An innovative investigation on chip thickness model with application to cutting forces modelling in micro milling

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INTRODUCTION
Modelling of cutting forces in micro milling is a critical aspect of the research interest. Due to the scaling down of the milling cutter from an mm-level to µm-level and the associated machining parameters, many issues appear showing different phenomenon which cannot be appropriately explained by the conventional macro cutting mechanics. Extensive research has been undertaken to understand the fundamental cutting mechanism in micro-milling. Bao etc. first introduced an analytical model to calculate the instantaneous chip thickness based on which cutting forces were predicted [1]. Later many researchers included Minimum Chip Thickness (MCT) effect in modelling and divided chip formation into two separate regimes: ploughing dominant regime and shearing dominant regime [2-4]. Minimum Chip Thickness not only relies on the workpiece material, but is strongly dependent on the cutting edge radius [5]. Besides, machine dynamic and spindle runout also add variation to real chip thickness. Thus accurate determination of the chip thickness is essential and very much needed particularly in modelling cutting forces. This paper attempts to investigate an innovative approach to model chip thickness combined with tool run-out in micro milling with further application to cutting force modelling and cutting process optimizations.

MINIMUM CHIP THICKNESS
In micro cutting, when chip thickness decreases beyond certain threshold (MCT), no chip will be generated, workpiece material undergoes ploughing/rubbing and plastic deformation. Conditions are more complicated with cutting edge entering and exiting workpiece periodically. Efforts have been made by different methods to determine minimum chip thickness, where cutting transits from material ploughing to shearing. Kim applied an experimental technique to estimate the MCT based on recorded cutting forces [6], the chip formation model proposed in [4] is adopted. When chip forms, material goes through 3 cutting mechanisms, pure elastic deformation, mixed elastic-plastic deformation and complete removal. When instantaneous chip thickness is lower than certain value \( t_{c0} \), material deforms elastically and will fully recover; as chip thickness increases, tool edge ploughs over material, and a constant percentage of \( \rho \) of the material recovers; when chip thickness reaches \( t_{c\text{min}} \) (MCT), material is removed as a chip and \( \rho \) drops to zero.

A simplified criteria proposed by Johnson for quasi-static indentation was used to obtain the \( t_{c0} \). The ratio of \( t_{c0} \) to the cutting edge radius \( r_e \) for metals was computed as

\[
t_{c0} / r_e = 1/2(2\sigma/E)\text{ } (1)
\]

where \( E \) is Young’s modulus and \( \sigma \) is the yield strength of the material.

Minimum Chip Thickness is defined by following equation [7]

\[
t_{c\text{min}} / r_e = 0.5 - \frac{T_a}{\sigma} \text{ } (2)
\]

where \( T_a = \frac{0.427}{3} L_m \rho \ln \left( \frac{T_m}{T_2} \right) \)

where \( L_m \) is the latent heat of melting (J/kg), \( \rho \) is the density of the material (kg/m³), and \( T_m \) is the melting point of the metal.

All the material coefficients can be found in literatures, while cutting edge radius \( r_e \) can be obtained with a SEM machine (see Figure 1).

FIGURE 1. SEM image of a micro-milling tool: topological profile and cutting edge

NEW CHIP THICKNESS MODEL INCLUDING TOOL RUN-OUT
As the chip thickness approaches micron-level, tool run-out adds additional fluctuation of chip
load, which can significantly change contact behavior between material and tool. Excessive run-out could lead to disengagement of cutting flute from substrate. Moreover, tool run-out also changes actual cutting tool geometry. Thus, tool run-out must be considered while accurately predicting cutting forces. Previous researchers created many models to calculate chip thickness under such conditions by decomposing tool runout and adding its components to the tool tip [1-4], however this fails to tackle the change of cutting geometry and to take the tooling system and workpiece as a whole. In this paper, a new algorithm is proposed based on the real engagement of the tool and substrate.

Tool position error may arise from many aspects including tool dynamics, manufacturing error, alignment error (tilt error and parallel offset). This paper will focus on tool parallel offset, which impacts chip load most significantly. The analysis is based on a two-fluted micro end mill. The diagram of the tool spinning with run-out of \( R \) at angle \( \alpha \) is shown below in figure 2 (top view).

\[
\begin{align*}
R_k &= \sqrt{R^2 + r^2 - 2Rr \cos\left(\frac{2\pi}{N} (k-1) + \alpha\right)} \quad (3)
\end{align*}
\]

where \( k \) is the tooth number, \( R \) is the nominal diameter, \( N \) is the number of flutes. It should be noticed that the real radius of cutting edge which engages material removal is \( R_1 \) and \( R_2 \). The trajectory of \( k \) th tooth may be written as

\[
\begin{align*}
x(t, k) &= ft / 60 + R_k \sin(\omega t - (k-1)\alpha) \\
y(t, k) &= R_k \cos(\omega t - (k-1)\alpha) \\
\end{align*}
\]

Zero angle is defined when 1st cutting edge aligns with y axis.

The two flutes alternatively remove chips from the workpiece. Suppose current tool tip which engages material at time \( t \) has the position angle \( \theta \), previous tool tip at time \( t \), locates at the point which forms current chip. \( t \), is determined with Newton-Raphson iterative methods. Then chip thickness can be formulated:

\[
h(\theta, k) = R_k + f(t - t_s) / 60* \sin(\theta) - \sqrt{R_i^2 - f^2(t - t_s)^2 \cos^2(\theta) / 36000} \quad (5)
\]

**DISCUSSION**

The existence of MCT results in that each tool path has to undergo elastic and plastic deformation before chip forms, leaving vicinities of entering and exiting point saw-tooth like profile. Moreover, additional tool run-out, as shown in Figure 2, can seriously change tool radius and cutting angle and real chip load. Thus considering these issues, innovative MCT modelling and associated algorithm is proposed toward micro milling, their in-depth details will be presented in the full paper submission.

**REFERENCES**


