

Numerical Simulation and Analysis for Metal Cutting Processes Based on FEM and SPH*

Abstract—By using the coupling method of FEM and SPH, constitutive behavior of material in the metal cutting process was simulated and cutting mechanisms were analyzed. The simulation results show that the cutting process is a plastic deformation process in which cutting layer material produces shearing slip due to the extrusion of cutting tool; the extrusion and friction from cutting edge result in cold plastic deformation of material in formed surface layer, and form residual stress; the cutting force increases rapidly and then decreases, eventually varies in a certain range; the maximal effective stress varies at a certain distance to the cutting edge in stable cutting stage.

Key words: metal cutting; numerical simulation; finite element method; SPH method

I. INTRODUCTION

Metal cutting process is a complex machining technology. It not only relates to elasticity, plasticity and fracture mechanics but also involves tribology and thermodynamics. Cutting quality is influenced by many factors, such as the shape of tool, cutting parameters, cutting heat, cutting-tool wear and so on [1]. It is very different to quantitatively analyze and research cutting mechanism by analytic method. It wastes man-hour and increases production costs by trial and error method. As a new research method for metal cutting mechanism, computer simulation method is convenient and efficient. Among them, finite element method is most widely used in the simulation of metal cutting, and has got some significant achievements [2, 3]. Finite element method is a mesh method. Separation criterion and fracture criterion of chip have to be artificially set in the simulation of metal cutting process, or the meshes in the cutting deformation area will be distorted. It is not exactly in agreement with actual conditions. The development of meshless method provides an effective solution for the problem. Smooth particle hydrodynamics (SPH) is a kind of mature meshless method. Simulation model is built with discrete particles in SPH, so big deformation in metal cutting process can be effectively solved [4-6].

In the simulation of mechanical deformation of continuum medium, FEM is more efficient than SPH, but it is inferior to SPH in the simulation relates to big deformation and discontinuous medium. So the paper simulates metal cutting process by the coupling method of FEM and SPH based on LS-DYNA software. It complements the shortcomings of single method.

II. BASIC PRINCIPLES OF THE SPH METHOD

In SPH, simulation model is built with discrete particles. The mass of particle is fixed in its coordinate system. Therefore SPH method is similar to Lagrange method. Its basic equations are also energy conservation equation and constructive equation of solid material. Physical flow field in SPH is described with a set of flowing particles which has a certain velocity. Each particle is an interpolation point with characteristics of flow field. The whole solution can be got by the interpolation function of these particles [7, 8].

The basis of SPH is interpolation principle [9]. Any macro variable (such as density, press, temperature etc) can be got by integral interpolation of a set of disordered particles. Interactions of particles are expressed by interpolation function. Approximate function of particles is

$$\Pi^h f(x) = \int f(y) W(x-y, h) dy, \quad (1)$$

where W is the kernel function (interpolation kernel), it is expressed below:

$$W(x, h) = \frac{1}{h(x)^d} \theta(x), \quad (2)$$

where d is the space dimension, h is the smoothing length. Assistant function θ is

$$\theta(u) = C \times \begin{cases} 1 - 1.5u^2 + 0.75u^3 & |u| \leq 1 \\ 0.25(2-u)^3 & 1 < |u| \leq 2, \\ 0 & |u| > 2 \end{cases} \quad (3)$$

where C is a normalization constant.

The smoothing length h is an important influence factor of computation efficiency and precision. In order to avoid negative influence due to material compression and expansion, varying smoothing length is proposed by W. Benz. Smoothing length h dynamically varies with the variation of time and space. It increases with the increase of distance between particles. It decreases with the decrease of distance between particles. Its variation range is

$$HMIN * h_0 < h < HMAX * h_0, \quad (4)$$

where h_0 is the initial smoothing length.

Influence range of SPH particle is a spherical region, whose radius is h . In every time step, it must be known that which particles are in the region. Therefore search must be implemented. Bucket classification method of contact searching algorithm is used for the search in SPH. As shown in Fig. 1, firstly, the whole region is divided into some sub-regions, and then the region of each particle and its

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neighbor regions are searched. By using the searching method, computation is greatly reduced.

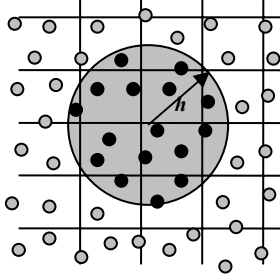


Fig. 1 Bucket classification and local search

III. MODELING AND SIMULATION

A. Coupling model of FEM and SPH

In this paper, big deformation area of workpiece is modeled with SPH particles, and small deformation area of workpiece and cutting tool are modeled with Lagrange meshes. Fig.2 shows the coupling schematic illustration of SPH

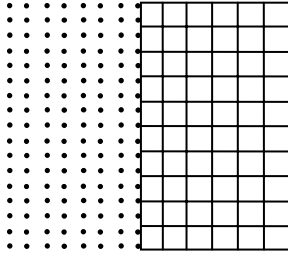


Fig. 2 Coupling schematic illustration of SPH particles and Lagrange meshes.

particles and Lagrange meshes. Its left part is SPH particles. Its right part is Lagrange meshes. SPH particles and Lagrange meshes are coupled by using node-surface contact type in LS-DYNA. Failure criterion of coupling contact [10] is

$$\left(\frac{|f_n|}{f_{n,fail}} \right)^{m_1} + \left(\frac{|f_s|}{f_{s,fail}} \right)^{m_2} \geq 1, \quad (5)$$

where f_n , f_s , $f_{n,fail}$, $f_{s,fail}$ are the normal stress, shear stress,

TABLE I

	MATERIAL CHARACTERISTICS OF CUTTING TOOL AND WORKPIECE					UNIT SYSTEMS: kg-mm-ms					
	Elastic ratio(E)	Poisson ratio	Density (ρ)	Strain rate parameters (C)	Strain rate parameters (P)	σ_1	σ_2	σ_3	σ_4	σ_5	σ_6
						ε_1	ε_2	ε_3	ε_4	ε_5	ε_6
workpiece	200	0.30	7.8×10^{-6}	40	5	0.36	0.38	0.42	0.50	0.56	0.60
Cutting tool	600	0.15	1.3×10^{-5}			0.015	0.025	0.05	0.075	0.1	0.15

C. Boundary conditions

Cutting tool moves along the negative direction of the x-axis, therefore y, z translations and all rotations are constrained. All translations and rotations of the bottom of finite element model are constrained. For SPH part, symmetric planes must be established by virtual particles. These particles

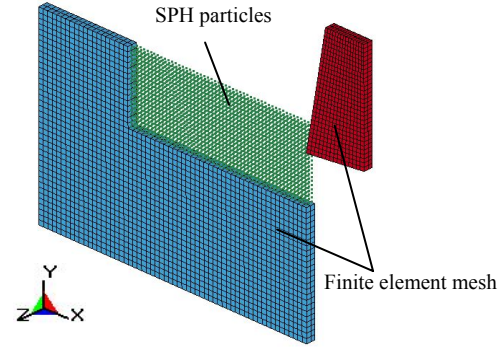


Fig. 3 3D simulation model of metal cutting

normal failure stress and shear failure stress. m_1 , m_2 are exponents of normal stress and shear stress, respectively.

In order to reduce computing time, simulation model is simplified, as shown in Fig.3. Workpiece is a cuboid of 6mm (length) $\times$ 4mm (height) $\times$ 0.2mm (width). The size of finite element mesh is 0.1mm. Cutting deformation area is modeled with SPH particles of 0.33mm (radius). Tool rake angle γ_0 is 10° and relief angle α_0 is 6° .

B. Material model

Workpiece material is 45 steel. Material model is piecewise linear isotropic plasticity with an arbitrary stress versus strain curve. It is suitable for steels. Strain rate is accounted for using the Cowper-Symonds model. The relation between strain rate and yield stress [10] is

$$\sigma_y = \left[1 + \left(\frac{\dot{\varepsilon}}{C} \right)^{\frac{1}{P}} \right] \left(\sigma_0 + f_n(\varepsilon_{eff}^P) \right), \quad (6)$$

where $\dot{\varepsilon}$ is the strain rate, C and P are the strain rate parameters, σ_0 is the initial yield stress and $f_n(\varepsilon_{eff}^P)$ is the hardening function with effective plastic strain.

Tool material is hard alloy (YT5). Its hardness and strength are much higher than workpiece. It is considered as elastic body. Table 1 lists some material characteristics of cutting tool and workpiece, where $\sigma_1 \dots \sigma_6$ are corresponding yield stress values to effective plastic strain values $\varepsilon_1 \dots \varepsilon_6$.

are actually mirror particles of solid particles nearby the boundary of $2h_0$ (h_0 is initial smoothing length), as shown in Fig. 4. Physical quantities of virtual particles and solid particles are symmetric about the fixed boundary plane. Therefore virtual particles can produce constraint to solid particles. It makes the velocity of solid particles keep in the

value of zero, and solid particles can not penetrate boundary.

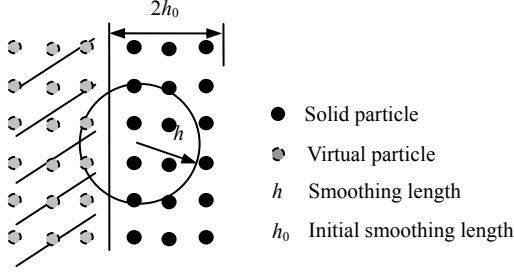


Fig. 4 Symmetric plane of SPH model

IV. ANALYSIS OF SIMULATION RESULTS

A. Chip formation

In this paper, the processes of cutting deformation and chip formation of 45 steel are simulated. Cutting velocity v_s is 10m/s. Cutting depth a_p is 0.5mm. From Fig. 5(a) it can be seen that there exists biggish contact stress at the contact zone between tool edge and cutting layer material. It is high up to 658.6MPa. The value is higher than yield strength of 45 steel. Therefore the material at the contact zone produces irreversible deformation; the material of other zones is still in elastic state. With the continuous moving of tool, the contact area between tool edge and cutting layer increases gradually. The cutting layer material happens to pile up on the rake face. Inner stress of the material increases gradually. As shown in Fig. 5(b), the effective stress in primary deformation zone is

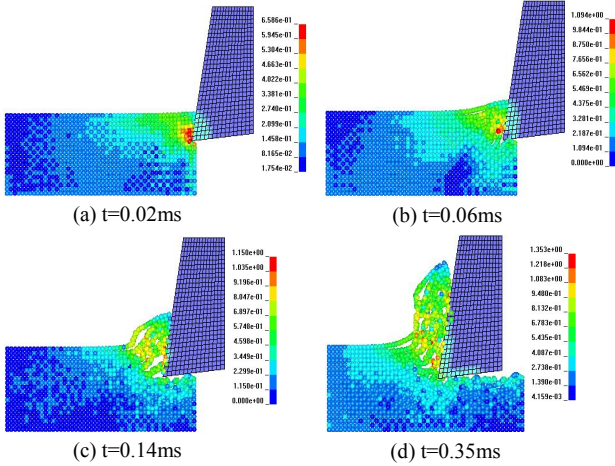


Fig. 5 Deformation process of the cutting layer material

much higher than yield strength. Therefore the material in primary deformation zone is in plastic state. Under the extrusion of cutting tool and subsequent flowing material, the material in plastic state moves upward along rake face. The material forms chip after flowing out primary deformation zone, as shown in Fig. 5(c). From Fig. 5(d) it can be seen that internal structure of formed surface layer material happens to change, and exist residual stress in the formed surface layer. The simulation process shows that the extrusion and friction from cutting edge result in cold plastic deformation of material in formed surface layer, and form residual stress.

Fig. 6 shows variation curve of maximum effective stress of workpiece in metal cutting process. It can be seen that maximum effective stress sharply increases in the starting phase. The value is high up to 1.4GPa at 0.11ms, and then decreases. Chip forms gradually at this time. The maximum effective stress eventually varies at the range of 1.2~1.4GPa.

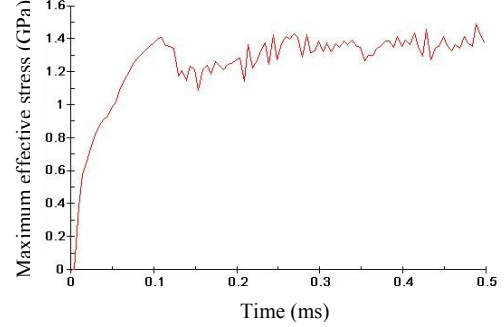


Fig. 6 Variation curve of maximum effective stress

B. Analysis of cutting force

From Fig. 7 it can be seen that the cutting force increases sharply and then decreases, eventually varies in a certain range. In the metal cutting process, with the increase of contact area between cutting tool and cutting layer material, cutting force

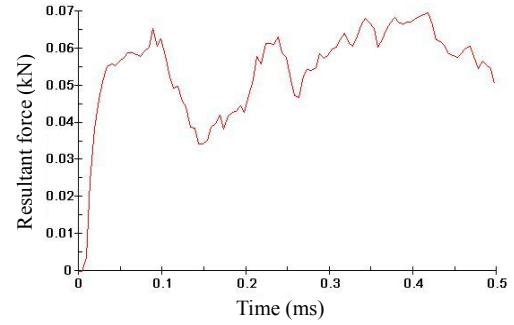


Fig. 7 Variation curve of cutting force

and inner stress of the material at contact zone increase gradually. When the inner stress is up to yield strength, the material produces shearing slip and flows out from primary deformation zone. It makes cutting force decrease a little. Material yielding and chip formation continuously happen, therefore cutting force waves in a certain range.

C. Analysis of stress and strain of cutting tool

From dynamic simulation process it can be seen that there exists biggish contact stress at cutting edge in the beginning of cutting. With the proceeding of cutting, the material deformed moves upward along rake face and extrudes rake face. The maximum contact stress at rake face moves upward too. After the formation of chip, the maximum effective stress waves at a certain distance to the cutting edge (as shown in Fig. 8). Therefore cutting-tool wear is severe in the position.

Stress distribution curve of rake face at 0.2ms is shown in Fig. 9. It can be seen that contact stress at cutting edge is biggish. It is up to maximum value at 0.4mm to cutting edge,

and then decreases gradually.

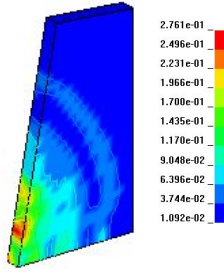


Fig. 8 Effective stress distribution at 0.2ms

Fig. 10 shows variation curves of maximum effective stress and strain at cutting tool surface. Without considering the abnormal local jump in the curves, it can be seen that the maximum effective stress sharply increases to 0.28GPa, and

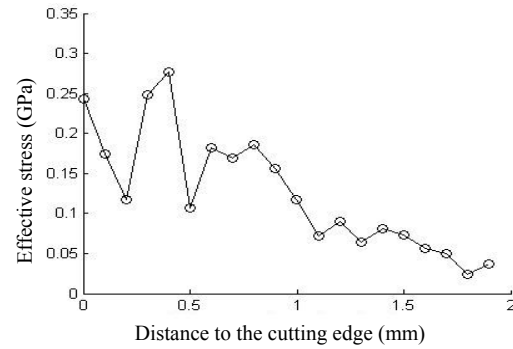
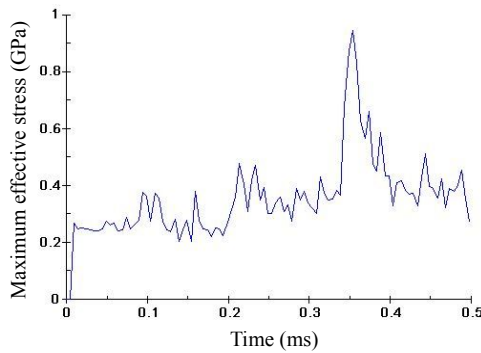
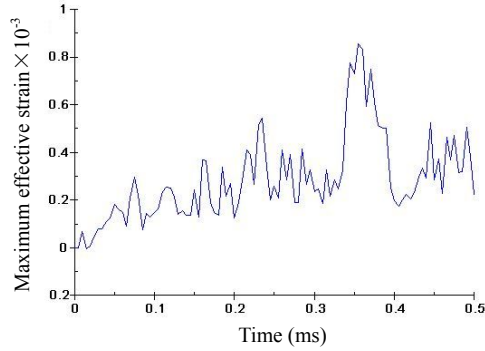


Fig. 9 Stress distribution curve of rake face at 0.2ms

eventually keep waving at 0.35GPa. The maximum effective strain keeps waving at 0.03%. Elastic deformation of cutting tool is very small



(a) Variation curves of maximum effective stress



(b) Variation curves of maximum effective strain

Fig. 10 Variation curves of maximum effective stress and strain at cutting tool surface

V. CONCLUSION

1) The coupling method of FEM and SPH complements the shortcomings of single method. The simulation results show that it is effective in the simulation of metal cutting process.

2) The cutting process is a plastic deformation process in which cutting layer material produces shearing slip due to the extrusion of cutting tool.

3) The extrusion and friction from cutting edge result in cold plastic deformation of material in formed surface layer, and eventually form residual stress.

4) After the formation of chip, the maximum effective stress waves at a certain distance to the cutting edge. Therefore cutting-tool wear is severe in the position.

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