Machining forces and tool deflections in micro milling

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Abstract

The analysis of cutting forces plays an important role for investigation of mechanics and dynamics of cutting process. The importance of force analysis is due to its major role in surface quality of machined parts. Presented force model calculates instantaneous chip thickness by considering trajectory of the tool tip while tool rotates and moves ahead continuously. The model also takes plowing force component into consideration relating it to elastic recovery based on interference volume between tool and workpiece. Based on the mathematical model, distribution of the force acting on the tool is calculated. It is known that this force will create deflection of the tool during cutting, which will result in imperfections of the final part. From this point of view, it is important to predict tool deflections in order to control the cutting process and to avoid failure of the tool. Both force and deflection models are validated on Aerospace Aluminum Alloy (Al-7050), through micro end milling experiments for a wide range of cutting conditions using micro dynamometer and laser displacement sensors.

Keywords: Micro milling; force model; deflection model; Aluminum 7050;

1. Introduction

Micro milling is extensively used machining method used in biomedical, micro sensor, actuator, micro dies and molds manufacturing sectors. Manufacturing of high quality parts, dies, and molds, having a miniature size and 3D complex geometry within desirable tolerances is becoming possible via micro machining. One of the major obstacles towards achieving higher productivity in this field is form errors. Significant amount of surface error on machined components is induced by cutter deflections.

This paper presents a method to analyze the cutter deflection due to the elastic compliance of micro end mill based on micro force model predicting generated forces during cutting process. The tool deflection responding to the cutting force was calculated by considering the cutter stiffness. The cutter was modeled as a multi cross sectional cantilever beam. It is clear that cutting forces will have the direct effect on the amount of cutter deflection, thus, force modeling for micro end milling becomes a key point.

Modeling of the micro milling forces has been studied by many researchers, in order to understand and control the process and, finally, to improve the part quality. Martellotti [1,2] established the basic theory about surface quality, cutting power and chip generation. Merchant [3] investigated the cutting forces in orthogonal cutting considering the shear angle, friction angle and tool rake angle. Stabler [4] suggested the chip flow rule that chip flow angle is equal to the inclination angle in oblique cutting based on experimental observations. Koenigsberger et al. [5,6] introduced the cutting force coefficients to predict the cutting forces under the assumption that the tangential component of cutting forces is proportional to the undeformed chip area. Vogler et al. [7] and Waldorf et al. [8] have developed shear plane plasticity model which is used as a tool for prediction of forces in micro milling. Based on these studies June [9] and Fang et al. [10] have developed more complex plasticity model which covers elastic recovery of plowed material. It should be noted that mechanistic models are efficient models for predicting forces during milling process. That is why force model used in this paper was developed as a...
mechanistic force model for predicting forces during micro milling.

Generated cutting force leads to tool deflection and unwanted form error of machined surface. Therefore, many researchers have tried to increase the form accuracy of the milled surface. P. Dépincé et al. [11] worked on the compensation of tool deflection using the mirror method. Larue [12,13], Ryu [14] proposed some methodology to predict surface deformation in end or flank milling and worked on form error prediction during the side wall machining. S. Ratchev et al. [15] investigated milling error in machining of low-rigidity parts. However, all of these researches were performed for conventional macro scale milling.

In this study, a new mathematical model is proposed to estimate cutting forces and cutter deflection of micro end-mill resulting in surface errors of the final workpiece.

2. Modeling

2.1. Force model

Presented force model is estimating differential cutting forces in the feed (y) and cross feed (x) directions for each engaging cutting flute. Due to the nature of the micro end milling there are two cutting mechanisms – cutting with chip formation and plowing without chip formation.

A comprehensive chip thickness model was developed by Li et al. [16]. The same chip thickness model is utilized in the developed force prediction model. The proposed chip thickness model is given below,

\[ h = R \sqrt{1 - \frac{2t_c \sin \theta}{R \left( \frac{t_c}{2} \cos \theta \right)^2} - \frac{t_c \cos (2\theta)}{\left( \frac{t_c}{2} \cos \theta \right)^2} - \frac{t_c \sin \theta \cos \theta}{\left( \frac{t_c}{2} \cos \theta \right)^2}} \]  

(1)

where \( R \) is the radius of the tool, \( N \) is number of flutes, \( t_c \) is feed per tooth and \( \theta \) is rotational angle. Using this formulation for calculating uncut chip thickness, force model for predicting forces during the micro milling process was established.

Formation of the chip during the cutting process mostly depends on the uncut chip thickness, if actual uncut chip thickness is less than minimum uncut chip thickness, which is represented as \( h_{\text{min}} \), then no chip formation occurs and process becomes plowing. However, if actual uncut chip thickness is greater than \( h_{\text{min}} \) then a shear dominant regime is present.

During the shear dominant regime the differential cutting forces are estimated using following formulation;

\[
\begin{bmatrix}
\frac{dF_{xs}}{dK_{te}} \\
\frac{dF_{xr}}{dK_{te}} \\
\frac{dF_{ys}}{dK_{re}} \\
\frac{dF_{yr}}{dK_{re}}
\end{bmatrix} = \begin{bmatrix}
\cos \phi & \sin \phi & 0 & 0 \\
-\sin \phi & \cos \phi & 0 & 0
\end{bmatrix} \begin{bmatrix}
K_{te} h(\theta) a \\
K_{re} h(\theta) a
\end{bmatrix}
\]  

(2)

where \( dF_{xs} \) and \( dF_{ys} \) are shearing components of differential x and y forces, \( K_{te} \) and \( K_{re} \) are cutting coefficients, \( K_{te} \) and \( K_{re} \) are edge coefficients, \( a \) is axial depth of cut, \( h \) is uncut chip thickness and \( \phi \) is transformation angle from feed to x-y coordinate system.

During the plowing dominant regime generated forces are related to the volume of the plowed material and are estimated using following formulation [17];

\[
\begin{bmatrix}
\frac{dF_{xp}}{dK_{tp}} \\
\frac{dF_{yp}}{dK_{rp}}
\end{bmatrix} = \begin{bmatrix}
\cos \phi & \sin \phi & 0 & 0 \\
-\sin \phi & \cos \phi & 0 & 0
\end{bmatrix} \begin{bmatrix}
K_{tp} A_p a \\
K_{rp} A_p a
\end{bmatrix}
\]  

(3)

above \( dF_{xp} \) and \( dF_{yp} \) are plowing components of differential x and y forces, \( K_{tp} \) and \( K_{rp} \) are plowing coefficients and \( A_p \) is plowed area which depends on height of elastically recovered material (\( h_{er} \)) which is described in Park et al. paper [17].

The total cutting forces during micro milling process can be expressed as

\[
F_x = \sum dF_{xs} + \sum dF_{xp}
\]  

(4)

\[
F_y = \sum dF_{ys} + \sum dF_{yp}
\]  

(5)

In the presented force model wear of the tool was not taken into consideration.

2.2. Deflection model

Tool is considered as a multi cross sectional cylinder with effective diameter in the fluted portion, which is 80% of nominal diameter of the tool. Forces obtained from force model are arranged in form of matrix, which occurs to be an input for deflection model. Tool is divided into discrete disks and from the force matrix elemental forces acting on the disk at each cutter position are calculated.

Tool is considered as a two dimensional Timoshenko beam element and solved by arranging the global element stiffness matrix \( K_e \) for a two dimensional Timoshenko beam element. \( c_e \), \( c_e \) and \( c_e \) are the inputs for the beam element that supply the element nodal coordinates, modulus of elasticity E, the shear modulus G, the cross section area A, the moment of inertia I and the shear correction factor \( k_s \).

The element stiffness matrix stored in global element stiffness matrix \( K_e \), is computed according to
Later element matrices are assembled and the global element stiffness matrix is added to the structure stiffness matrix $K$, according to the topology matrix $edof$.

$$K = \sum_{e=1}^{n} K_{e}$$

where $K_{e}$ is the element stiffness matrix, $n$ is the number of elements, and $edof$ is the element topology matrix.

$$\mu = \frac{12EI}{L^2AGK_e}$$

In order to have more precise result cutting portion of the tool, which is consequently exposed to cutting forces, is discretized in smaller elements. For each element, nodal forces and deflections are calculated in form of matrix, which can be plotted to see the instantaneous deflection of the cutter at desired position.

### 3. Experimental setup & validation

#### 3.1. Experimental setup

Experiments were conducted with aerospace grade Aluminum 7050 using 1.5 mm diameter 2 fluted Tungsten Carbide micro end mill on Mori Seiki NMV5000DCG 5-axis CNC milling machine and cutting forces were measured with table type mini dynamometer. Cutter deflection measurements of micro end mill were performed by laser displacement sensors. The experimental setup used for validation of force and deflection models is shown below in Fig 2.

![Fig. 2. Experimental setup](image)

#### 3.2. Model validation

Cutting experiments were performed on widely used engineering material Al-7050 at 20,000 rpm spindle speed and 300 μm depth of cut. Tool and material properties of the workpiece are given in Table 1.

<table>
<thead>
<tr>
<th>Tool and workpiece material properties</th>
</tr>
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<tbody>
<tr>
<td>Tool diameter</td>
</tr>
<tr>
<td>Helix angle</td>
</tr>
<tr>
<td>Depth of cut</td>
</tr>
<tr>
<td>Density of Al 7050 (ρ)</td>
</tr>
<tr>
<td>Elasticity modulus of Al-7050 (E)</td>
</tr>
<tr>
<td>Yield strength of Al-7050</td>
</tr>
</tbody>
</table>

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Fig. 1. Discretized model of micro end mill
Experimental forces were measured by dynamometer to validate the force model. It can be seen from Fig 3 and Fig 4 that the simulation results are in a very good agreement with experimental force measurements.

![Fig. 3. Simulated and experimental forces in x-direction for feed per tooth value of 20 μm](image)

The validation of the deflection model was performed by comparing predicted cutter deflection with instantaneously measured deflection of the tool. The measurements of deflection were performed at a point that was 1 mm away from the tool tip of the micro end mill and then were extrapolated to the tool tip in order to calculate maximum geometrical error and to compare with simulation results. Fig 5 shows that measured deflection of the micro end mill stays in the predicted deflection boundary of -40 μm and +45 μm deviation from nominal position. As it can be seen from Fig 5 maximum measured deflection varies from +39.34 μm to -38.99 μm for X axis and from 41.81 μm to -41 μm for Y axis. Based on that, it can be said that theoretical model for predicting deflection of the micro end mill gives reasonable result and is in a good correlation with experimental results of the deflection at the tool tip.

![Fig. 5. Simulated and experimental deflection values of the tool tip](image)

In order to validate the simulations, cutting experiments have been performed with same cutting conditions and the results of the experiments show that both force model and deflection model give a valuable information about forces and deflections generated during the cutting process.
4. Conclusion

In this paper, comprehensive force and deflection models for micro end milling were presented. The main focus were on prediction of cutting forces during micro end milling and estimating the deflection amount of the micro end mill occurred due to the cutting forces acting on the tool. Both force and deflection models were validated through the experiments and showed good agreement.

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