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MODELING AND ANALYSIS OF ORTHOGONAL CUTTING OF STEEL USING FEM

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ABSTRACT
The orthogonal metal cutting process was analysed with the finite element method (FEM) under the plain strain conditions. A commercial finite element code, ABAQUS was employed. Workpiece material was modeled as elasto-viscoplastic. Frictional interaction along the tool – chip interface was modeled with modified coulomb frictional law, the frictional value was assumed as 0.3 and chip separation was based on a critical stress criterion. Experiments were performed to predict the exact forces (cutting, feed and radial forces). During experiments the feed and depth of cut of cut were kept constant at 0.14 mm/rev and 0.25mm. Experimentally obtained forces were used to calculate the maximum shear stress and shear strain. The finite element results were compared with the experimental results. The deviation in the FEM simulated maximum shear stress value from experimental value was 2%. The deviation between FEM simulated and experimental value regarding the shear strain was 3.7%.
Keywords: Metal Cutting, FEM, Shear stress, Shear strain

1. INTRODUCTION
Machining is one of the processes of manufacturing in which the specified shape is imparted to the workpiece by removing surplus material. Conventionally this surplus material from the workpiece is removed in the form of chips by interacting the workpiece with an appropriate tool. One of the state-of-the-art efforts in manufacturing engineering is computer simulation of the machining process to predict power requirements, cutting forces and chip formation using numerical models. These computational models would have great value in reducing or even eliminating the number of trial-and-error experiments which traditionally are used for tool design, machinability evaluation, and chip breakage investigation. The difficulty of reaching a better theoretical understanding of the metal cutting process impelled researchers in the field to apply the finite element analysis to model the cutting process. The advantage of the finite element method in the study of machining is that various material model and various complex boundary conditions can be simulated.

Strenkowski and Carroll [1,2] used the general-purpose finite element code NIKE2D and employed an updated Lagrangian formulation to model the orthogonal metal cutting process. They developed a technique for element separation in front of the tool tip and used to simulate the cutting process from the incipient stage to the steady state and to predict cutting force, chip geometry, plastic deformation and residual stress in the workpiece. Alternatively, Strenkowski and Moon [3] proposed a steady-state metal cutting technique based on an Eulerian formulation. They used the technique to predict chip geometry and temperature distribution. A good correlation between model predictions and metal cutting measurements was found. Shih and Yang [4] conducted a combined experimental and numerical investigation of the orthogonal metal cutting process. The effects of large strain, high strain-rate and temperature were considered. The chip separation criterion used in this investigation was based on the distance in the cutting direction between the tip of the cutting tool and the finite element nodal point located immediately ahead of the tip. Shih. [5] Developed a plane-strain finite element simulation of the orthogonal metal cutting process with continuous chip formation. Shear and normal stress distribution on the primary and secondary deformation elements were presented. Kug Weon Kim and Hyo-Chol Sin [6] developed a thermo-viscoplastic FEM to analyse the study state orthogonal cutting process. The model was capable of dealing with free chip geometry and chip-tool conduct length. Orthogonal cutting experiments are performed for 0.2% carbon steel to validate the FEM cutting model. Good correlation between experiments and FEM simulations was found for the principal forces and the thrust forces. Ceretti, Taupin and Altan (7) investigated the ductile fracture initiation and propagation in plastic deformation processes by finite element method. The predictions from the finite element method were good correlation with experimental results in terms of crack propagation and capability to predict internal defects.

2. FINITE ELEMENT MODELING OF WORKPIECE

2.1 Finite Element Modeling

A schematic diagram (1) shows the finite element modeling of workpiece. Surface EG represents the bottom side of the chip, with its outward normal pointing downward, while surface EF represents the upper side of the machined surface, with its outward normal pointing upward. The two surfaces form a contact pair, with EG and EF providing master and slave surfaces, respectively. Initially, the corresponding nodes on EG and EF are perfectly bonded. During the simulation, the nodes debond to form a chip surface and a machined surface. This separation is governed by a debonding criterion specified in the model. The master and slave surfaces of the tool-chip contact pair consist of the rigid tool surface and the surface EFH.

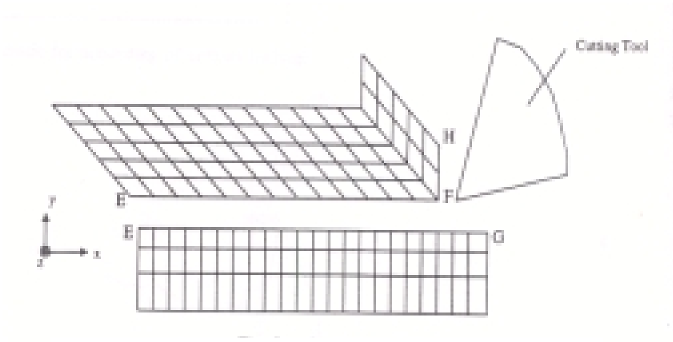

Fig.1 Finite element modeling of metal cutting

2.2 Boundary Conditions Of Workpiece And Cutting Tool

The boundary conditions are sown in fig.2. The workpiece constraining the left , bottom and right sides of the worhpiece from any move movement, while allowing all other boundaries to move. The cutting speed is assigned to the cutting tool by choosing the time interval.

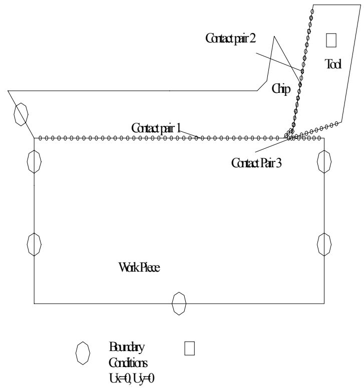

Fig.2 Boundary conditions.

The workpiece modeled as the chip layer has a height of 0.25mm and the rest of the work piece has a length of 2.540 mm and a height of 0.889 mm. The workpiece modal was mashed with quadrilateral and four node plane strain element (CPE4). The discretization results the in-plane geometry of the tool–workpiece system is discredited by the finite element mesh shown in Fig. 3.

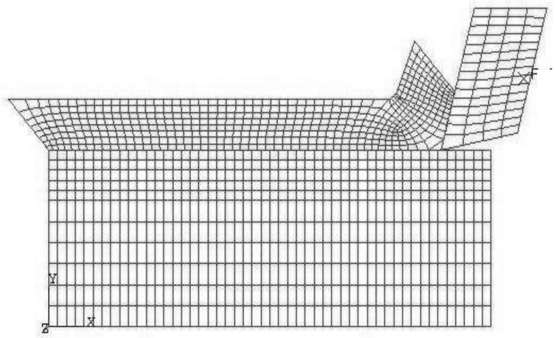

Fig .3. The finite element mesh used in the orthogonal metal cutting simulations

3. CUTTING TOOL AND WORKPIECE MATERIAL PARAMETERS

The cutting tool was considered much harder than the work piece with an high Young's modulus (e.g. $E=2.1\times10^{15}$MPa). In view of the large elastic modulus of the cutting tool relative to the work material, the cutting tool was modeled as a rigid body. The rigid tool was defined by four-node, two-dimensional rigid elements (CPE4).

The workpiece material is taken to be AISI 1045 steel, which is described in this study by the following commonly accepted rate-dependent elastic–plastic material model (1)

$$\dot{\varepsilon}_{\mathrm{p}} = D\left(\frac{\sigma}{\sigma_0} - 1\right)^p \quad \text{for } \sigma \geqslant \sigma_0, \qquad (1)$$

4. CHIP SEPARATION CRITERIA

In this study, critical stress separation based chip separation criterion was employed. When the stress state at the specified distance reaches a critical combination, the pair of bonded nodes just ahead of the tool tip will be released, resulting in chip separation from the work piece. Specifically, the critical stress criterion (2) refers to the attainment of a critical value of 1.0 by the stress index

$$f = \sqrt{\left(\frac{\sigma_n}{\sigma_f}\right)^2 + \left(\frac{\tau}{\tau_f}\right)^2} \quad \text{where } \sigma_n = \max(\sigma_2; 0): \ (2)$$

In this study, the specified distance in the critical stress criterion was set to equal to 0.0254mm. The failure stress in tension was assumed to be σ_f =948 MPa and the failure stress in shear was taken to be τ_f = 548 Mpa i.e. ($\sigma_f / \sqrt{3}$) (von Mises equivalent stress concept).

5. MODIFIED COULOMB FRICTION LAW

Friction along the tool chip interface is a important role in the metal cutting process. The modified Coulomb friction law applied in the FEM simulation. The friction coefficient was assumed as 0.3. in FEM model applied to the contact pair 2 in Fig. 1. Let τ be the chip shear stress at a contact point along the tool chip interface and p the normal pressure at the same point. This law states that relative motion (slip) occurs at the contact point when τ is equal to or greater than the critical friction stress τ_c. When τ is smaller than τ_c there is no relative motion and the contact point is in a state of stick (built-up edge formation). The critical friction stress is determined by

$$\tau_c = \min(\mu p, \tau_{th}) \qquad (3)$$

Where μ is the friction coefficient and τ_{th} the threshold value related to material failure. For the AISI1045 steel, τ_{th} was chosen to be 549 MPa, which is slightly higher than the shear failure stress τ_f.

6. EXPERIMENTAL WORK

Cutting experiments were conducted to validate the finite element model results. AISI 1045 grade steel was used as the workpiece. The following machining parameters were used for metal cutting experiments

Feed: 0.14 mm/rev

Cutting Speeds: 60 m/min

Cutting forces were measured by a dynamometer, and chip thickness was obtained by examining the chip cross section under an microscope. The average stress and strain were obtained by using the measurements in conjection with orthogonal machining theory. The experimental results are summarized in Table .1

Table1. Experimental results

Cutting speed M/min	**Shear stress (MPa)**	**Shear strain**
60	959.08	1.652

7. FEM SIMULATION RESULTS

Simulation starts as the tool moves towards the workpiece at a 60 m/min. The chip separates from the workpiece as debonding occurs at the contact surfaces and establishes contact with the tool rake face.

7.1 Stress distribution

Stress distributions, which result from the combined effect of strain and strain rate are shown in fig.4. The stress are nearly uniform along the central shear zone, with lower values at the tool-chip interface. The maximum shear stress value 939.83Mpa is observed in the primary shear deformation zone in simulation. From Table.1 it is evident that the values obtained from the simulation are matching with the calculated values closely within a deviation ranging from 2 %

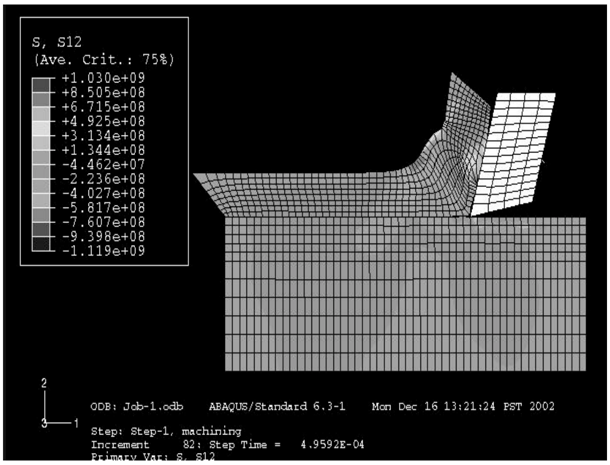

Fig.4 Distribution of shear stress for cutting velocity 60 m/min

7.2 Strain distribution

The distribution of strain component for 60m/min is shown in Fig.5. It is evident that deformation begins ahead of the shear zone, the strain rate increases as the material moves towards the shear zone, until it reaches the upper boundary of the zone. When viewed along the shear zone from the tool tip to the free surface, strain decreases quickly at first, from a maximum value at the tool tip, and then remains almost constant throughout the shear zone. Fig 4. A show that in the chip is compressive on the side of the tool chip interface and is tensile on the side of the free boundary and most of the shear deformation occurs in the chip. The shear strain observed in the simulation was 1.592. From Table.1 it is evident that the values obtained from the simulation are matching with the calculated values closely within a deviation ranging from 3.74 %

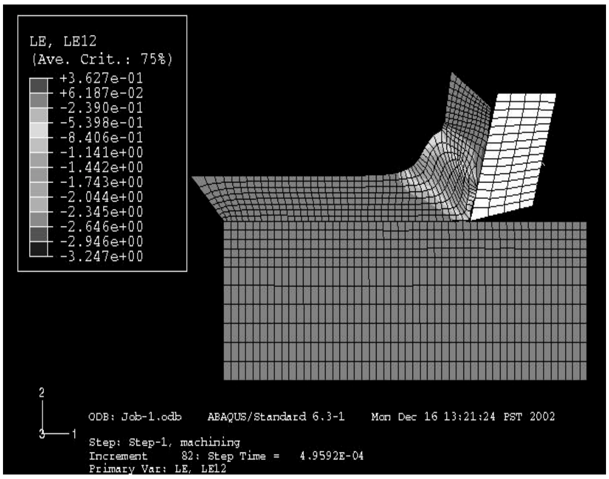

Fig.5 Distribution of shear strain for cutting velocity 60 m/min

7.3 Strain rate

Distributions of the rate of change of strain component 60m/minare shown in Fig. 5 The contours of the strain rates are localized in the primary shear zone, with peak strain rates found at the tool tip and near the turning point of the chip free boundary.

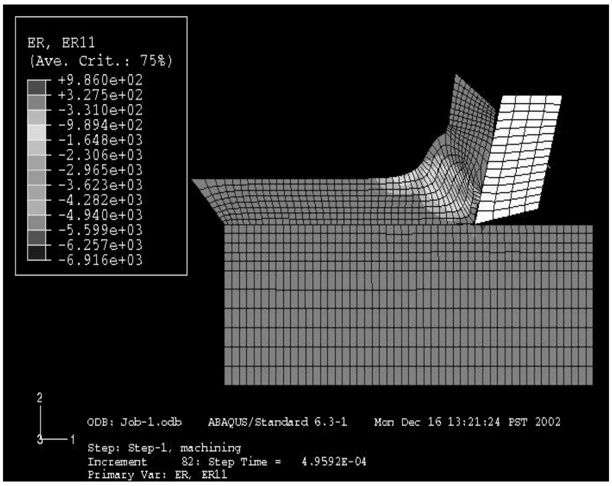

Fig.6 Distribution of strain rate for cutting velocity 60 m/min

8. CONCLUSION

A plain strain, Finite element simulations of the AISI1045 metal cutting process have been carried out using the general-purpose finite element code ABQUS. Distributions of shear stress, shear strain and strain rate along the shear zone are presented for machining conditions corresponding to those considered experimentally, and the corresponding values are in good agreement with those obtained from the measurement. Shear stress values predicted by finite element model closely follow with the theoretically calculated values. The deviation between experimental and simulated value of the shear stress are with in a range of 2%.High strain values are observed in the area of tool chip contact. The deviation between experimental and simulated value of the shear strain was 3.7%

8. REFERENCES

1. J.S. Strenkowski, J.T. Carroll, A finite element model of orthogonal metal cutting, ASME Trans. J. Engineering for Industry, (1985) Vol. 107. pp. 349-354
2. Carroll III J.T, Strenkowski J.S,' Finite element models of orthogonal cutting with application to single point diamond turning', Int. J. Mech. Sci. 30 (1988) 899–920.
3. Strenkowski J.S, kyoung-Jin Moon, 'finite element prediction of chip geometry and tool/workpiece temperature distributions in orthogonal metal cutting', ASME Trans. J. Engineering for Industry, (1990) Vol. 112. pp. 313-318
4. Shih A.J, Yang H.T.Y, Experimental and Fnite element predictions of the residual stresses due to orthogonal metal cutting, Int. J. Numer. Meth. Eng. 36 (1993) 1487-1507.
5. Shih, A. J., (1995), " Finite Element Simulation of Orthogonal Metal Cutting", ASME Trans., J. of Engineering for Industry, Vol. 117, pp. 84-93.
6. Kug weon Kim and Hyo-Chol Sin (1995)" Development of a thermo-viscoplastic cutting model using finite element method', Int.J.Mech.Tools Manufact.Vol. 36, pp. 379-397.
7. Ceretti E., Taupin E. and Altan T. (1996), 'Simulation of Metal Flow and Fracture Applications in Orthogonal Cutting, Blanking and Cold Extrusion', (ERC/NSM), The Ohio State University, December 27, pp. 187-190.

9. NOMENCLATURE

Symbol	Meaning	unit
P	Mass Density	kg/m^3.
$\dot{\varepsilon}_p$	Effective plastic strain rate,	
. σ	Current yield stress	Mpa
σ_0	Initial yield stress	Mpa
D and p	Material parameters	s-1
τ	shear stress	Mpa
σ_2	normal stress	Mpa
σ_f	failure stress in tension	Mpa
τ_f	failure stress in shear	Mpa
τ_c	critical friction stress	Mpa
τ_{th}	threshold value related to material failure	Mpa
M	friction coefficient	