FINITE ELEMENT CHIP FORMATION ANALYSIS FOR HIGH SPEED MILLING OPERATIONS

Usama Umer¹ Lijing Xie², Xibin Wang²
¹Institute of Manufacturing Engineering, National University of Sciences and Technology, PNS Jauhar, Karachi, Pakistan
²School of Mechanical and Vehicular Engineering, Beijing Institute of Technology, Haidian District, Beijing, P.R, China
Contact: usama@pnec.edu.pk

Received July 2008, Accepted December 2008
No. 08-CSME-24, E.I.C. Accession 3062

ABSTRACT
High speed end milling of hardened steel offers several advantages over EDM in die/molds applications especially due to recent development in machine tools, spindles and controllers. However successful implementation of this technology is limited mainly due to faster tool wear and undesirable surface properties. Finite element modeling and simulation techniques are capable of optimizing the cutting conditions and tool geometry by predicting the temperature and stresses distributions. In this study a finite element model has been developed to predict cutting forces, temperature and stresses distributions in flat end milling processes of hardened steel using PCBN at high cutting speeds. High speed end milling experiments were conducted using flat bottom end mills with single insert having straight cutting edge. Comparison of simulated and experimental cutting forces data shows reasonable agreement at high speed regime using the developed model.

UNE ANALYSE DE LA FORMATION DE COPEAUX D'ÉLÉMENTS FINIS DANS LES OPÉRATIONS DE FRAISAGE À GRANDE VITESSE

RESUME
Le fraisage en bout à grande vitesse d'acier trempé offre plusieurs avantages sur l'EDM dans l'application moules/matrices, dû spécialement aux récents développements dans le domaine des machines-outils, broches et appareils de contrôle. Cependant, la réussite de l'implantation de cette technologie est limitée à cause principalement de la rapidité de l'usure des outils et des imprévisibilités à la surface. La modélisation d'éléments finis et les techniques de simulation peuvent établir des conditions optimales des grandeurs de coupe et de géométrie de l'outil en prévoyant la température et la distribution des tensions. Pour les fins de la recherche, on a développé un modèle d'éléments finis pour prévoir les forces de coupe, la température et la distribution des tensions dans le procédé de fraisage d'acier trempé utilisant des fraises à bout plat PCBN à grande vitesse de coupe. On a mené des expériences de fraisage en bout à grande vitesse utilisant des fraises à bout plat à insertion simple et parois rectilignes. La comparaison des données simulées et expérimentales des forces de coupe pour notre modèle démontre un rendement acceptable à grande vitesse.
INTRODUCTION

During the last ten years, High speed machining (HSM) has given a revolutionary change in productivity for the manufacture of dies and moulds, especially for die casting and forging dies.

The driving force behind the developments in HSM is mainly the highly competitive environment associated with industries that require an increase in productivity and an improvement in quality of high-volume production of parts made of high strength and difficult to machine materials such as hardened steels. In general, HSM has found applications in three major industries: machining of aluminium parts in the automotive industry, finishing of hardened materials in the die mould industry and machining of weight saving long/thin aluminium parts in the aerospace industry [1].

HSM is used extensively for the manufacture of moulds and dies for die castings, injection moulding and forging, press tools, graphite and copper EDM electrodes and rapid manufacture of prototypes.

Major advantages of high-speed machining are reported as: high material removal rates, the reduction in lead times, low cutting forces, dissipation of heat with chip removal resulting in decrease in workpiece distortion and increase part precision and surface finish. However, problems related to the application of high-speed machining differ depending on the work material and desired product geometry [2].

The definition of high-speed machining is based on the type of workpiece material being machined. For instance, a cutting speed of 500 m/min is considered high-speed machining for cutting alloy steel whereas this speed is considered conventional in cutting aluminium. In general, machining at cutting speeds and feed rates of 60 percent or higher than conventional machining is considered to be in high speed range [3].

High-speed milling (HSM) of tool steels (usually hardness .30 HRC) has become possible with the advent of new cutting tools. However, milling at high speeds results in high temperature and stress development at the chip-tool and workpiece–tool interfaces leading to a faster tool wear, distortion of workpiece surface finish and increased tooling cost. It is evident that the cost effective application of this technology requires a fundamental understanding of the relationships between process variables (cutting forces, tool stresses and temperatures developed) and performance measures (tool wear, tool life, and surface finish). Thus, modeling of the HSM process in order to predict process variables is an essential development to improve insert design and to optimize the cutting conditions [4].

In the traditional mechanistic models, cutting forces coefficients were determined by doing a large number of experiments and empirical curve fitting methods. However these models were unable to predict stresses and temperature distributions which are helpful in predicting tool wear and optimization of cutting parameters.

This study aims to develop a 2D FE model that could be able to simulate high speed flat end milling processes. Through this model cutting forces, chip morphology temperature and stresses distributions are predicted. The cutting forces obtained from simulation are compared with the experimental data to check validity of the proposed model.

MILLING CONFIGURATION

Flat bottom end mills with single indexable insert were being selected for high speed milling of hardened steel. The geometric features of tool holder and insert are listed in Table 1.

In this study the workpiece selected was AISI-H13 at 50 HRC which is commonly used in die castings and forging dies. The cutting tool selected was PCBN, with 80% CBN content.

The cutting takes place at both the cutting edges of the insert namely primary and secondary cutting edge. It has been observed that most of the cutting action takes place at the primary cutting edge. The tangential and radial cutting forces at the secondary cutting edge have negligible contribution. Since the approach angle is zero and small nose radius we can assume zero force in the axial direction. Hence only cutting action at the primary cutting edge is modelled and the tangential and radial cutting forces are compared with the experimental data. Due to constant thickness of the chip, the cutting action at primary cutting edge can be modelled by plane strain formulation.

Orthogonal milling experiments were conducted with the cutting parameters listed in Table 2 on hardened H-13 steel plates. Tangential and radial forces were measured, using a Kistler model 9257B force dynamometer. The force signals from the dynamometer fed into Kistler model 5017B dual-mode charge amplifiers. The analog force signals from the charge amplifier were then passed through a data acquisition card. A PC-based data acquisition program (Dynoware) was used to acquire the sampled data and save for analysis.
### Geometric features

<table>
<thead>
<tr>
<th>Geometric features</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helix angle</td>
<td>zero</td>
</tr>
<tr>
<td>Diameter</td>
<td>16 [mm]</td>
</tr>
<tr>
<td>Rake angle</td>
<td>-8°</td>
</tr>
<tr>
<td>Clearance angle</td>
<td>14°</td>
</tr>
<tr>
<td>Edge preparation</td>
<td>Honed [0.01mm]</td>
</tr>
<tr>
<td>Nose radius</td>
<td>0.8 [mm]</td>
</tr>
</tbody>
</table>

Table 1 Geometric features of tool holder and insert.

### FINITE ELEMENT MODEL

In the present study ABAQUS/Explicit has been used to simulate the chip formation process. In literature, metal cutting processes were usually simulated by the implicit method. The implicit method may have difficulty in convergence because of contact and material complexities in machining, resulting in an expensive analysis due to a large number of iterations for a large set of linear equations. The explicit method determines the solution without iterating by explicitly advancing the kinematic state from the previous increment. Even though an analysis requires a large number of time increments using the explicit method, every increment is efficient and often results in an economical solution. Another advantage is that the explicit method requires much less disk space and memory than the implicit method for the same simulation. This advantage becomes more obvious if mesh refinement is needed [5].

Plastic deformation in the primary shear zone is such that elastic deformation can be neglected and the workpiece modeled as a nearly incompressible, elastic-plastic material. The workpiece material was represented by the Johnson–Cook plasticity model.

The Johnson–Cook formulation involves the yield stress at nonzero strain rate, strain hardening index n, equivalent plastic strain, equivalent plastic strain rate, the melting temperature of the workpiece, operating temperature, and strain rate sensitivity exponent m as shown in equation (1); B and C are constants. This particular plasticity model is suitable for deformation of materials at high strain rates, which typically occur, in a machining process.

\[
\sigma = B \varepsilon^n \left[ 1+C \ln \left( \frac{\dot{\varepsilon}}{1000} \right) \right] \left[ 1- \frac{T-T_{room}}{T_{mel}-T_{room}} \right]^m
\]

(1)

Where \( \sigma \) = equivalent stress, \( \varepsilon \) = equivalent strain, \( \dot{\varepsilon} \) = equivalent strain rate, \( T_{mel} \) = melting temperature; for AISI H13, \( B = 981.7 \) MPa, \( C = 0.023 \), \( n = 0.182 \), \( m = 2.7 \), \( T_{mel} = 1753 \) °K, \( T \) = operating temperature [6]. The equation is valid for the variables range as follows:

- Strain = 0.96-1.66, strain rate = 1809-35682 s\(^{-1}\) and Temperature = 536-1155 °K

---

Transactions of the CSME / de la SCGM Vol. 32, No. 3-4, 2008
When Zorev's sliding-sticking friction model is employed in the simulation, the division of the sliding and sticking regions is determined by two methods: one is to prescribe the length of each region, the other is to determine the sliding and sticking region automatically by a program according to a criterion [7], given by equation (2).

\[ s = \mu p \text{ when } \mu p < \tau_{\text{max}} \]
\[ s = \tau_{\text{max}} \text{ when } \mu p \geq \tau_{\text{max}} \]

Where \( s \), \( p \) and \( \tau_{\text{max}} \) are the friction, normal and equivalent shear stress at the tool rake face. The second approach was adopted this analysis. A coefficient of friction of 0.5 is used by Ozel [8] for AISI H13 and the same is used here as an initial trial value.

<table>
<thead>
<tr>
<th>Cutting Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>200, 400, 600 m/min</td>
</tr>
<tr>
<td>Radial depth of cut</td>
<td>16 mm</td>
</tr>
<tr>
<td>Axial depth of cut</td>
<td>1 mm</td>
</tr>
<tr>
<td>Feed per tooth</td>
<td>0.15, 0.25 mm</td>
</tr>
</tbody>
</table>

Table 2 Cutting parameters used in experiments and simulations.

In this model, Lagrangian formulation with element removal technique was used. The workpiece was fixed and the chip formation took place by the rotation of the tool. In order to reduce calculation time only part of the workpiece and cutting tool was modelled. The workpiece was meshed according to the rotating path of the cutting tool. In order to make cutting tool rotate as a deformable body, its bottom was pinned and rotate with the rotation centre of the tool as shown in Fig. 1.
RESULTS AND DISCUSSIONS

Figures 3-4 show the forces obtained in the x and y-directions from the simulations at different cutting conditions. For feed of 0.15mm/tooth the simulations were run for 120° of cutter rotation. However due to symmetry of the curve, simulations for 0.25 mm/rev were run only for 60° of cutter rotation. Figure 2 shows periodic variation in the cutting force signals due to varying load at the tool tip which is a consequence of the element removal method. The curves in Figures 3-5 were smoothed out using the moving average method.

The forces in x and y-directions have non zero values at zero degree of cutter rotation because of non zero chip thickness at the starting point in the finite element model in Figure 1. Both forces are varying in cyclic manner like a sine curve (Figure 3) due to varying chip load. At about 60° of cutter rotation Fx reaches its maximum value in contrast to Fy which shows zero value.

It can be seen that machining AISI-H13 at 50 HRC in the high speed range of 200 to 600 m/min do not affect the cutting forces too much and are nearly constant. However at maximum chip load the difference in cutting forces signals is quite obvious which shows a 50 to 80 N reduction in cutting forces due to increase in cutting speed (Figure 3).

The effect of feed rate is quite simple as shown in Figure 4. Increasing the feed per tooth increase the cutting forces by the same proportion due to increase in chip load.

Figure 5 shows the comparison between simulated forces with the experimental ones. The cutting force variation with cutter rotation is much similar for both cases, however the FE model overestimates the cutting forces particularly in the x direction. This requires the need for adjustments in the coefficients for the Johnson cook model.
Figure 3 Cutting forces Fx (a) and Fy (b) at feed=0.15mm/tooth.

Figure 4 Cutting forces Fx (a) and Fy (b) at feed=0.25mm/tooth.

Figure 5 shows the comparison between simulated forces with the experimental ones. The cutting force variation with cutter rotation is much similar for both cases, however the FE model overestimates the cutting forces particularly in the x direction. This requires the need for adjustments in the coefficients for the Johnson cook model.
The major advantage of FEM over mechanistic models is that in addition to cutting forces, chip geometry, stresses and temperatures at the deformed workpiece and tool-chip interface can be obtained. Figure 6 shows the deformed mesh indicating chip shape after 30° of cutter rotation when milling at 200 m/min with feed of 0.15 and 0.25 mm/tooth. It can be seen that with lower feed chip curls at low angle of cutter rotation which is also reported in [4].

Figure 6 Deformed meshes at feed of 0.25 mm/tooth (left) and 0.15/tooth (right).
Figure 7 Temperature contour (°C) for the workpiece and tool at speed=600 m/min, feed=0.25 mm/tooth.

The temperature contour when milling at 600 m/min with feed rate of 0.25 mm/tooth is shown in Figure 7. Temperatures are much higher at the secondary shear zone i.e. along the tool rake face as compared to the primary shear zone. This is mainly due to high sticking friction at the tool-chip interface and the maximum temperature occurs at the point of transformation into sliding friction. Further up the tool face temperature starts decreasing on the chip surface due to heat flux intake by the tool and surrounding.

Figure 8 Temperature variation (°C) for the workpiece and tool for different cutting conditions.
Figure 8 shows the maximum temperature in the tool and workpiece at different cutting speeds and feed rates. It is apparent that increasing cutting speed or feed/tooth increases the temperature. However the rate of increase in temperature varies with the feed rate, being higher at high feed/tooth values.

The mises stress contour when milling at 600 m/min with feed rate of 0.25 mm/tooth is shown in Figure 9. The primary shear zone shows a high stressed area in comparison to the secondary shear zone at the tool rake face. This is due to the fact that the equivalent stress increases with strain rate and decreases with the increase of temperature. The strain rate is maximum at the primary shear zone. In addition higher temperatures at the secondary shear zone also causes mises stress to decrease.

![Mises stress contour (MPa) for the workpiece and tool speed=600m/min,feed=0.25mm/tooth.](image)

Figure 9 Mises stress contour (MPa) for the workpiece and tool speed=600m/min,feed=0.25mm/tooth.

Figure 10 shows the maximum mises stress variation at primary shear zones for different cutting conditions. High mises stresses are observed with increasing cutting speed because of high strain rate deformation. In contrast higher feed results in low value of mises stress due to increase in specific cutting energy [9].

![Figure 10 Maximum mises stress at primary shear zone for different cutting conditions.](image)

Figure 10 Maximum mises stress at primary shear zone for different cutting conditions.
CONCLUSIONS
1. The comparison between simulated and experimental results indicate that, High speed milling operations using flat bottom end mills can be simulated using a 2D FE model with reasonable degree of accuracy.
2. The cutting forces do not show a marked difference when increasing speed from 200 to 600 m/min for H-13.
3. Increase of feed rate increases both cutting forces components by the same proportions.
4. At lower feed rate the chip curls earlier i.e. at low angle of rotation of the cutter.
5. Maximum temperature found on the secondary shear zone near the tool-tip.
6. Temperatures on the tool and workpiece found to be increased with the increase of cutting speed and feed rate.
7. High mises stress are observed on the primary shear zone due to high strain rate and lower temperatures.

ACKNOWLEDGMENTS
This project is supported by National Natural Science Foundation of China (No.50505003) and National Defense Science Foundation of China (No. 41318.1.2.2).

REFERENCES