

# Prediction of Cutting Force and Tool Deflection in Micro Flat End Milling

Hye-Ri Gye, Byeong-Uk Song, Yong-Seok Lim, Yong-Wook Shin, Sung-Hui Jang, and Tae-Il Seo

**Abstract**—This paper presents an investigation of prediction of cutting force and tool deflection in micro flat end milling. To predict cutting forces specific cutting force coefficients  $K_T$  and  $K_R$  were used. In fact, various cutting forces prediction models were proposed in past researches for conventional sized machining processes. However, micro end-milling processes were known as different phenomenon as respect to macro end-milling. Many past researches concerned complicated different models for micro end-milling from macro end-milling. However, cutting force models for both macro and micro end milling were fundamentally based on measured cutting forces for a series of experimental machining processes. Then, cutting force model proposed by Thusty, which was developed for macro end-milling, was applied for micro flat end milling because this model is relatively simple. Finite element method was used to predict tool deflection based on predicted cutting forces. Predicted tool deflection amounts and actual machined profiles were compared each other in order to check out the differences between them.

**Index Terms**—Cutting force, micro end-mill, finite element method, tool deflection.

## I. INTRODUCTION

Recently ultra-precision micro patterns and shapes are widely used in a number of industrial fields [1]. Various processes based on semi-conductor processing techniques are used in fabrication of micro shapes and patterns, however mechanical cutting method has lately attracted considerable attention because of various available materials, flexibility of process and high-productivity. The main purpose of this study strongly concerned cutting force prediction processes for micro machining. In fact, various cutting forces prediction models were proposed in past researches for conventional sized machining processes [2]-[4]. However, micro end-milling processes were known as different phenomenon as respect to macro end-milling. Many past researches concerned complicated different models for micro end-milling from macro end-milling [5]-[7]. However, cutting force models for both macro and micro end milling were fundamentally based on measured cutting forces for a series of experimental machining processes. Then, in this paper cutting force model proposed by Thusty [2] and Lee [4] which was developed for macro end-milling, was applied for micro end milling because this model is relatively simple. This model will be installed platform system which can be

accessed by various users. To verify experimental micro flat end-milling processes were carried out and the composed results were presented in this paper.

## II. CUTTING FORCE PREDICTION MODEL

There were many researches about phenomenon of conventional end-milling using macro scale cutting tools. However it is difficult to apply these researches to micro end-milling processes because micro end mill size is quietly smaller than macro scale end mills. For this minimum chip thickness effect was studied by considering more significant size of tool tip nose radius than macro tools [5]-[6]. If micro end-milling phenomenon would be observed in a microscopic view point, the minimum chip thickness maybe certainly considered. In fact, cutting force prediction model was on the basis of a series of experimental works because it is very difficult to analytically estimate a relationship between a tool and a material, as known by tool-matter couple. Therefore, if resultant forces were predicted by measured cutting forces, it would be possible to apply the cutting force prediction model for macro scale end-milling to micro end-milling processes. In this paper a cutting force prediction model was applied as follows, which was developed on the basis of Thusty [2] and Lee models [4]. When  $S_t$  is feedrate per tooth and  $\Phi$  is engaged angle, chip thickness  $h$  can be depicted by Eq. 1.

$$\begin{aligned} h &= S_t \sin \Phi \text{ for down milling} \\ h &= S_t \sin(\Phi + \Phi_t) \text{ for up milling} \end{aligned} \quad (1)$$

Fig. 1 shows in cutting force components and geometric relationships of up and down milling. Considering instantaneous tangential and radial cutting force components  $K_T$  and  $K_R$ , tangential cutting force component  $F_t$  and radial cutting force component  $F_r$  can be depicted by (2).

$$F_t = K_T b h \text{ and } F_r = K_R b h \quad (3)$$

If  $\gamma$  is radius of cutting tool and  $\beta$  is helix angle of tool,  $dz$  can be depicted by (3).

$$dz = \frac{\gamma}{\tan \beta} d\Phi \quad (3)$$

The X-directional infinitesimal cutting force  $dF_X$  and Y-directional infinitesimal cutting force  $dF_Y$  can be arranged as (4) for down milling and (5) for up milling by (1)-(4).

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$$dF_X = \left\{ -\frac{K_T S_t \gamma}{\tan \beta} \sin^2 \Phi + \frac{K_R S_t \gamma}{\tan \beta} \sin \Phi \cos \Phi \right\} d\Phi \quad (4)$$

$$dF_X = \left\{ -\frac{K_T S_t \gamma}{\tan \beta} \sin \Phi \cos \Phi - \frac{K_R S_t \gamma}{\tan \beta} \sin^2 \Phi \right\} d\Phi$$

$$dF_X = \frac{K_T S_t \gamma}{\tan \beta} \sin^2(\Phi + \Phi_1) d\Phi$$

$$- \frac{K_R S_t \gamma}{\tan \beta} \sin(\Phi + \Phi_1) \cos(\Phi + \Phi_1) d\Phi$$

$$dF_Y = \frac{K_T S_t \gamma}{\tan \beta} \sin(\Phi + \Phi_1) \cos(\Phi + \Phi_1) d\Phi$$

$$+ \frac{K_R S_t \gamma}{\tan \beta} \sin^2(\Phi + \Phi_1) d\Phi \quad (5)$$

Therefore  $dF_X$  and  $dF_Y$  can be integrated according to different cutting regions as shown in Fig. 1. This cutting force model could be completed by experimentally measured cutting forces.

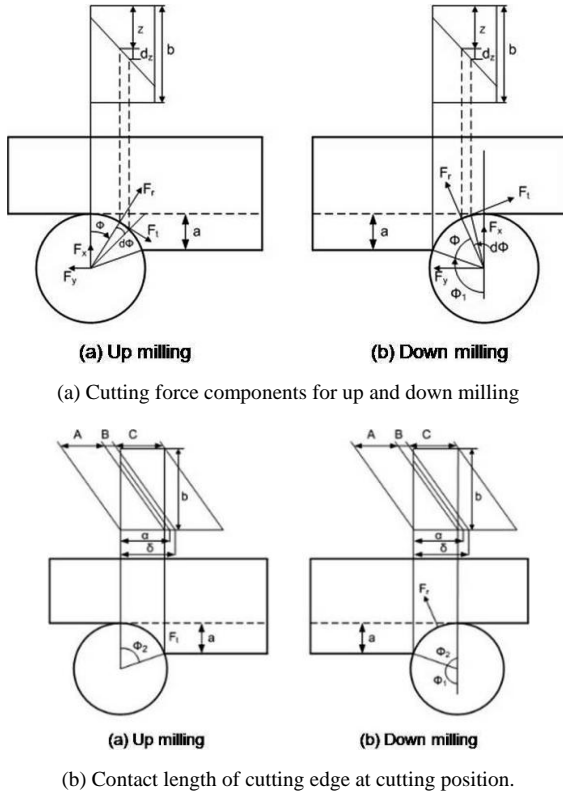


Fig. 1. Cutting force components and Contact length of cutting edge.

### III. EXPERIMENTAL WORKS

#### A. Micro End-Milling System

For experimental works of micro end-milling process, a micro machining stage was established as shown in Fig. 2, which has 3-axis of degree of freedom (X-, Y-, Z-axis) and can be controlled in sub-micro unit and the control resolution is  $0.1\mu\text{m}$ . A high speed spindle was used in experimental works. This spindle consists of air-bearings, AC Motor and an inverter, which can rotate until 100,000rpm. The air-bearing make the spindle cannot generate sufficient torque when tool diameter is relatively large; however the air-bearing allows rotating in high speed and micro

end-milling do not need large torque for cutting when using micro end-mills. For more information about the micro machining system was depicted in Table I.



Fig. 2. Micro end-milling system.

TABLE I: SYSTEM SPECIFICATION

Traveling range	X, Y-axis : 600mm, Z-axis : 200mm
Resolution	X, Y, Z-axis : $0.1\mu\text{m}$
Accuracy	X, Y-axis : $0.2\mu\text{m}$
Repeatability	X, Y, Z-axis : $0.2\mu\text{m}$
Max. velocity	X, Y-axis : 200mm/sec, Z-axis : 100mm/sec
Rotational speed	Max. 100,000rpm
Spindle run-out	Max. $0.6\mu\text{m}$
Static radial load	Min. 6kgf
Workpiece weight	Max. 45kgf
Lubrication	Dry cutting

#### B. Experimental Conditions

In experimental works two end-mills were mainly used. The end-mills of 1mm diameter were used for roughing and the end-mills of 0.3mm diameter were used for finishing of micro end-milling. The study concerned micro end-milling. Table II shows other experimental conditions and Fig. 3 shows schematic of experimental works.

TABLE II: CUTTING EXPERIMENTAL CONDITIONS

Micro cutting mode	Side cutting
Feedrate (mm/min)	300
Axial depth of cut( $\mu\text{m}$ )	350
Radial depth of cut( $\mu\text{m}$ )	100, 150, 200(130, 170)
Tool	300 $\mu\text{m}$ 2-flute flat end-mill
Workpiece	Brass
Cutting speed(RPM)	40,000
Cutting mode	Down milling

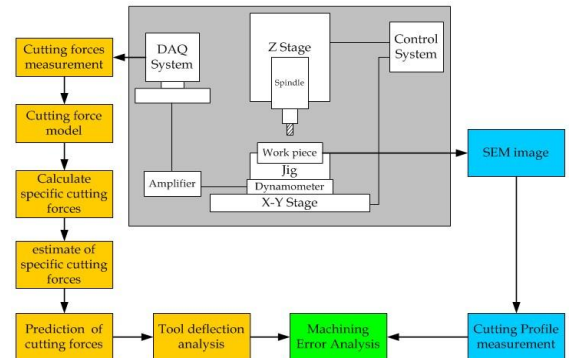
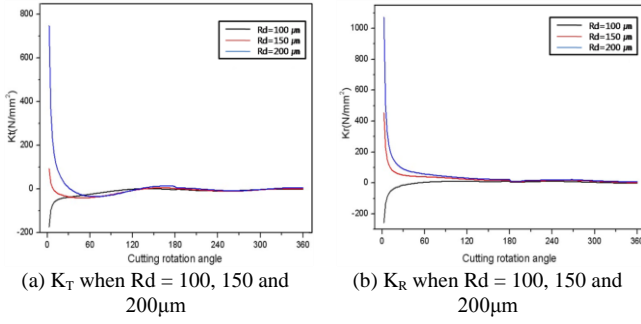
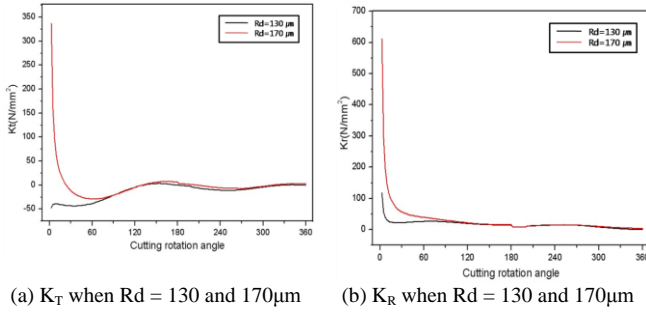


Fig. 3. Experimental system schema.


Fig. 4. Measured  $K_T$  and  $K_R$ 

Fig. 5. Predicted  $K_T$  and  $K_R$ 

### C. Cutting Force Prediction

For cutting force prediction Tlustý model and Lee model were derived by instantaneous tangential and radial cutting force components,  $K_T$  and  $K_R$ , which can be determined by measured cutting forces through a series of actual machining tests under given certain cutting conditions. Therefore it is possible to predict discrete cutting forces as well as resultant cutting forces from measured resultant forces. However as mentioned above, it is obvious that there are differences between machining process phenomena using macro-scaled and micro-scaled tools. If cutting force prediction models were obtained by measured resultant cutting forces, it can be unnecessary to take into account an entire phenomenon of micro-scaled machining processes in a microscopic view point. Therefore in this paper the cutting force model was used, which was derived for macro-scaled machining processes.

### D. Experimental Results

For cutting force prediction, resultant cutting forces were measured at every  $2.4^\circ$  of tool rotation and instantaneous tangential and radial cutting force components,  $K_T$  and  $K_R$ , were calculated by the cutting force prediction model on the basis of measured cutting forces. Fig. 4 shows calculated values of  $K_T$  and  $K_R$ , when radial depth of cut was  $100 \mu m$ ,  $150 \mu m$  and  $200 \mu m$ .

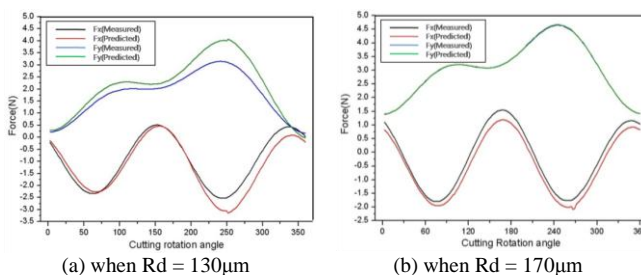


Fig. 6. Comparison between predicted and measured forces.

On the basis of values of  $K_T$  and  $K_R$  calculated from measured cutting forces, it was possible to predict values of  $K_T$  and  $K_R$  which were not measured and calculated. Fig. 5 shows predicted values of  $K_T$  and  $K_R$ , when radial depth of cut was  $130 \mu m$  and  $170 \mu m$ . The cutting forces could be predicted by the cutting force prediction model on the basis of predicted values of  $K_T$  and  $K_R$ . To verify predicted cutting forces, other machining tests were carried out. Fig. 6 shows predicted and measured cutting forces when radial depth of cut was  $130 \mu m$  and  $170 \mu m$ . Good agreements between predicted and measured cutting forces appear on experimental results.

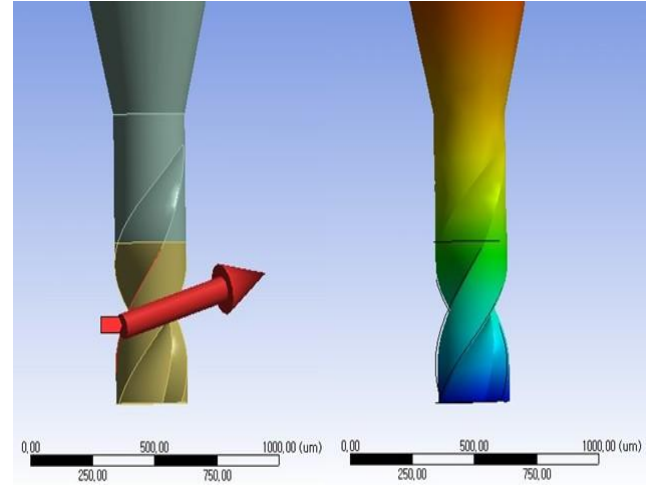


Fig. 7. Graphic results of FEM analysis.

### IV. FEM ANALYSIS OF TOOL DEFLECTION

To estimate micro tool deflection amounts, a FEM (Finite Element Method) approach was used with ANSYS WorkBench. Considering predicted cutting forces it was possible to also predict micro tool deflection amounts as shown in Fig. 7. In fact deflected cutting shapes do not exactly correspond upon actual machined profiles because cutting forces vary according to tool rotation. However if this kind of investigation would be tried according, it can be expected that this analysis would help to predict machining errors caused by excessive cutting forces during machining processes. This is very important because the machining errors strongly affect the machining quality.

### V. CONCLUSIONS

This paper presents a process of cutting force prediction for micro-scaled machining through a model which was originally derived for macro-scaled machining. It is because that excessive cutting forces can cause tool deflection, and then significant machining errors can appear. In this paper, cutting force models for both macro and micro end milling were fundamentally based on measured cutting forces for a series of experimental machining processes. Then, cutting force model proposed by Tlustý and Lee for macro end-milling was applied for micro end milling in this paper because this model is relatively simple. To verify proposed

approach, experimental works were carried out and it was possible to predict the cutting forces with good agreements as respect to measured cutting forces. Moreover a Finite Element Analysis was conducted to predict tool deflection. It can be expected that this process can help to improve the quality of micro end-milling processes.

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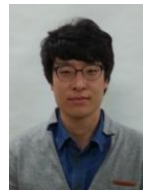
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