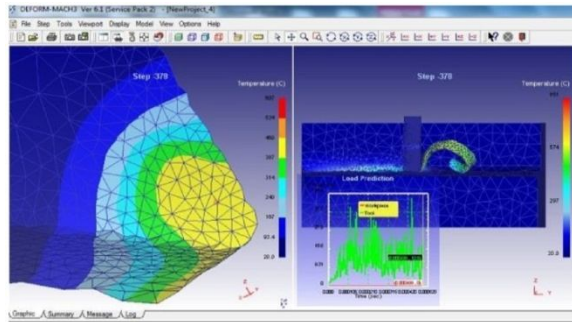


Figure 10. Simulation results for tool temperature

CONCLUSION

The model of three dimensional cutting forces is proposed to predict and analyze chip formation and milling force based on finite element method. The influence laws of cutting parameters on chips and milling forces are obtained in milling process. The comparison of milling forces in simulation and experiment values is analyzed to verify the feasibility based on finite element method. With the increase of rake angle, the chip shape becomes thin and long. Cutting speed increases much, the curling radius of chip becomes smaller, and at the same time, cutting force can decrease and cutting efficiency is very high, which can realize the optimization of tool life and the production efficiency.

In addition, the model of milling cutter is simplified, so that there are some results compared with the real milling cutter. In the simulation process, the cutter is in ideal condition, which the cutter is regarded as a rigid model and not considered the existing friction and vibration, but in the real cutting process, there is some wear existing on the milling cutter, which may affect the critical value of cutting force.

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