The Analysis and Simulation for Improved Cutting Process based on Finite Element Method (FEM) Analysis

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Abstract

The paper proposed the practical metal cutting process using FEM to simulate the traditional cutting process, the simulation and the analysis of the results are based on the support of DEFORM-3D finite element software, and the characteristic between Galerkin Algorithm and FEM analysis is also analyzed. Then the paper processed the modeling procedure for FEM using Lagrange and Euler algorithm, the simulation result is then compared to traditional ones and proved to be more efficient and with higher accuracy.

Keywords: FEM, Galerkin Algorithm, Lagrange and Euler Algorithm

1. Introduction

Metal cutting process is the work piece and tool processes of interaction, the processing of the method is to through the tool in material surface resection excess material layer to get the ideal work piece shape, size and smoothness of mechanical processing method, no matter in theory or in practice to see, is a complicated dynamic process, both elastic deformation and plastic deformation, both large deformation and high strain rate, and has high cutting temperature and complicated friction conditions, so it is difficult to use the traditional analysis method of cutting mechanism of quantitative analysis and research.

Since the 1990 s, foreign CNC machining presents a high speed, high precision, high efficiency, optimization etc. In order to obtain the reasonable optimization numerical control machining parameters, based on the machining process simulation and optimization technology, has gradually replaced by cutting test and experience value is given priority to traditional machining parameter acquisition method. Along with the computer graphics technology, simulation technology has greatly improved, more and more finite element analysis software arises at the historic moment, a large general finite element software ABAQUS is to use shear failure and element deletion method as the chip separation criterion, the cutting process of numerical simulation.

However, China's average NC machining efficiency [1], when compared to the technique abroad, has only 0.25 times accuracy, or even lower. The most fundamental reason is that, the machining process simulation analysis of less. In recent years, the finite element method in cutting in the process of application shows that through the finite element simulation of cutting force, cutting temperature, stress and strain, the optimal choice of cutting tool and cutting parameters, cutting process improvement, improve the production efficiency, and reduce the time of trial and error, but also helps to understand cutting mechanism and improve the cutting quality. So, using the ABAQUS [2] finite element analysis software, with the considering tool of the Angle of machining process influence and chip and tool contact and friction, we are able to complete the two-dimensional milling processing on the simulation and analysis.

2. The simulation methodology of Metal cutting process

2.1. The significance of the metal cutting process

Machinery manufacturing industry in the whole national economy occupies a very important position, and the metal cutting processing is the most basic and reliable precision machining means, in mechanical, electrical, electronic, etc. Various kinds of modern industry department play an important
role. Metal cutting processing machinery manufacturing industry is one of the basic processing methods.

With the quick development of science and technology, all kinds of new materials are constantly emerging, difficult to machine materials used more and more widely, the components of the quality requirements and continuously improve; At the same time, cutting processing automation and computer application in mechanical manufacturing industry wide that require more in-depth grasp the law of metal cutting process, in order to create more advanced cutting method and high quality tool to meet the actual production and technical progress needs.

Metal cutting process, at home and abroad in recent years is very seriously, and spent a lot of manpower and material resources. In a foreign country, from the s, he has been using scanning electron microscopy (SEM) [3] on cutting form direct dynamic observation, now very advanced test technology and related disciplines basic theory to the development and application of metal cutting process, and contributed to the research work of the synchronous development. From our country since the end of the seventy's, the metal cutting process very mechanism research to get attention, made a lot of achievements. Because of the economic development of various reasons such as limit, the metal cutting research still inadequate, the speed of development is relatively slow. But some basic theory and practical technology is still in research, and have made great achievements, just as shown in figure 1, the basic model of the metal cutting for simulation.

2.2. The research of Metal cutting process methods

Research of metal cutting process methods including experimental methods and theoretical research method. For the theoretical analysis methods, there exists: Slip Line Field Analysis, Upper Limit Method And The Finite Element Analysis, etc. [4-6]; And experimental research has been in the metal cutting study dominant, not only like cutting process optimization, optimization of cutting parameters for problems to solve, and by experimental research about the mechanism of cutting process analysis, and by experiments. Therefore, modern metal cutting scientific research to both numerical simulation and so on the new research direction, and without including traditional experiment technology, various research methods.

In the traditional metal cutting process, the general is the basis, through a large number of experimental data and get a cutting process of regularity, such as cutting force, cutting heat, and then use the guidance display metal cutting parameters selection. Not only took a lot of time and money, and efficiency are very low, foreseeability is not strong. With the development of production and the new processing materials, as well as the emergence of high speed and high efficiency more and more become people the pursuit of the goal, the traditional research of metal cutting method cannot very good use the requirement of people. Commonly used experimental methods, including side grid deformation observation method, high speed photography method, fast falling knife method, scanning electron microscopic observation, light elastic (light plastic) method and X-ray [5] method, etc. Test method can we gain metal cutting process of perceptual knowledge and first-hand material, and in the test process, we found that the problem for theoretical study provides the basis.
2.3. Research on the finite element method (FEM) cutting simulation

In recent years, with the rapidly numerical simulation technology development, the numerical simulation method also tend to diversification and specialization, project commonly used numerical simulation methods are: Finite Element Method, Boundary Element Method And Discrete Element Method And Finite Difference Method [6], but its practicability and application in terms of universality, and the finite element method is the most commonly used, it is widely used in elastic mechanics and plastic mechanics, fracture mechanics, heat conduction, the electromagnetic fields.

![Figure 2. The establishment of finite element model](image)

2.3.1. Finite Element Method, FEM

It is a highly efficient, common calculation method. The finite element method in the early is variation principle as the foundation of the development of, so it is widely used in Laplace equation and Poisson equation describes all kinds of physical field (this kind of field and functional the extreme problems are closely linked). Since 1969, some scholars in fluid mechanics application of weighted method of residues of the Galerkin [7] or least square method, etc. [8]. Also for the finite element equation and finite element method can be used in any differential equation describes all kinds of physical field, and no longer requires that this class of physical field and functional extreme value problem to be linked.

The finite element method for the analysis of the engineering general process consists of three basic parts:
1. Pretreatment: The main original state of the system of the building of model, the finite element grid partition.
2. To solve calculation: Complete metal cutting into dust process simulation analysis of the basic operation, namely the cutting deformation stress and strain, cutting force, the system analysis and calculation of temperature field, etc.
3. After treatment: In the middle of the simulation results and the final results are data processing, list or the graphical display, the chip morphology change graphic description, etc.

2.3.2. Overview of Finite element method analysis process

The basic idea of finite element method is: to analysis of continuous body of discretization, the continuous body transformation become co., LTD., a unit of assembly, the element is between the node to connect and restriction. When the body by external effect occur deformation, it is composed of each unit will also occur deformation, and each node to produce different degree of displacement, the displacement called node displacement. In the finite element, usually in node displacement as the basic unknown quantity, the simulation condition is set up. And each unit according to block approximate thoughts, suppose that a simple function approximation that units of the displacement distribution, reuse mechanics theory of variation principle or other methods, the establishment of nodal force and displacement between the mechanical properties of the relationship, get a group to node displacement for an unknown quantity of algebraic equation, thus solving node displacement component. And by
using the interpolation function determine unit aggregate on the field function. Specific analysis process is as follows:

(1) The continuum of discretization: first of all, should be based on the shape of the continuum can choose the most perfectly describe continuous body shape of the unit. Common unit [9]: stem cell, beam element, triangular unit, rectangular element, quadrilateral element, curved edge quadrilateral element, tetrahedron element, parallelepiped unit and surface parallelepiped unit and so on. Secondly, cell division, cell division, after the completion of all the units and nodes in a certain sequence Numbers, each unit by load according to the static equivalence principle are transplanted into the node and the node displacement controlled according to the actual situation set constraint conditions.

(2) The unit analysis: to establish each element nodal displacement and force of the relation between nodes.

(3) The whole analysis “overall analysis for each unit is composed of the overall analysis. Its purpose is to build up a system of linear equations, to reveal the node load and node displacement relationship, which is used to solve node displacement.

3.2. The finite element method and the balance equation of before and after the treatment

3.1. Movement balance equation

In the finite element method, the general principle of virtual displacement is used to direct derivation element stiffness matrix, then use stiffness integration means to form the whole stiffness matrix, so as to establish solving nodal displacement of linear algebraic equations. The object deformation is continuous, from the initial time to \( t+\Delta t \) time any time between the object constitute all can be used as a reference configuration to establish finite element column. According to the Updated Lagrangian description in \( t \) time configuration as the reference configuration, the Virtual work balance equation of \( t+\Delta t \) is then changed to:

\[
\delta \pi = \int \rho \ddot{X}_i \delta \dot{X}_i \, dv + \int \sigma_y (\nabla \delta x_i) \, dv - \int \rho \int \int \sigma_{ij} \delta x_i \delta x_j \, ds - \int p \delta x_i \, ds = 0
\]  

In which, \( \rho \) stands for Mass density, \( \dot{X} \) stands for Particle acceleration, \( f \) stands for Unit body load, \( P \) stands for Surface load, \( \sigma \) stands for Piola-Kirchhoff stress [10].

According to the Lagrangian description, load object the deformation process has totally \( X_\alpha (\alpha = 1, 2, 3) \) are moved to \( X_i (i = 1, 2, 3) \). The deformation can have relative coordinates and time described as:

\[
X_i = X_i (X_\alpha, t)
\]

To the reference configuration for finite element discretization, unit at any point in the coordinate can use node coordinate difference for description:

\[
X_i (X_\alpha, t) = X_i (X_\alpha (\xi, \eta, \zeta), t) = \sum_{j=1}^{k} \varphi_j (\xi, \eta, \zeta) x_j (t)
\]

In which, \( \varphi_j \) is Shape function, \( k \) is Unit node number \( (j = 1, 2, ..., k) \), \( x_j \) stands for the values of first \( j \) a node coordinate.

By inserting equation (3) into (1), we can get:
\[ \delta \pi = \sum_{m=1}^{n} \delta \pi_m = \sum_{m=1}^{n} \left\{ \int_{v_n} \rho \dot{X} \varphi_i^m dv + \int_{v_n} \sigma_i^m (\nabla \varphi_i^m) dv \right\} - \int_{v_n} \rho f \varphi_i^m dv - \int_{s} p_i \varphi_i^m ds = 0 \]  

(3)

Where \( \varphi_i^m = (\varphi_1, \varphi_2, \ldots, \varphi_k)_i \)

And the Matrix expression of equation (3) is:

\[ \sum_{m=1}^{n} \left\{ \int_{v_n} \rho N^m_1 Nadv + \int_{v_n} B^m_\sigma dv \right\} = 0 \]

(4)

In which, \( N \) stands for Interpolation matrix, \( \sigma \) stands for External body load vector, \( B \) stands for Strain-Displacement transformation matrix, \( a \) stands for Node acceleration vector, \( b \) stands for the value of Unit vector and \( P \) stands for Surface load vector.

From equation (4) and get in the time \( t \) non-fully discrete motion balance equation, which is:

\[ M_a = P_t - F_t \]

(5)

Where \( M \) is Diagonal mass matrix, \( P_t \) is External body load vector, \( F_t \) is internal stress vector.

The internal stress vector by explicit central difference algorithm for motion balance equations (3-5) type for time domain discrete available, we are able to get:

\[ a_t = M^{-1} \left( P_t - F_t \right) \]

\[ V_{t+1}^{i} = V_{t}^{i} + a \Delta t \]

\[ U_{t+1}^{i} = U_{t}^{i} + V_{t}^{i} \Delta t \]

(6)

\[ \Delta t_{t+1}^{i} = \Delta t_t + \Delta t_{t+1} \]

(7)

In which

\( V \) stands for Node velocity vector and \( U \) stands for Nodal displacement vector.

Finally, update deformation geometry that:

\[ X_{t+1} = X_0 + U_{t+1} \]

(8)

The equation derivation is completed.

3.2. The finite element method (FEM) treatment

Finite element analysis of the pretreatment is to make the calculation model of geometric subdivision, data generation and data input these work or part or completely by the computer automatically, ready to data mainly include: node information, unit information, material information, load information, constraint information. The finite element analysis and post-processing is finite element calculation results by computer sorting into easy to read and analysis of numerical or graphic form.

3.2.1. Pretreatment

Finite element method has the following treatment before the main content:
3.2.2. Post-Processing

The finite element calculation result is a large amount of numerical data, it is difficult to directly to
the results of the analysis is correct, whether reasonable, whether to achieve the desired results, so we
have to finite element calculation results and analysis, and processing.

Finite element analysis of post-processing can be divided into numerical processing and graphics
processing two kinds. Numerical processing is the numerical results of the finite element analysis is
transformed into the form of commonly used in engineering or designer familiar forms, such as
principal stress calculation and equivalent stress calculation; Sometimes the results of calculation and
processing, make it more credible or a higher precision, such as stress smoothing. Graphics is the
numerical results of the finite element hormone with graphics intuitive that come out, in order to make
the calculation results be clear at a glance, such as deformation chart, contour map, color cloud, node
variable profile, etc.

4. The establishment of finite element simulation system

Analysis of the object from the elastic material spread to plastic, viscoelasticity, sticky plastic and
composite materials, from solid mechanics spread to fluid mechanics, heat transfer theory and
mechanics of continuous media field. The role of the engineering analysis has been extended to check
from analysis and optimization design and computer aided design technologies. Can be expected, with
the development of computer technology, finite element method as a has consolidated theoretical basis
and widely used effective numerical analysis tool, will in the science and technology development
plays a more important role, its also will get further development and perfection.

4.1. The establishment of the simulation system

For two dimensional models, using CPE4RT unit, for the physical plane strain quadrilateral thermal
coupling 4 node reduced integral unit. The 3d model C3D8RT entity 3d parallelepiped thermal
coupling and node reduced integral unit. Considering the metal cutting layer material deformation near
the intense and strong thermal effect produced, so the denser mesh; the impact on the surrounding area
is to reduce the scale of calculation is bulky unit; the middle is the transition form. The cutting tool and
the work piece in the same unit type, set to rigid body; Blade place with the work piece material phase
contact, and under a lot of stress concentration, and at the same time, to prevent rigid body unit into the
soft metal unit may, using a small grid, the rest part adopts a thick grid. Cell division is in
ABAQUS/CAE module, the division of the grid quality is good, can satisfy the needs.

Figure 3. The establishment of 2D model

Correctly determine material constitutive model is successful to realize metal cutting processing
simulation key. Because the process of chip with strong plastic deformation and chip and tool of the
friction between the strong function, is chip process produces a large amount of heat, and at the same
time, due to the high cutting speed, material plastic deformation is very big also, so the choice of material model to consider the material of the strain hardening effect and temperature rise caused by the softening effect, at the same time, considering the influence of strain rate on hardening, i.e., the selection of the relevant material model. Cutting process involves the material plastic yield criterion, flow rule, hardening rules of application, considering the thermal coupling and the influence of rate, the description said the Johnson-Cook constitutive relation [9]:

\[
\sigma = A + B\left(\frac{\varepsilon}{\varepsilon_o}\right)^n \left[1 + C \ln \left(\frac{\varepsilon}{\varepsilon_o}\right)\right] \left(1 - \frac{T}{T_m}\right)
\]  

(9)

\[
\dot{T} = \begin{cases} 
0 & T < T_i \\
\frac{(T - T_i)}{(T_m - T_i)} & T_i \leq T \leq T_m \\
1 & T > T_m 
\end{cases}
\]  

(10)

In which, A subject under the static yield strength; B for strain hardening coefficient; C for strain rate sensitive coefficient; N for strain hardening index, \(\varepsilon^{pl}\) is the equivalent plastic strain rate, \(\varepsilon_o\) is the reference strain rate, M for strain rate sensitive index, \(T_i\) is Transition temperature and \(T_m\) is the melting point temperature of work piece materials.

5. The simulation and the analysis of the results

This design main task is to establish two-dimensional cutting model and simulation analysis, get the simulation data and experimental data are compared, the metal cutting process should stand, strain field and the variation law of qualitative analysis, get the shear Angle, cutting force and chip shape parameters, the simulation results, and through the finite element analysis, simulation and experimental results contrast before that Angle and the relationship between the shear Angle.

![Figure 4. The matlab simulation result](image)
In this design, tool material selection for carbide YT15, work piece material for 45 steel or A3 steel, concrete performance parameters, see table 4-1. The work piece material hardening parameter is 0.10, the coefficient of friction chosen as 0.25. Cutting process, the cutting tool hardness than the high hardness many, so in modeling, tool as a rigid, work piece as the soft body, and this is the actual cutting process is conform. So, the work piece with large strain elastic-plastic unit elastoplastic analysis; And tool do not involve in plastic deformation problem, don't need to input the stress strain curve.

From the figures we can see that in the main chip for compressive stress and its value in the chip sinuosity maximum; in the work piece, the cutting tool tip in front for compressive stress. In the tool tip and near the lower tensile stress and in the chip and work piece, the separation place stress' value is the largest. In the chip, the work piece, the cutting tool tip in the region near the main stress is tensile stress. This is the chip and the separation of the necessary, thus the result of simulation is consistent with the facts.

6. Conclusion

Under the guiding ideology of finite element, the paper processed Object-Agent Oriented Analysis for the metal cutting procedure and completed the modeling and simulation of the cutting procedure using DEFORM-3D software. With the simulation result and the mathematical derivation, we are able to confirm that such method are able to decrease the number of experiments as well as increase the simulation precision, provided theoretical accordance for the future cutting designs.

7. References