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# Numerical Simulation of Chip Ploughing Volume and Forces in 5-axis CNC Micro-milling Using Flat-end Mills

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## Abstract

It is a challenging task to avoid ploughing effects in micro-milling. When one tooth of the cutting tool crosses the minimum chip thickness boundary, the tool would enter into the ploughing zone with no chip formation. Therefore, it is significant to predict the ploughing volume and forces in micro-milling. In this work, the ploughing mechanism for micro-milling is proposed by considering the minimum chip thickness effects. A 3D chip geometry is developed to calculate chip thickness, ploughing volume and ploughing forces in micro 5-axis flat-end milling with a flat-end mill. The local parallel sliced tool based method is then applied to get cutter-workpiece engagement domain where the cutting flutes entry and exit the workpiece, minimum chip thickness and depth of cut are required to predict ploughing forces. Local parallel sliced method divides the cutting tool into several slices that are perpendicular to the tool axis along the local coordinate system. On each layer, the removal chip area is dividing into ploughing zone and shearing zone by the minimum chip thickness. Ploughing zone is the area as chip thickness is less than the minimum chip thickness. In the shearing zone, chip thickness is larger than the minimum chip thickness. The total chip ploughing volume is obtained by adding all ploughing area along axial direction.

*Keywords:* Ploughing volume, ploughing forces, 5-axis, Micro-milling, Flat-end mill

## 1 Introduction

Comparing with traditional 3-axis micro-milling, 5-axis CNC micro-milling is widely applied in biomedical, automotive, aerospace and electronics industries with the ability to potentially provide better tool accessibility to complex surfaces, reduce machine setup time, produce high surface quality

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and increase material removal rate (Lin, et al., 2009). Machining dynamic research plays a significant role when high efficiency is required (Erdim, et al., 2006; Erdim, et al., 2007; Ozturk, et al., 2007). The kinematics of tool motions is the most investigated aspect when smoothly changes of tool orientation are needed. In 5-axis CNC micro-milling, the tilt and lead angles affect mechanics and dynamics of the machining process in terms of cutting forces, cutting forces coefficients, torque, chip thickness, stability, and tool breakage (Ozturk, et al., 2009). Small micro tools with low cutter stiffness can easily cause tool breakage and wear if machining parameters are not proper selected (Bono, et al., 2002).

It is difficult to avoid ploughing effects in micro-milling with low feed rate and small uncut chip thickness. Unlike traditional macro-milling, chip thickness is not always larger than the cutting edge radius in micro-machining. Ikawa (Ikawa, et al., 1992) defined the minimum chip thickness as the minimum undeformed chip thickness at a cutting edge under perfect performance of the machine tool without system deflection and tool wear out. Ploughing domain or zone is the area which the chip thickness is less than the minimum chip thickness. In micro-milling, the minimum chip thickness is relative with cutting edge radius. The influence of minimum chip thickness is significant if the cutting tool enters into a ploughing zone, since no material would be removed in ploughing zone (Weule, et al., 2001). The effects of minimum chip thickness have been studied by many researchers. Vogler (Vogler, et al., 2005) discussed the effects of minimum chip thickness by cutting experiments. It was discovered that chip formation occurs only as the chip thickness is larger than the minimum chip thickness and no chip is formed if the feed rate is low and the minimum chip thickness is not exceeded. Jun (Jun, et al., 2006) proposed that the effects of tool edge radius to the chip formation mechanisms. The effects of ploughing to cutting dynamics and minimum chip thickness were investigated by a chip thickness model with considering the elastic-plastic and elastic recovery in the ploughing process. Ramos (Ramos, et al., 2012) investigated that ploughing effects influence the chip formation process, burr formation, surface roughness and residual stress. The minimum chip thickness is decreased while the cutting velocities are enlarged and it is increased with higher cutting tool edge radii.

Ploughing force is defined as zero-feed force by Stevenson (Stevenson, 1998). Ploughing forces induced by cutting edge radius lead to the wear of the cutting tool in micro machining and increase cutting forces and surface roughness at low feed rate (Jun, et al., 2006). Predicting ploughing forces are significant in tool wear monitoring, chip formation mechanism and machined surface integrity (Guo, et al., 2004). The ploughing force calculating can also be used to choose optimal cutting parameters such as feed rate, depth of cut. It is challenging to obtain ploughing forces directly from measured cutting forces data; however, there are still some techniques to determine ploughing force. The extrapolation method (Albrecht, 1960; Hsu, 1966) is applied to get ploughing forces at zero-feed by plotting force data vs. feed rate at constant cutting speed and get zero-feed by extrapolation. However, this method cannot get the exact ploughing forces, due to the chip thickness, the strain, tool wear and the temperature were not considered. To improve the extrapolation method, Stevenson (Stevenson, 1997) proposed the zero-feed method to estimate ploughing forces based on the local maximum force of the cyclic force after the end of steady-state cutting. But the cyclic force cannot guarantee consistently in many cutting conditions. Guo (Guo, et al., 2004) predicted the ploughing force by extrapolation method and zero-uncut chip thickness. The ploughing force was used to correct the estimate of material flow stress. Lipatov (Lipatov, et al., 2010) presented the comparison method of total forces at various levels of the rear surface of the tool wear. But Popov (Popov, et al., 2014) proved that the extrapolation method on zero uncut chip thickness had greater accuracy than the comparison method.

Uncut chip thickness is an important parameter to calculate ploughing cutting forces. For 3-axis CNC machining using a flat-end mill, chip thickness is constant along the axial direction, and chip volume calculation is relatively simple by discretizing the tool axially. However, in 5-axis CNC machining using a flat-end mill, due to the inclination and ration angles, the contact area between

cutter and part surface changes all the time, causing challenges to calculate chip volume and engagement zone. Knowing values of removed chip volume can help choose optimal cutting parameters. Comparing the ploughing volume and shearing volume with different feed rates, it can be easily know how much material is removed and how much material is unremoved. For high feed rate, more shearing volume or removed material is obtained, and the ploughing volume or uncut material is few, which means the machining efficiency is high. Therefore, chip thickness and chip volume calculation using flat-end mill in 5-axis CNC machining should be studied to offer another approach to select optimal cutting parameters.

There are many researches about ploughing effects in 3-axis micro milling but very limit studies in 5-axis flat-end micro machining due to the complexity of cutter-workpiece contact geometry. The object of this work is to develop a new 3D chip model with micro flat-end mill to accurately calculate the chip ploughing volume and cutting forces.

## 2 Chip Geometry of 5-axis Micro Flat-end Mill

Chip thickness and volume calculation for macro 5-axis flat-end milling by local parallel sliced method is presented in the previous paper (Luo, et al., 2015). This method can also be used in micro 5-axis flat-end milling. The projection of a flat-end mill on a plane is an ellipse. The formula of the ellipse is relative to the two neighbouring NC points, which are denoted by  $(x_{i-1}, y_{i-1}, z_{i-1}, \alpha_{i-1}, \beta_{i-1})$  and  $(x_i, y_i, z_i, \alpha_i, \beta_i)$ .  $x, y, z$  are coordinates of the tool,  $\alpha$  and  $\beta$  are two rotational angles. The equations of the ellipse at the  $i^{th}$  NC point can be got from (Luo, et al., 2015):

$$X_{ellipse} = r \cos \phi \cos \beta_i - r \sin \phi \sin \beta_i \cos \alpha_i + \sin \beta_i \sin \alpha_i \frac{h_i - r \sin \phi \sin \alpha_i - \Delta z_i}{\cos \alpha_i} + \Delta x_i \quad (1)$$

$$Y_{ellipse} = r \cos \phi \sin \beta_i + r \sin \phi \cos \beta_i \cos \alpha_i - \cos \beta_i \sin \alpha_i \frac{h_i - r \sin \phi \sin \alpha_i - \Delta z_i}{\cos \alpha_i} + \Delta y_i \quad (2)$$

$$Z_{ellipse} = |h_i| \quad (Z_{min} \leq h_i \leq 0) \quad (3)$$

where  $r$  is the tool radius,  $\phi$  is the immersion angle,  $\alpha_i$  is lead angle,  $\beta_i$  is tilt angle,  $h_i$  is height of the plane,  $\Delta x_i$  and  $\Delta y_i$  are translation steps along  $x$  and  $y$  axes at the  $i^{th}$  NC point.

Figure 1 (a) shows the process of modeling chip geometry in a 5-axis CNC machining using a micro flat-end mill. Chip thickness is obtained by identifying intersections of tool edges at the previous tool position (denoted by  $O_{i-1}-X_{i-1}-Y_{i-1}-Z_{i-1}$ ) and the current tool position (represented by  $O_i-X_i-Y_i-Z_i$ ). Numerical method is used to get the intersections of tool edges and chip thickness by slicing the tool into many slices along the direction which is vertical to tool axis. In Figure 1 (b), it shows the instantaneous chip thickness distribution on one layer.  $C_i$  and  $C_i'$  are the current and previous tool centers on the  $i^{th}$  layer.  $P_{i,k}$  is the  $k^{th}$  interval point on the current tool's cutting edge,  $P_{i,k}'$  is the intersection of line segment  $C_i P_{i,k}$  and tool edge at previous position.  $\phi_k$  is the immersion angle at the  $k^{th}$  interval point.



### 3 Chip Ploughing Area/Volume by Local Parallel Sliced Method

Figure 1 (a) illustrates a chip shape is divided many layers along the direction which is perpendicular to the current tool axis. From Figure 1 (b), it can be seen that on each layer, the removal chip area is a polygon shape generated by connecting two neighboring edge points  $P_{i,k}$  and  $P_{i,k}'$  on the current and precious tool edges. Ploughing area is obtained by connecting edge points which chip thickness is less than the minimum chip thickness  $t_{cmin}$ . It is expressed in the following equation:

$$A_{ploughing} = \sum_{k=1}^s P_{i,k} P_{i,k+1} \times P_{i,k} P_{i,k}' + \sum_{k=t}^{M-1} P_{i,k} P_{i,k+1} \times P_{i,k} P_{i,k}' \quad (6)$$

where  $M$  is the number of interval points on each layer;  $t$  and  $s$  are the index of edge points which chip thickness starts and exits to be less than the minimum chip thickness. The shearing area shown in Figure 1 (b) is the area as the chip thickness is larger than the minimum chip thickness.

$$A_{shearing} = \sum_{k=s+1}^{t-1} P_{i,k} P_{i,k+1} \times P_{i,k} P_{i,k}' \quad (7)$$

A chip shape is composed by many parallelepipeds. Total chip volume can be obtained by adding volume of all parallelepipeds along axial direction. Total ploughing volume is integrated by adding all parallelepipeds which the length along radial direction is smaller than the minimal chip thickness. Figure 2 shows the chip modeling of ploughing and shearing volume. The equation of total chip ploughing volume is defined by:

$$V_{ploughing} = \sum_{k=1}^s \sum_{i=1}^{N-1} P_{i,k} P_{i,k+1} \times P_{i,k} P_{i,k}' \times \Delta z + \sum_{k=t}^{M-1} \sum_{i=1}^{N-1} P_{i,k} P_{i,k+1} \times P_{i,k} P_{i,k}' \times \Delta z \quad (8)$$

where  $M$  is the number of interval points on each layer,  $N$  is the number of slices;  $\Delta z$  is the integrating height along current tool axis.

The shearing volume can be obtained by adding all parallelepipeds which the length along radial direction is larger than the minimal chip thickness.

$$V_{shearing} = \sum_{k=s+1}^{t-1} \sum_{i=1}^{N-1} P_{i,k} P_{i,k+1} \times P_{i,k} P_{i,k}' \times \Delta z \quad (9)$$

The total volume is the sum of ploughing volume and shearing volume:

$$V_{total} = V_{ploughing} + V_{shearing} \quad (10)$$

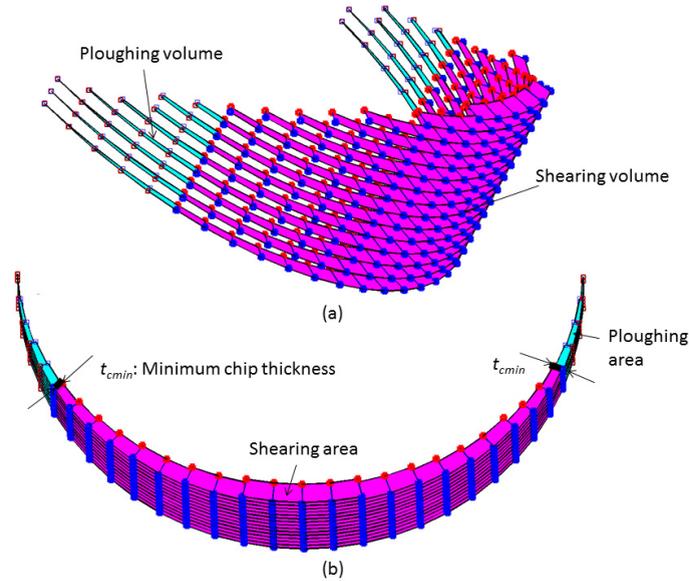


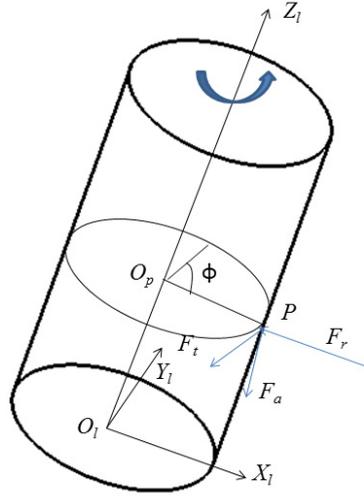
Figure 2: (a) ploughing and shearing volume; (b) ploughing and shear areas on layers

## 4 Ploughing Cutting Forces

Predicting ploughing cutting force accurately is significant to the machine dynamics research and it is the foundation to determine optimal cutting parameter. The ploughing cutting force prediction mainly consists of the instantaneous undeformed chip thickness calculation and cutter-workpiece engagement feature extraction such as entry/exit angles. A numerical technique is used to slice the cutter into many discs and sum the differential cutting forces along the immersion angle and axial depth of cut for each tool motion along a tool path.

For five-axis CNC machine, ploughing cutting forces are relative to chip thickness, cutting coefficient, feedrate, two rotation angles. Chip thickness is also a significant parameter for chip volume. The following steps demonstrate the chip volume calculation:

- 1) Model removed chip model (shown in Figure 3) and calculate chip thickness
- 2) Get Engagement area to calculate immersion angle or start and exit angles
- 3) Calculate cutting forces in tangential, radial and axial directions with cutting coefficients in local coordinate system (LCS)
- 4) Transform cutting forces from local coordinate system (LCS) to world coordinate system (WCS)



**Figure 3:** Cutting force model of a flat-end mill

For a given NC point on the flat-end milling, the three differential cutting forces radial ( $F_r$ ), axial ( $F_a$ ) and tangential ( $F_t$ ) are given by the following equation (Makhanov, et al., 2007; Ozturk, et al., 2007; Budak, et al., 2009):

$$\begin{aligned} dF_r &= (K_{rc} \times t_c + K_{re}) \times dz \\ dF_a &= (K_{ac} \times t_c + K_{ae}) \times dz \\ dF_t &= (K_{tc} \times t_c + K_{te}) \times dz \end{aligned} \quad (11)$$

where  $K_{rc}$ ,  $K_{ac}$ , and  $K_{tc}$  are the radial, axial and tangential cutting force coefficients, and  $K_{re}$ ,  $K_{ae}$ , and  $K_{te}$  are the edge force coefficients, determined by experimental tests and the workpiece material properties.  $dz$  is the integrating height along z-axis.  $t_c$  is the instantaneous undeformed chip thickness given in Eq. (5). To calculate ploughing forces, the chip thickness  $t_c$  should be less than the minimal chip thickness  $t_{cmin}$ .

In the feed coordinate system, ploughing cutting forces are obtained by transforming the differential radial, axial and tangential forces using the immersion angle  $\phi$ :

$$\begin{aligned} dF_{xl} &= -dF_t \cos \phi(i, k, n) - dF_r \sin \phi(i, k, n) \\ dF_{yl} &= dF_t \sin \phi(i, k, n) - dF_r \cos \phi(i, k, n) \\ dF_{zl} &= dF_a \end{aligned} \quad (12)$$

Forces in the local coordinate system are then transformed into world coordinate system (WCS) to compare forces measured by dynamometer.

$$\begin{bmatrix} dF_{xw} \\ dF_{yw} \\ dF_{zw} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \alpha & -\sin \alpha \\ 0 & \sin \alpha & \cos \alpha \end{bmatrix}^{-1} \times \begin{bmatrix} \cos \beta & -\sin \beta & 0 \\ \sin \beta & \cos \beta & 0 \\ 0 & 0 & 1 \end{bmatrix}^{-1} \times \begin{bmatrix} dF_{xl} \\ dF_{yl} \\ dF_{zl} \end{bmatrix} \quad (13)$$

where  $\beta$  and  $\alpha$  are rotation angles by z and x axes. Finally, differential ploughing forces in the feed coordinate system are summed for all layers in a tool path segment. For shearing force calculations, it has similar formulas with ploughing forces. The only difference is that selecting chip thickness which is larger than the minimum chip thickness.

## 5 Cutting Constants and Edge Constants Calculations

This following section introduces the method to calculate cutting constants ( $K_{rc}$ ,  $K_{ac}$ ,  $K_{tc}$ ) and edge constants ( $K_{re}$ ,  $K_{ae}$ ,  $K_{te}$ ) using experiment data with different feed rate. They are required to calculating forces. The experiment was conducted in a 3-axis ALIO micro-milling machine with a spindle speed of 12,000 rpm and different feed rates from 700 mm/rev to 1200 mm/rev. A four-flute flat-end mill with a diameter of 2 mm was used to cut an AL 6061 workpiece with slot machining. The depth of cut is 0.8 mm. The cutting forces were measured and the average forces were given in Table 1. Assuming the force model is given in Eq. (14) (Altintas, 2012):

$$\begin{aligned} F_t &= K_{tc}ah + K_{te}a \\ F_r &= K_{rc}ah + K_{re}a \\ F_a &= K_{ac}ah + K_{ae}a \end{aligned} \quad (14)$$

**Table 1:** Cutting parameters for slot machining in 3-axis micro-milling

feedrate (mm/rev)	spindle speed (rpm)	feed per tooth (mm/tooth)	depth of cut (mm)	immersion angle (°)	Average Fx (N)	average Fy (N)	average Fz (N)
700	12000	0.0146	0.8	180	-24.6393	2.8470	2.7050
800	12000	0.0167	0.8	180	-25.4856	3.5036	3.3974
900	12000	0.0188	0.8	180	-25.6002	3.9009	3.5197
1000	12000	0.0208	0.8	180	-25.7261	4.0828	3.6230
1100	12000	0.0229	0.8	180	-25.9135	4.4313	3.4066
1200	12000	0.0250	0.8	180	-26.2096	4.5467	3.5082

Full immersion milling experiments are most convenient. Here the entry and exit angles are equal 0 and  $\pi$  respectively. Full immersion conditions are applied into (15). (Altintas, 2012), the average forces per tooth period are simplified as

$$\begin{aligned} \overline{F_x} &= -\frac{Na}{4}K_{rc}h - \frac{Na}{\pi}K_{re} \\ \overline{F_y} &= \frac{Na}{4}K_{tc}h + \frac{Na}{\pi}K_{te} \\ \overline{F_z} &= \frac{Na}{\pi}K_{ac}h + \frac{Na}{\pi}K_{ae} \end{aligned} \quad (15)$$

where  $N$  is number of cutting flutes,  $a$  is the axial depth of cut,  $K_{rc}$ ,  $K_{ac}$  and  $K_{tc}$  are radial, axial and tangential cutting constants. The average cutting forces in  $x$ ,  $y$  and  $z$  direction are obtained from **Table 1**. They are plot in the Figure 4.

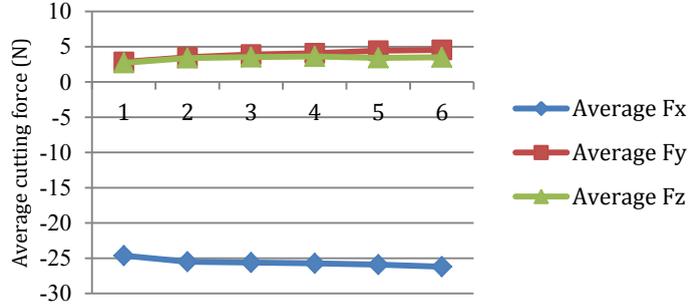


Figure 4: Average cutting forces for different groups

Compare Eq. (14) and Eq.(15), it can get the radial, axial and tangential cutting constants:

$$K_{rc} = -\frac{4F_x}{Na}; \quad K_{tc} = \frac{4F_y}{Na}; \quad K_{zc} = \frac{\pi F_z}{Na} \quad (16)$$

The linear interpolation function of average force in x-axis is obtained from the six groups' data of average forces and feed rates, shown in Figure 5 (a). The interpolation function is given in (17).

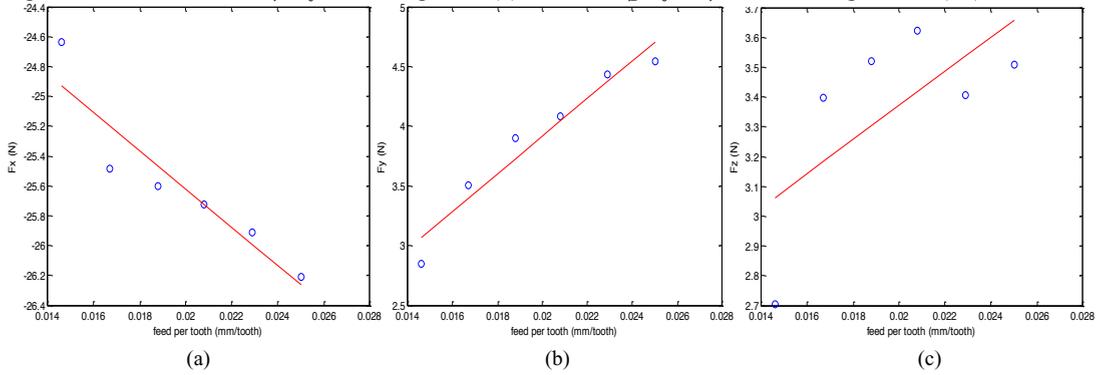


Figure 5: Linear function of feed rate and an offset contributed by the edge forces  $F_{xc}$ ,  $F_{ye}$  and  $F_{zc}$

$$y = \overline{F_{xc}}x + \overline{F_{xe}} = -127.7x - 23.1 \quad (17)$$

Substitute the values of  $\overline{F_{xc}}$  and  $\overline{F_{xe}}$  from (17) to Eq. (18) and Eq. (15), it can get the values of  $K_{rc}$  and  $K_{re}$ :

$$K_{rc} = -\frac{4\overline{F_{xc}}}{Na} = -\frac{4 \times -127.7}{4 \times 0.8} = 159.6 \quad (18)$$

$$K_{re} = -\frac{\pi\overline{F_{xe}}}{Na} = -\frac{4 \times -23.1}{4 \times 0.8} = 22.7$$

The linear interpolation function of average force in y-axis is shown in Figure 5 (b). The interpolation function for average force  $\overline{F_y}$  is given in (19).

$$y = \overline{F_{yc}}x + \overline{F_{ye}} = 157.98x + 0.76 \quad (19)$$

Substitute the values of  $\overline{F_{yc}}$  and  $\overline{F_{ye}}$  from Eq. (19) to Eq. (18) and Eq. (15), it can get the values of  $K_{tc}$  and  $K_{te}$ :

$$K_{tc} = \frac{4\overline{F_{yc}}}{Na} = \frac{4 \times 157.98}{4 \times 0.8} = 197.5 \quad (20)$$

$$K_{te} = \frac{\pi\overline{F_{ye}}}{Na} = \frac{4 \times 0.76}{4 \times 0.8} = 0.75$$

The linear interpolation function of average force in z-axis is shown in Figure 5 (c). The interpolation function for average force  $\overline{F_y}$  is given in Eq. (21).

$$y = \overline{F_{zc}}x + \overline{F_{ze}} = 57.2x + 2.2 \quad (21)$$

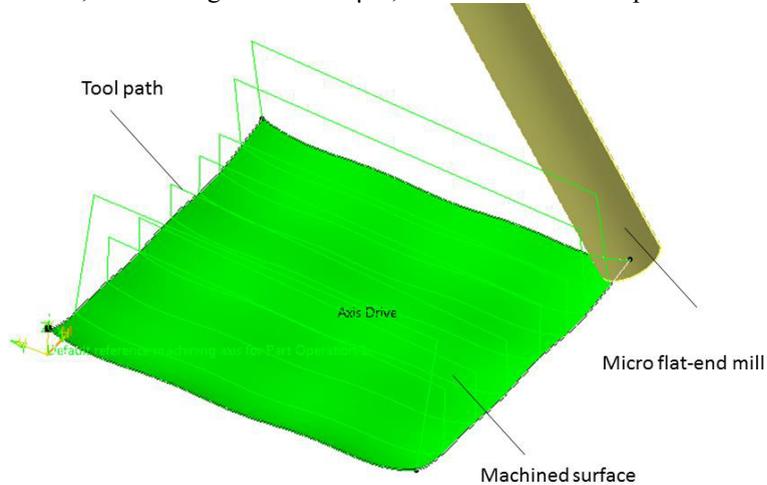
Substitute the values of  $\overline{F_{zc}}$  and  $\overline{F_{ze}}$  from Eq. (21) to Eq. (18) and Eq. (15), it can get the values of  $K_{ac}$  and  $K_{ae}$ :

$$K_{ac} = \frac{\pi\overline{F_{zc}}}{Na} = \frac{4 \times 57.2}{4 \times 0.8} = 56.2 \quad (22)$$

$$K_{ae} = \frac{2\overline{F_{ze}}}{Na} = \frac{2 \times 2.2}{4 \times 0.8} = 1.4$$

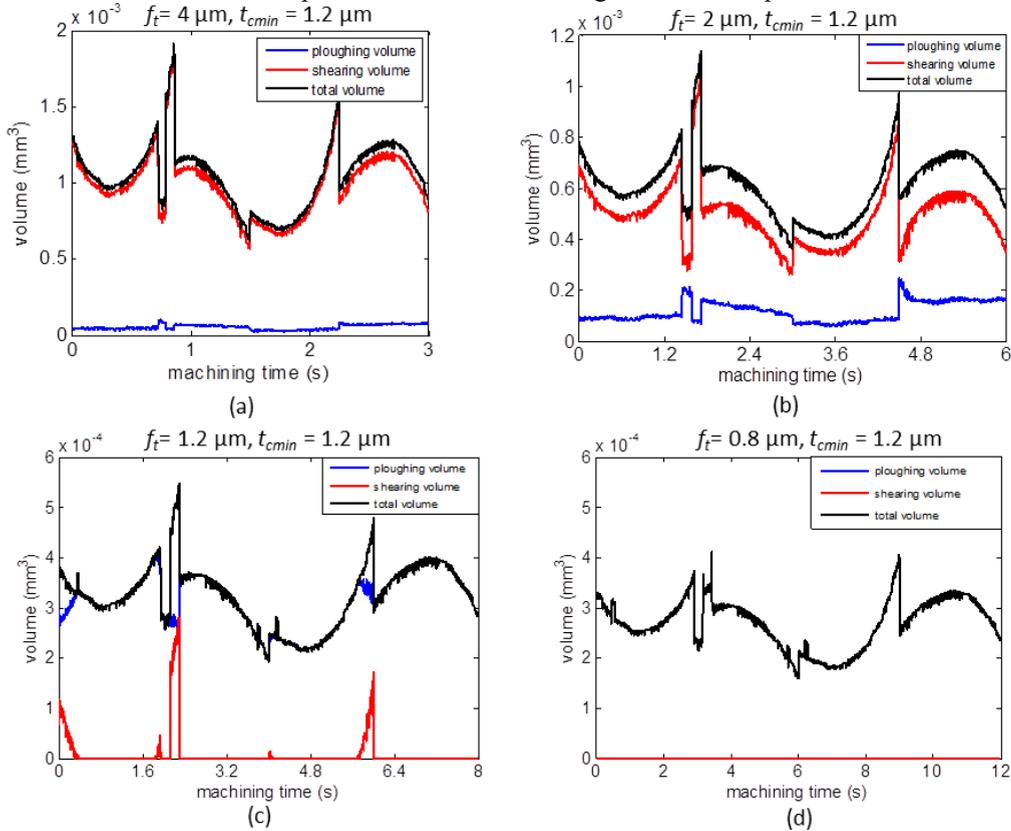
## 6 Case Studies and Results

In this section, a 5-axis micro CNC machine is used to simulate chip ploughing volume and ploughing cutting forces. A free form surface shown in Figure 6 is machined by a two flutes flat-end mill, with a tool diameter of 1/32". The length, width and height of the workpiece size are 5 × 5 × 3 mm. The depth cut varying from 0.1 mm to 2 mm. The spindle speed is selected as 30,000 rpm, and the feed rate is 4 μm/tooth, the tool edge radius is 4 μm, and the minimum chip thickness is 1.2 μm.



**Figure 6:** A free-form surface in micro machining with flat-end mill

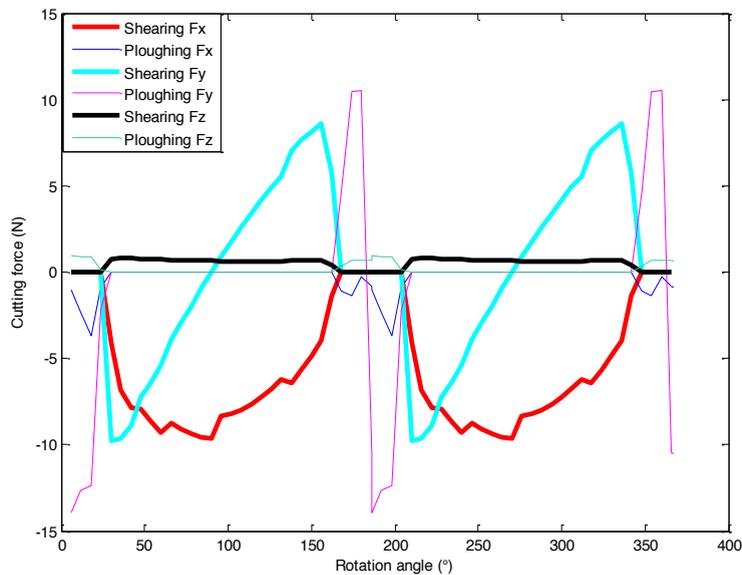
The one-way tool paths for the free-form surface are generated in CAM software with surface normal as the tool orientation method. NC points got by CAM software are required to be interpolated with uniform distance of feed per tooth to calculate cutting forces and chip volume.



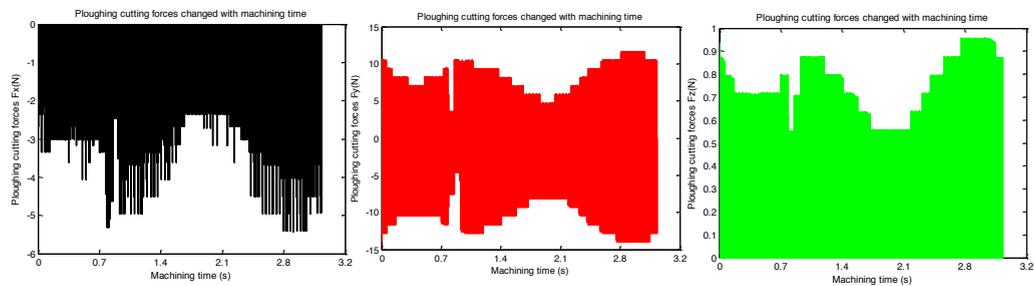
**Figure 7:** Comparison of total, ploughing and shearing volume: (a) feed per tooth is 4μm; (b) feed per tooth is 2μm; (c) feed per tooth is 1.2μm; (d) feed per tooth is 0.8μm;

Ploughing and shearing volume are obtained from Eqs. (8) and (9). Total volume is the sum of ploughing and shearing volume. Figure 7 shows the total, ploughing and shearing volume are changes with machining time for the whole tool path in different feed rates. From Figure 7 (a) and (b), it can be seen that the ploughing volume increase as the feed per tooth decreases. Therefore; ploughing effects become serious at low feed rate. In Figure 7 (c), as the feed per tooth is equal to the minimum chip thickness, most of the shearing volume is zero, which means not too much material is removed. As the feed per tooth is less than the minimum chip thickness, no material is removed at all. The results are shown in Figure 7 (d): only ploughing volume exists. All shearing volume is zero, so the total volume is the ploughing volume.

From Eqs. (11), (12) and (13), it can get the ploughing and shearing cutting forces. In Figure 8 shows the ploughing forces change with rotation angles in one revolution. The ploughing forces for the whole toolpath are illustrated in Figure 9.



**Figure 8:** Ploughing and shearing forces in  $x$ ,  $y$  and  $z$  directions change with rotation angle in one revolution.



**Figure 9:** Ploughing forces for the whole tool path

## 7 Conclusions

The local parallel sliced method is applied to model 3D chip geometry to calculate ploughing chip volume and cutting forces in micro 5-axis flat-end milling. To get the ploughing volume and cutting forces, the cutter is divided into many layers. Chip thickness is a very important parameter for chip volume calculation. It can be obtained by removing the tool a distance of feed per tooth. Ploughing and shearing volume are calculated by adding volumes of small pieces of parallelepipeds along radial and axial direction. 5-axis simulation of cutting forces and chip volume has been carried out for milling cases that tool orientation and depth of cut change continuously. To better understand the ploughing effect problems in micro machining and to increase cutting efficiency, different feed rate were simulated to reduce the ploughing volume. The simulation cases led to the conclusion that high feed rate can reduce ploughing effect. As the feed per tooth is smaller than the minimum chip thickness, only ploughing volume exists. No material is machined in the ploughing zone.

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