2D finite element modeling of face milling with damage effects

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Abstract: - The present paper details a 2D FE model for face milling of AISI 4340 using ABAQUS/Explicit. This model take into account dynamic effects, thermo-mechanical coupling, constitutive damage law and contact with friction. The yield stress is taken as a function of the strain, the strain rate and the temperature in order to reflect realistic behavior in face milling. Johnson-Cook work material model is used for elastic plastic work deformations. process simulation needs a material separation criterion (chip criterion) and thus The Johnson-Cook damage constitutive law adopted in model presented here allows defining advanced simulations of tool's penetration in workpiece and chip formation. Plane strain condition was used throughout this study The workpiece is discretized with a mesh composed of CPE4RT elements, and local fine mesh is given along the moving path of the cutting edge because of very high gradients of solutions in this area, such as temperature, stress, etc. Stresses and chip formation and cutting force are shown at different stages of the cutting process. The calculated cutting force are compared with experimental data and found to be in good agreement, validating, therefore, the proposed FE model.

Key-Words: - face milling, finite element, damage law, chip formation, Johnson-cook plasticity

1 Introduction

Machining operations comprise a substantial portion of the world's manufacturing infrastructure. They create about 15% of the value of all mechanical components manufactured worldwide [1]. Because of its great economic and technical importance, a large quantity of research has been carried out in order to optimize cutting process in terms of improving quality, increasing productivity and lowering cost. but the deformation characteristics of machining processes are not well understood, and accurate models able to predict machining performances have yet to be improved. Precise knowledge about the optimal cutting parameters is essential. Process features such as tool geometry and cutting speed directly influence chip morphology, cutting forces, the final product dimensionality and tool life. Many investigators have now developed analytical and numerical models to gain a better understanding of the processes which involve deformation with large strains, strain rates and temperatures.

Chip formation is the essential phenomenon in the cutting process. It is the basic of the research on physical phenomena-cutting force, cutting temperature, tool wear, chatter, burr, built-up-edge, chip curling and chip breakage.

In the last years, some research has been made in the modeling and simulation of cutting processes. The purpose has been to predict cutting forces, temperature, roughness and residual stresses, without the need to perform a series of experimental tests. These output tools, to check the behavior of a new coating or material without expensive tests. Many parameter prediction allows to improve process conditions, to design new cutting studies of machining have been investigated over the years, however the phenomenon of chip formation is still not completely understood. The complex dynamic behavior of chip formation is due to the shearing process by which small sizes of chip are produced. Studying the process of chip formation can give relatively important insights in conventional machining applications. The study of this metal cutting process by which chips are formed considers how the properties of both the work piece and tool are effected by friction, strain rate, and thermal effects generated during the machining process. Finite element method has been used to simulate machining by Klamecki [2], Okushima [3], and Tay et al [4] since the early 1970s. With the development of faster processor with larger memory, model limitations and computational difficulty have been overcome to some extent. Great progress has been made in this research field: Lagrangian approach is used to simulate the cutting process including incipient chip formation state [5]; segmental chip formation is modelled to simulate high speed cutting [6], hard-turning [7] or large negative rake angle [8], 3D simulation is performed to analyse oblique cutting [9], etc. A diversity of cutting tool and workpiece materials is used in the simulation of cutting process. For example, the modelled cutting tool materials include uncoated carbide [10], coated carbide [11], CBN [12], cermet, ceramic cutting tool and diamond [13]. The modelled workpiece materials include carbon steel, composite, high alloy steel, cast iron, ductile iron, etc.

Eulerian models have been developed since 1980 [14]. In 1985, Strenkowski and Carroll [15] have presented a thermo-mechanical model which predict residual stresses in the workpiece, as Shih et al. [16] in 1990.

The present paper details a 2D FE model for face milling of AISI 4340 using ABAQUS/Explicit. This model is able to simulate the chip formation during the process. Dynamic effects, thermo-mechanical coupling, constitutive damage law and contact friction are taken into account. The yield stress is taken as a function of the strain, the strain rate and the temperature. The damage constitutive law adopted here allows advanced simulations of tool penetration and chip formation. Stress fields, chip formation and cutting force are shown at different stages of the cutting process. Experiments have been performed to verify the simulation results.

2 Simulation procedure

2.1 Analysis procedure

Plane strain condition was used throughout this study. In every milling cycle, the produced chip will separate with the newly produced workpiece surface without any connection when the cutting tool disengages from the workpiece. In this model, chip separation is realized by defining shear failure criterion. The diameter of the milling tool is 100mm. In order to reduce the calculation time, only a small part of the workpiece and the cutting insert is included in the model. Fig.1 shows the initial geometry, mesh and assembly of the workpiece and the cutting insert.

The workpiece is simplified as a small segment of a ring; whose outside radius is 50.3mm and inside radius 49.7mm. The centre of the ring is positioned at the rotation centre of the cutting insert. The workpiece is 12mm high. The extension of its upper surface passes through the center of the ring and the lower surface is parallel to the upper surface. The workpiece is discretized with a mesh composed of CPE4RT elements, and local fine mesh is given along the moving path of the cutting edge because of very high gradients of solutions in this area, such as temperature, stress, etc. The cutting insert is modelled as a rigid body. The chip formation process is treated as a Lagrangian problem. Every boundary segment of workpiece is defined as a Lagrangian boundary region. The cutting condition is given in Table 1.

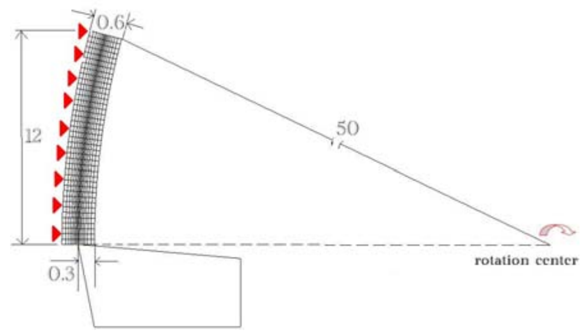

Fig. 1 Initial geometry, mesh and assembly of the tool and the workpiece in chip formation analysis

Table 1 Cutting condition

Cutting type	Orthogonal cutting, milling operation, dry cutting
Work material	AISI 4340
Tool geometry	$\gamma = 5,\ \alpha = 11,$
Cutting parameters	$v_c = 630rpm$, $a_e = 12mm$, $a_p = 0.5mm$, $f_z = 200\ mm/\min$

There are different ways to assign shear failure criterion to form different shape of chips. Ng et al designed two different kinds of shear failure criteria, one criterion is assigned to a line of element along the moving path of the cutting edge to separate the chip from the workpiece; another criterion is assigned to part of the chip material to generate cracks in order to simulate serrated chips [17]. Bacaria defined only one material shear failure model for the whole workpiece material [18]. In the model the Johnson cook damage assigned to the whole workpiece.

2.2 Material modeling

In this study, AISI 4340 steel (33 HRc) is modeled with the Johnson–Cook plasticity model of Eq. (1) [19]. The flow stress is a function of the plastic strain ε^P, the strain rate $\dot{\varepsilon}^P$ normalized by the reference strain rate $\dot{\varepsilon}_0$, the homologous temperature $T^* = \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)$, and the material constant *m*.

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

where A, B, C, m, n are material constants.The material failure strain ε_f is assumed to be dependent on a non-dimensional plastic strain rate, $\dot{\varepsilon}^P / \dot{\varepsilon}_0$; a dimensionless pressure-deviatoric stress ratio, σ_P / σ_e (where σ_P is the pressure stress and σ_e is the von Mises stress); and the homologous temperature T^*, defined in Eq. (1).

The dependence is assumed to be separable and is of the form

$$\varepsilon_f = \left[d_1 + d_2 \exp\left(d_3 \frac{\sigma_P}{\sigma_e}\right)\right]\left[1 + d_4 \ln\left(\frac{\dot{\varepsilon}^P}{\dot{\varepsilon}_0}\right)\right] \times \left[1 + d_5\left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)\right] \quad (2)$$

where d1–d5 are failure parameters. The values of the material constants and the physical properties data are specified in Table 2. The material properties can be used in two ways, i.e. the parameter format and the tabular format, which gives little difference. The values of the material constants and the physical properties data are specified in Table 2.

Table 2
AISI 4340 steel material properties [20]

A(M Pa)	1150
B(M Pa)	739
C	0.014
m	1.03
n	0.26
$\dot{\varepsilon}_0$	1
d_1	-0.8
d_2	2.1
d_3	-0.5
d_4	0.0002
d_5	0.61
$T_{melt}(°C)$	1450
$T_{room}(°C)$	20
Density(Kg m^{-3})	7850
Young's modulus (GPa)	208
Poisson ratio	0.3
Specific heat	477
Thermal expansion	11.5e-6
Inelastic fraction heat	0.9

2.3 Chip separation modeling

Johnson and Cook have developed a damage law which takes into account strain, strain-rate, temperature, and pressure. The Johnson–Cook damage model was used in conjunction with the Johnson–Cook plasticity model [19]. The Johnson–Cook damage model is based on the value of equivalent plastic strain at element integration points. Failure is assumed to occur when the damage parameter exceeds one and the concerned elements are removed from the computation. The damage parameter is defined as

$$D = \sum \frac{\Delta\varepsilon}{\varepsilon_f} \quad (3)$$

Where $\Delta\varepsilon$ and ε_f are increment of the equivalent plastic strain and failure strain, respectively. Each element is assessed for damage over all time increments in the analysis. The Johnson–Cook damage model is suitable for high strain rate deformation, such as high-speed machining, therefore, it is most applicable to truly dynamic situations. A few studies have shown that cutting speeds, and thus strain rates, play a key role on chip type. For example, when the cutting speeds are sufficiently high, saw-tooth chips even occur when machining soft steels. Therefore, the incorporation of strain rate in the material plasticity model and damage model is essential for predicting correct chip types.

2.4 Contact law

In a metal cutting process, due to high stresses, high strain rates and high temperatures, a high mechanical power is dissipated in the tool–chip interface thus leading to many structural modifications of the contacting pieces. Therefore, Shih and Yang [21] shows that no universal contact law exists which can predict friction forces among a wide range of cutting conditions. Childs and Maekawa [22] show that stick and slip zones along the inter-facial zone between the chip and the tool depend on cutting conditions, pressure, temperature, etc.

In our model, a classical Coulomb friction law is assumed to model the tool–chip and the tool–workpiece contact zones.

The contacting bodies will be assumed sticked together if $\|T_t\| < \mu |T_n|$ and in a relative motion if $\|T_t\| = \mu |T_n|$ with T_n and T_t representing the normal and tangential components of the surface traction at the interface and μ the friction coefficient assumed as a constant depending on the nature of the contacting bodies.

3 Numerical and experimental results

While metal cutting is one of the most frequent operation in manufacturing today, a general predictive model of the cutting process is not yet available. The reason is that the physical phenomena associated with the process are extremely complex: friction, adiabatic shear bands, free surfaces, heating, large strains and strain rates. The model of chip formation presented here tries to take into account most of these physical phenomena.

In order to make the cutting insert rotate, its reference point rotates with the rotation center point. Therefore cutting force is exerted on the rotation center point. Fig. 2 shows the cutting force progress during the cutting process for the simulation condition. Because the cutting insert has exited from the workpiece and no contact with the workpiece any more after 0.3ms, cutting force components in x-direction and y-direction are reducing to zero. The 'noise' of the cutting force signal is caused by the removal of the elements; they reach the shear failure criterion and then stresses in these elements are set to zero, which result in the fluctuation of cutting force.

An experiment was carried out on a Deckel vertical milling machine. A Kistler 9255B dynamometer was mounted on the worktable and a workpiece was mounted on the top of the dynamometer. Cutting force signals were transmitted from the table mount dynamometer to the amplifier. The signals were processed through the A/D board and then transmitted to the system. The workpiece material was AISI 4340 steel. The dimensions of the workpiece were $100 \times 200 \times 100\, mm^3$. The cutter diameter was 100 mm and the insert specifications was Sandvik SPKN 12 03 EDR grade. Table 1 gives the cutting conditions used. Fig. 3 shows the cutting force progress during the cutting process for the experimental condition.

This simulation shows the tool penetration and the formation of the chip. Fig. 4 shows von Mises stress fields at different stages of the simulation. At the beginning, the cutting insert is at the bottom of the workpiece, and there is no contact with the workpiece. With the tool rotating in clock-wise direction, the cutting insert engages in the fixed workpiece. A small chip is formed, and the contact between the chip and the cutting insert concentrates in a small area near the cutting edge, which results in a high stress in this area, as shown in Fig.4 (1). Fig.4 (2) shows that the primary deformation zone has the maximum stress in the workpiece.

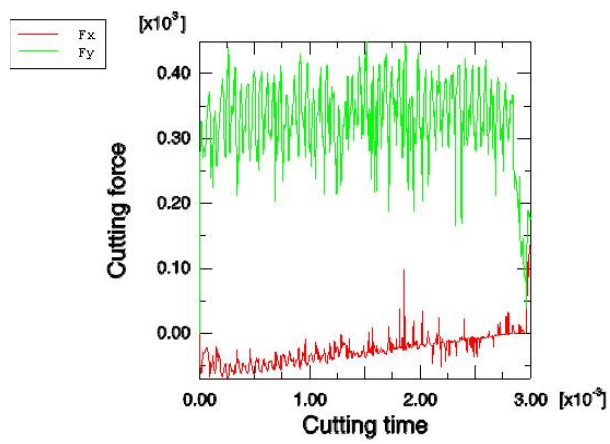

Fig. 2 Cutting force progress during the cutting process simulation

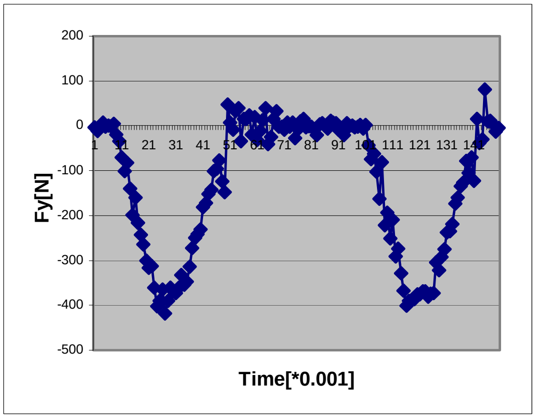

Fig.3 Cutting force progress during the experimental cutting process

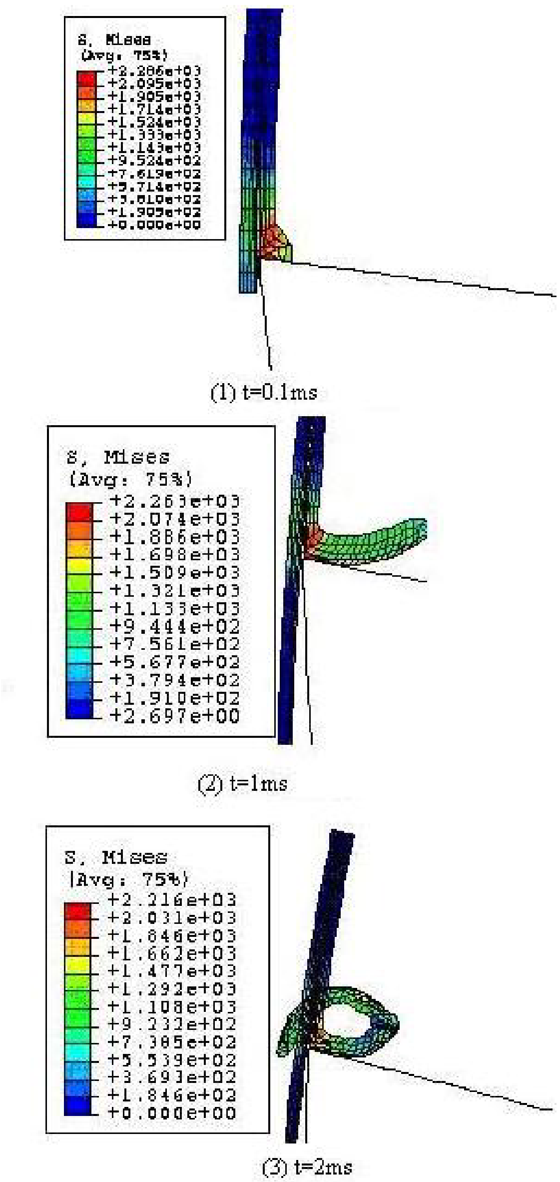

Fig. 4 Stress field (Mpa) in the chip formation analysis

4 Conclusion

In this paper we have presented a complete procedure for the simulation of the cutting operation. Starting from the identification of the constitutive and damage laws of the material, a numerical model is built, for which it must be emphasized that the formation of the chip involves the intrinsic behavior of the material. The machining simulation demonstrates the importance of having a material damage model as a mechanism for generating new free surfaces. Johnson–Cook plasticity and damage models are capable of simulating chip formation.

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