Investigations on Mechanics-Based Process Planning of Micro-End Milling in Machining Mold Cavities

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In this article, a model-based micro-end milling process planning for machining micromold cavities is proposed. The goal is to facilitate proper selections of the process parameters for a given workpiece material, cavity geometry, and micro-end mill. Specifically, the axial depth of cut and the feed per tooth are critical in achieving performance objectives in terms of low cutting forces and high surface accuracy and material removal rate. An analytical model based on process mechanics is used to select feed per tooth range in micromilling to avoid size effects. Further, a time-domain simulation model is utilized to provide predictive capability in practical micromachining performance, such as cutting forces, surface form, and surface roughness. The generalized process planning strategy consists of two steps: roughing and finishing. In roughing, the objective is to control the cutting force within a predefined threshold to prevent premature tool breakage and to maximize the material removal rate. In finishing, the primary objective is to control the form error within the tolerance and to obtain satisfactory surface roughness.

Keywords Analytical modeling; Micro-end milling; Process planning; Size-effect.

1. Introduction

With the growing importance of product miniaturization and the ever-increasing popularity of micro-end milling operation in fabricating miniature components, significant amount of research has been undertaken to gain a better understanding of the micro-end milling process [1]. Although process kinematics do not change, the cutting and surface generation mechanisms involved in the micro-end milling process change dramatically as the process scales down from macro to microscale. These changes are mostly due to the different cutting mechanics induced by the tool-workpiece engagement, cutting geometry, and scaling relationship between the micro-end milling tool (flexural strength, tool edge geometry, and tool material grain size) and workpiece material microstructure.

In micromechanical machining, due to limited strength of the edge of the micro-cutting tool, the uncut chip thickness is constrained to be comparable or even less than the tool edge size and—as a result—a chip will not be generated. The chips will be generated, and material removal will be achieved only when the uncut chip thickness reaches a critical value, the so-called minimum chip thickness, \( t_{\text{min}} \) [2]. The minimum chip thickness requirement significantly affects machining process performance in terms of cutting forces, tool wear, surface finish, process stability, etc. [3–7]. Hence, knowledge of the minimum chip thickness is important to the selection of appropriate machining conditions. Previous investigators have resorted to experimentation [8], molecular dynamics (MD) simulations [9], and microstructure-level finite element simulations [10], as well as analytical slip-line plasticity based models [11] to estimate the normalized minimum chip thickness. However, none of these studies explicitly addressed the implication of the minimum chip thickness on the selection of the feed rate for optimal machining performance. The axial depth of cut and radial depth of cut are known to have a strong influence on the cutting forces, process stability, productivity, and surface error in conventional milling process, yet little is known about the micro-end milling process. Achievement of a wide range of axial depth of cut from a few microns to several hundred microns has been reported in the micro-end milling process by several researchers, but no direct comparison is made for the achieved process performance.

The literature reveals that a considerable amount of knowledge has been gained to date about the micro-end milling process, but little or no work can be found that presents a systematic approach for process planning, which is a critical element for economical and reliable use of this emerging fabrication technique to produce miniaturized 3-D features on metal parts.

In this article, we propose a process planning guideline for successful micro-end milling of cavities on metal molds. Interrelation between process parameters (feed per tooth \( f_z \), axial depth of cut \( ADOC \)), radial depth of cut \( RDOC \), spindle speed, \( \Omega \), and achieved process performance has been analyzed for a variety of cutting tool edge radii. We introduce a sequential process planning consisting of a roughing and a finishing to achieve prescribed process performance specifications. Experimental and modeling studies on micro-end milling of 2024-T6 aluminum (Al 2024-T6) are also presented.
2. Mechanics of micro-end milling

The difference in mechanics of cutting arises from scaling of the end milling operation. The current manufacturing method utilizes fine grain carbide tools fabricated mostly out of tungsten carbide in a cobalt matrix (WC-Co). However, micro-end mills with sharp cutting edges cannot be fabricated due to the limitation of structural strength of the tool at the edge. Widely available microtools have edge radius ranging from 1 to 5\(\mu\)m with considerable nonuniformity of the radius value along the flutes of the cutter. As the tool diameter decreases, the rigidity of the tool also decreases, which leads to tool deflections under heavy chip load and sudden tool breakage. This limits the chip load, especially in micro-end milling, to a few microns per tooth. With the small feed rates, the well-known size effect, originally discovered in ultra precision diamond cutting [2], becomes prominent in micro-end milling. Specific cutting forces depend mostly on the ratio of the uncut chip thickness to the tool edge radius. Due to the highly localized shearing, the specific cutting forces in ultraprecision cutting is almost twice that in conventional cutting.

The tool edge radius and small feed/tooth makes the phenomenon of minimum chip thickness very dominant in the micro-end milling. A minimum chip thickness is observed where tool engagement with workpiece results in chip formation. In full-immersion micro-end milling uncut chip thickness of \(t_u\) varies from zero to full feed per tooth value of \(f_t\) as shown in Fig. 1. When the cutter engages with the workpiece at the tool tip, a very small uncut chip thickness is applied, increasing gradually as illustrated in Fig. 2(a). The particular cutter rotation angle, \(\phi\), where the minimum chip thickness is achieved and the chip begins to form, is denoted as the chip formation angle (CFA), as illustrated in Fig. 2(b). Hence the minimum chip thickness for micromilling \(t_{c_{\text{min}}}\) can be defined as formation of chip when the uncut chip thickness becomes greater than a minimum chip thickness \(t_u > t_{c_{\text{min}}}\) at a certain rotation angle of \(\phi\). Unlike precision diamond turning where diamond tools are up-sharp with nanometric edge radius and the uncut chip thickness is often constant [12], the minimum chip thickness in micro-end milling is greatly affected by the radius of the cutting edge \(r_e\), which is usually greater than 1\(\mu\)m (see Fig. 2). The chip is not formed and mostly elastic deformations are induced to the workpiece until tool reaches to a certain rotation angle where a minimum uncut chip thickness develops. A smaller edge radius causes early formation of minimum chip thickness, whereas a larger edge radius will result in ploughing of the workpiece.

Kim et al. [13] experimentally determined that the minimum chip thickness depends upon the ratio of uncut chip thickness to the cutting edge radius which was claimed between 10–25\% for the ductile metals. Liu et al. [7] calculated the minimum chip thickness and utilized a ratio \(\lambda = \frac{t_u}{r_e}\) to describe as function of edge radius. In that study, minimum chip thickness to tool edge radius ratio was found about 35–40\% for micromilling of 6082-T6 aluminum and 20–30\% for AISI 1018 steel at a wide range of cutting speed and edge radius.

3. Analytical minimum chip thickness model

The influence of edge radius on minimum chip thickness for micromilling of 2024-T6 aluminum is investigated by utilizing an analytical model developed by Liu et al. [11].
In their analytical model, the workpiece material model and a slip-line field analysis are utilized to estimate the minimum chip thickness for a given tool edge radius, feed rate, and surface cutting speed as shown in Fig. 3. This analytical model accounts for strain hardening, thermal softening, and elastic recovery effects of work material with the Johnson–Cook (J–C) constitutive model under high strain, strain-rate, and temperate conditions as given in Eq. (1):

\[
\bar{\sigma} = \left[ A + B (\bar{\varepsilon})^n \right] \left[ 1 + C \ln \left( \frac{\bar{\varepsilon}}{\bar{\varepsilon}_0} \right) \right] \times \left[ 1 - \left( \frac{T - T_{room}}{T_{melt} - T_{room}} \right)^m \right].
\] (1)

In the J–C model, the constant \(A\) is the yield strength of the material at room temperature, and \(\bar{\varepsilon}_0\) represents the plastic equivalent strain. The strain rate \(\bar{\varepsilon}\) is normalized with a reference strain rate \(\bar{\varepsilon}_0\). The temperature term in the J–C model reduces the flow stress to zero at the melting temperature of the work material, leaving the constitutive model with no temperature effect.

By using cutting geometry (uncut chip thickness, surface cutting speed, rake angle, and tool edge radius), work and tool material thermal-mechanical properties (as given in Table 1), and slip-line field analysis, average normal and shear stress values in the primary deformation zone (\(P_s\) in Fig. 3) are calculated. A criterion by utilizing the Kragelskii–Drujuanov equation [11] for the deformation transition from ploughing to shearing has been utilized as given in Eq. (2):

\[
\lambda = \frac{t_{\text{min}}}{r_e} = 0.5 - \frac{\tau_m}{\sigma}.
\] (2)

In this criterion, the minimum chip thickness-to-tool edge radius ratio is written as functions of normal and shear stresses in the primary shear zone. Uncut chip thickness values (\(t_c\) in Fig. 3) increased gradually until the solutions provided by the slip-line fields analysis satisfied the criterion given in Eq. (2). The uncut chip thickness value that satisfies the Eq. (2) is determined as the minimum chip thickness (\(t_{\text{min}}\)) required for shearing to take place.

The following J–C work material model parameters for 2024-T6 aluminum (Al 2024-T6) are utilized in the analytical minimum chip thickness model; \(A = 369\) MPa, \(B = 684\) MPa, \(n = 0.73\), \(C = 0.0083\), \(m = 1.7\), \(T_{\text{melt}} = 502^\circ\text{C}\). The tool material is tungsten carbide in a cobalt matrix (WC-Co).

By using the analytical minimum chip thickness model, the minimum chip thickness-to-edge radius ratio is estimated to be between 42% and 45% for the range of edge radius (1–5 \(\mu\text{m}\)) and the cutting speed (120–360 \(\text{m/min}\)) as shown in Fig. 4. Chip formation angle in relation to the uncut chip thickness, \(t_u\) has also been calculated by using the analytical model developed by Liu et al. [11].

Variation of chip formation angle with respect to tool edge radius and workpiece feed rate is computed for micromilling of 2024-T6 aluminum as shown in Fig. 5. For micromilling of 2024-T6 aluminum, Fig. 5(a) depicts the relationship in the plane of \(\frac{CFA}{r_e}\) with three levels of feed per tooth, where as Fig. 5(b) shows the relationship in the plane of \(\frac{SLE}{r_e}\) with three level of edge radius, respectively. This is mostly due to higher modulus of elasticity of 2024-T6 aluminum, where elastic deformations are larger than tool steels.

### 4. Time domain process simulation model for micro-end milling

In previous research, Liu et al. [14, 15] developed a time-domain simulation model of the micro-end milling process for the predictions of process performance, including cutting forces, tool vibrations, and the surface location error (SLE) and surface roughness. The surface location error of micro-end milling can be computed as the distance of the mean surface plane of the milled surface from the commanded surface plane for any given process condition. The model accounts for the effects of the minimum chip thickness due to the tool edge radius, dynamic vibrations, and spindle run-out. In this article, the predictions of the cutting forces and surface location errors were utilized for process planning. In order to compute the surface location error, the model generates a set of point cloud data for the micromilled sidewall surfaces. The distance from the mean plane of the point cloud data to the commanded surface plane is defined as the surface location error. For both up-milled

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**Table 1.**—Thermomechanical properties of work and tool materials.

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<tr>
<th>Property</th>
<th>Al 2024-T6</th>
<th>WC-Co</th>
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</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>2.78</td>
<td>15.7</td>
</tr>
<tr>
<td>Modulus of elasticity (GPa)</td>
<td>73.1</td>
<td>650</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.33</td>
<td>0.25</td>
</tr>
<tr>
<td>Specific heat capacity (J/g-K)</td>
<td>0.875</td>
<td>0.26</td>
</tr>
<tr>
<td>Thermal conductivity (W/m-K)</td>
<td>121</td>
<td>28.4</td>
</tr>
<tr>
<td>Thermal expansion (μm/m-°C)</td>
<td>23.2</td>
<td>5.2</td>
</tr>
</tbody>
</table>

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**Figure 3.**—Slip-line field analysis of cutting with a finite edge radius tool and its hodograph [11].
and down-milled surface, positive surface location error (SLE) is defined in the overcut direction as shown in Figs. 6 and 7.

The surface generation model of micro-end milling for both sidewall and floor surfaces accounts for both deterministic and stochastic surface components. Six fundamental factors that influence the machined surface roughness in micro-end milling are: (1) process kinematics; (2) process dynamics; (3) cutting edge geometry; (4) elastic recovery of the workpiece material; (5) minimum chip thickness effect and ploughing/rubbing; and (6) micro-burr formation. The surface generation models were developed in [14–16] that fully account for all these factors except for factor (6). Except for the edge serration (factor (3)), which only affects the sidewall surface generation, the other factors have significant effects on both the sidewall and the floor surface generation [16].

The deterministic sidewall surface generation model records the sidewall surface as a surface point set \( S(x; y; z) \), where \( x \) is in the feed direction, \( y \) is in the normal to the feed direction, and \( z \) is along the axial direction. The surface point set can be further divided into three subsets: the arc surface \( \text{SURFa} \), the up-milled surface \( \text{SURFu} \) and the down-milled surface \( \text{SURFd} \) as shown in Fig. 6. Although the arc surface \( \text{SURFa} \) is important in some applications where the arc surface is part of the generated surfaces, in this work, we focus only on the sidewall surfaces. The surface location error \( \text{SLE} = \text{SLE}_u + \text{SLE}_d \) for the up-milled surface \( \text{SLE}_u \) and for the down-milled surface \( \text{SLE}_d \) are derived from \( y \) coordinates of the points in the sets of \( \text{SURFu} \) and \( \text{SURFd} \), respectively:

\[
\text{SLE}_u = \sum_{i=1}^{N_u} \left( \frac{y(P_i^{\text{Su}})}{N_u} - R \right), \quad P_i^{\text{Su}} \subset \{\text{SURFu}\}
\]

Figure 4.—Predicted minimum chip thickness in micro-end milling of Al 2024-T6 aluminum: (a) Variation with cutting speed and (b) Variation with edge radius.

Figure 5.—Chip formation angle (a) Variation with feed per tooth and (b) Variation with edge radius.
\[ SLE_d = \sum_{i=1}^{N_d} \left( \frac{y(P_{Su}^i - R)}{N_d} \right), \quad P_{Su}^i \subset \{SURF_u\}, \]  

where \( P_{Su}^i \) and \( P_{Sd}^i \) are the points on the up-milled and down-milled surfaces in the sets \( SURF_u \) and \( SURF_d \), respectively, \( N_u \) and \( N_d \) are the total numbers of the points on the corresponding surfaces, and \( R \) is the radius of the micro-end mill. Equation (4)

Figure 6.—Surface location error of up-milled and down-milled surfaces.

In micromilling, conventional strategies used in milling process planning become ineffective due to intricacies of micromechanical machining [17]. The cutting forces with increased feed rate can easily snap the fragile micro-end mills. Tool path planning and selection of machining parameters are highly important [18]. In addition, very low feed rates may not achieve minimum chip thickness requirements. Therefore, advanced process planning strategies are required for efficient micro-end milling [19]. In this section, the process planning strategy is presented using a simple example. The task is to make the profile of a 3 × 3 mm square pocket as mold cavity. The pocket is 0.3 mm in depth and has 0.5 mm radius at the corner, as shown in Fig. 8. Since the feed rate and axial depth of cut are the two parameters that have most significant impact on the process performance, they are selected as the variables to be optimized. Other parameters (spindle speed, radial depth of cut, and edge radius) are fixed. The machining conditions for roughing and finishing are shown in Table 2. In the roughing operation, 100 \( \mu \)m of radial depth of cut is used. In finishing operation, the radial depth of cut is set at 20 \( \mu \)m.

The constraint of the achievable maximum feed rate is first examined from the machine tool capability. The manufacture of miniature part requires the feed drive making a lot of segmented moves with short distance, which allows even smaller distance for the feed drive to accelerate from 0 to the programmed feed per tooth of \( f_i \) and to decelerate from \( f_i \) back to 0. Assuming the maximum achievable feed per tooth \( (f_{i_{\text{max}}}) \) is defined as the feed at which only small fraction of the segmented distance (10%) is used for acceleration and deceleration. The maximum feed per tooth \( (f_{i_{\text{max}}}) \) is limited by the acceleration capability \((a)\) of the feed drives, the segment length of the cut \((d)\), the spindle speed \((\Omega)\), and the number of tooth of the micro-end mill \(n_t\), which can be expressed as:

\[ f_{i_{\text{max}}} = \sqrt{\frac{d \times 0.1}{a} \times a \times 10^6 \times \frac{60}{\Omega \times n_t}}, \]  

Figure 9 shows the \( f_{i_{\text{max}}} \) under different spindle speed and segment distance, assuming the feed drive acceleration is 1 g (9.8 m/s\(^2\)). It is seen that \( f_{i_{\text{max}}} \) decreases when the spindle speed \( \Omega \) increases and the segment distance \( d \) increases.

Table 2.—Micro-end milling process parameters for time-domain simulations.

| Tool diameter (\( \mu \)m) | 635 | 635 |
| Edge radius, \( r_e \) (\( \mu \)m) | 5 | 2 |
| Radial depth of cut, \( RDOC \) (\( \mu \)m) | 100 | 20 |
| Spindle speed, \( \Omega \) (rpm) | 40000 | 40000 |
| Axial depth of cut, \( ADOC \) (\( \mu \)m) | 20 ~ 200 | 20 ~ 200 |
| Feed per tooth, \( f_i \) (\( \mu \)m/tooth) | 0.5 ~ 20 | 0.5 ~ 20 |

Figure 7.—Illustration of computing SLE from predicted surface topography.

Figure 8.—Sample mold cavity geometry.
For spindle speed of 40,000 rpm and segment distance of 2 mm, as used in this case study, the maximum achievable feed rate is 33.5 μm/tooth.

In order to facilitate the process planning, time domain simulations were performed with ten levels of feed rates and five levels of axial depth of cut for both roughing and finishing 2024-T6 aluminum. In the roughing operation, the objective is to limiting the cutting forces to avoid tool breakage and maximize the material removal rate (MMR). Figure 10 shows the contour map of the peak-to-valley force in the normal to the feed (Y) direction. It is noted that the peak-to-valley forces increase rapidly as the axial depth of cut increases beyond 140 μm for a range of feed rates (around 5–10 μm/tooth). This range of feed rate is likely to be the range where low feed rate instability occurs. It is also noted that the cutting forces is much more sensitive to the increase in the axial depth of cut than the feed per tooth. Since the axial depth of cut and feed rate per tooth are both proportional to the MMR, the optimal strategy of limiting the cutting forces while maintaining high MMR is the combination of low axial depth of cut and high feed rate. For example, to limit the cutting force below 5 N, an axial depth of cut of 100 μm and a feed rate of 20 μm/tooth would be a good selection.

In the finishing operation, the objective is to minimize the form error, which was quantified by the surface location error (SLE). For all the simulations, a 3 μm spindle runout is considered, which causes 3 μm overcut. Figure 11 presents the contour plot of the surface location error in the plane of feed per tooth and axial depth of cut. Similar to the cutting forces, the SLE is also more sensitive to the axial depth of cut. Because of the existence of the spindle runout, the SLEs are positive (overcut) under all the conditions examined. The tool vibrations cancel part of the SLE caused by the spindle runout. It is also noticed that at the lower right corner of the plot, there exist an isoline of SLE = 3 μm, which indicates that the SLEs are not influenced by the tool vibrations under these conditions ($f_r = 10–20 \mu m/tooth, ADOC = 30–60 \mu m$). If the spindle runout can be accurately measured and compensated, then the aforementioned process conditions are likely the optimal process condition for minimizing the form error. From the above analysis, it is clearly seen that the spindle runout plays a dominant role in the surface location error. Therefore, the development of the online measurement technique for spindle runout is crucial for improving the machining accuracy in micro-end milling.

6. Micro-end milling experiments for verification

In order to validate the process planning strategy presented in this article, micro-end milling tests were performed with two-fluted, solid carbide micro-end mills to make the rounded square pocket shown earlier in
Fig. 8. The micro-end mill has 508 μm nominal diameter, 30° helix angle, and 10° clearance angle. Tests were conducted on Microlution 310-S, a high precision, 3-axis computer numerical control (CNC) micromilling machine tool specifically designed to manufacture small parts. The machine provides 2 μm positioning accuracy throughout its 63 mm travel in the X, Y, and Z directions, enabled by 20 nm resolution optical linear encoders. Each axis is driven by high specific-force linear motors to provide up to 2G acceleration, which is critical to the contouring performance. An electrically driven, air-bearing NSK Astro E800Z spindle, featuring a maximum speed of 80,000 rpm, is mounted on the Z axis using a kinematic mounting system. Figure 12 shows the experimental setup.

First, a roughing operation was conducted to remove most of the material and leave 20 μm on the side for finishing operation. The process conditions for the roughing operation were selected based upon the optimization analysis presented in Section 4. A MRR of 16 mm³/min is achieved with a spindle speed of 40,000 rpm, feed rate of 1600 mm/min (20 μm/tooth), an axial depth of cut of 100 μm, and a radial depth of cut of 100 μm. The operation takes about 10 s. Six pockets were manufactured without much tool wear. Five of the pockets were further processed with finishing profiling. A range of the conditions as listed in Table 3 were used to test the effectiveness of the model-based process planning strategy. To reduce the effect of the spindle runout, the effective tool diameter was estimated by measuring the diameter of a hole pecked by the micro-end mill using a non-contact metrology system: Mitutoyo Quickvision Apex system. The effective diameter was estimated to be 513 μm (indicating a 2.5 μm dynamic runout) and was used to generate the numerical control (NC) code to compensate the spindle runout. The surface location errors (SLE) were then obtained with the same metrology system by taking the measurements of the width of the pocket W. For each pocket, five measurements were taken for the width and averaged. The SLE can be computed as

\[
SLE = \frac{W - W_o}{2},
\]

where \(W_o\) is the nominal pocket width of 3 mm. Figure 13 shows the image of the round corner of the machined pocket taken by the vision-based metrology system.

The experimental results were summarized in Table 3. It is noticed that the SLEs are positive (overcut) for tests 1–3, which use lower ADOC of 50 μm, while the SLEs are negative (undercut) for tests 4 and 5, which use higher ADOC of 150 μm. The model prediction suggests that the tests 1–3 have negligible SLE if spindle runout was compensated. The positive SLE is very likely caused by the overcompensation due to the measurement error in the effective diameter. However, the overall trend of larger negative SLE (undercut) with higher ADOC matches well with the model predictions.

7. Conclusions

In process planning for micro-end milling, selection of axial depth of cut and feed per tooth are critical in achieving good machining performance in terms of cutting forces, surface accuracy, and tool effectiveness. Process models can provide performance measures such as forces, stresses and temperatures generated, minimum chip thickness required, surface form, and accuracy. In this study, an analytical workpiece material-based model is used for predicting minimum chip thickness for various cutting condition and tool geometry. Further, a mechanistic time-domain simulation model is used to predict peak-to-valley forces, surface form error, and accuracy. A generalized process planning strategy that consists of two steps (roughing and finishing) is proposed. In roughing, the objective is to control the cutting force within a predefined threshold to prevent premature tool breakage and to maximize the material removal rate. In finishing, the primary objective

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is to control the form error within the tolerance and to obtain satisfactory surface roughness. The proposed process planning strategy was applied for micromilling of a square pocket as mold cavity in 2024-T6 aluminum and feasible ranges of process parameters for roughing and finishing were determined. Micro-end milling experiments were conducted to validate the process planning scheme.

REFERENCES