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A mechanistic model of cutting force in the micro end milling process

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Abstract

The analysis of cutting force in micro end milling plays an important role in characterizing the cutting process, as the tool wear and surface texture depending on the cutting force. In this paper, an analytical mechanistic model of micro end milling is proposed for predicting the cutting force. The tool–workpiece contact at the flank face is considered in this model. The cutting force model which is considering on cutting edge radius of micro tool is simulated and the validity of that is investigated through the newly developed tool dynamometer for micro end milling. The characteristics of cutting force are used for evaluating the tool condition, damaged layer, and surface roughness in micro machining.

Keywords: Cutting force; Micro end milling; Cutting edge radius; Micro tool

1. Introduction

Micro end milling was first applied to specific fields like electronics, biomedical and aerospace industries. The scope of its applications has gradually expanded to meet the increasing demands for micro parts. Currently, tools with a diameter of 1 mm or below are regarded as micro tools and recently micro tools with a diameter of 0.05 mm or less began to be produced commercially.

Micro end milling and conventional end milling processes are similar as a whole. In micro end milling, however, the ratio of feed per tooth to tool radius is considerably higher compared with conventional end milling. Therefore, how to set cutting conditions is very important. When cutting conditions are not appropriate, tools are easily fractured, which wastes time and money. In addition, it is not easy for the operator to detect tool wear or fractures. Accordingly, in micro-end-milling, cutting force analysis plays an important role in the determination of the characteristics of cutting processes like tool wear and surface texture, the establishment of cutting plans, and the setting of cutting conditions.

Cutting force analysis in the milling process was first attempted by Martellotti [1], and a study on the analytic cutting force of the conventional end mill process was first presented by Tlusty et al. [2]. In the model of Tlusty et al., cutting force was expressed as cutting area, a function of chip thickness, and specific cutting force. A similar model was also presented by Gygax [3] and Kline et al. [4]. Afterwards, studies on three-dimensional cutting force models have been conducted by Yucesan et al. [5] and Jemlelniak [6]. An analytic cutting force model of micro-end-milling was first introduced by Bao et al. [7]. This model is based on the model of Tlusty et al., but it took into account the differences of the tool tip trajectories between micro-end-milling and conventional end milling.

Unlike conventional macro cutting, micro cutting with a micro depth of cut cannot ignore the effect of the tool edge radius. Considerable studies that consider the tool edge radius in two-dimensional orthogonal cutting have been conducted but studies that take into consideration the tool edge radius in end milling are very limited. Accordingly, based on the cutting force model of Tlusty and MacNeil, this study presents an analytic model that considers the tool edge radius and performs the verification of the model through experiments.

2. Cutting force model in micro-end-milling

2.1. Micro cutting mechanism

Fig. 1 shows the difference between macro cutting and micro cutting. When the depth of cut is larger than the tool edge radius, the effect of the tool edge radius can be ignored. However, in

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Nomenclature

b	width of cut (mm)
C	experimental constant
f	feed rate (mm/min)
f_t	feed per tooth (mm/tooth)
F_c	principal cutting force (N)
F_{fc}	flank face contact force (N)
F_{ft}	flank face normal force (N)
F_s	shear plane force (N)
F_t	thrust cutting force (N)
F_x	feed direction cutting force (N)
F_y	normal direction cutting force (N)
h	chip thickness (mm)
K	strength coefficient
L_f	flank face contact length (mm)
n	work-hardening exponent
N	Spindle revolution (rpm)
N_s	shear plane normal force (N)
r	tool radius (mm)
r_t	tool edge radius (mm)
t_0	depth of cut in orthogonal cutting (mm)
x	feed direction
y	normal direction
Y	yield strength (N/mm^2)
Z	the number of tool teeth

Greek symbols

α_r	tool rake angle (rad)
β	tool helix angle (rad)
β_f	friction angle (rad)
ϕ	shear angle (rad)
θ	tool rotation angle (rad)
θ_s	tool start angle (rad)
θ_e	tool end angle (rad)
$\bar{\sigma}$	flow stress (N/mm^2)

micro cutting, this radius has an influence on the cutting mechanism. In particular, in cases where elastic recovery occurs in the flank face of the workpiece, sliding due to the contact between tool and workpiece and ploughing due to the tool edge are regarded as major cutting mechanisms [8,9].

The tool–workpiece contact length in micro cutting can be obtained by the relief angle and the springback of the material caused by the elastic recovery taking place in the flank face of the workpiece. The tool–workpiece contact length L_f in the flank face can be obtained with the following expression (1) [8].

$$L_f = \frac{S}{\sin\theta_f} \quad (1)$$

Here, springback S is $k_1 r_t H/E$, k_1 is a constant, r_t is tool edge radius, H and E are Vicker's hardness and the material elastic modulus, and θ_f is relief angle of tool, respectively.

When only the shear plane shear and the contact friction of the flank face are considered in the cutting force of micro cutting, the force of the normal component acting on the shear plane can be expressed as expressions (2) and (3).

$$F_s = \frac{(\bar{\sigma}/\sqrt{3})bt_0}{\sin\phi} \quad (2)$$

$$N_s = \frac{\bar{\sigma}bt_0}{\sin\phi} \quad (3)$$

Here, $\bar{\sigma} = CK\bar{\varepsilon}^n$.

An additional contact frictional force caused by sliding brought about by the tool–workpiece contact following the elastic recovery in the workpiece flank face can be obtained from the material yield strength and the contact length [10]. As for the tool–workpiece contact frictional force in the flank face, F_{fc} and F_{ft}, the horizontal and vertical components toward the cutting direction, can be obtained by expressions (4) and (5).

$$F_{fc} = \frac{CY}{\sqrt{3}}L_f b \quad (4)$$

$$F_{ft} = CYL_f b \quad (5)$$

The model of Tlusty and MacNeil obtained the cutting force by experimentally getting specific cutting forces but this model is heavily dependent upon the yield strength and flow stress related to the material property. In this study, a cutting force was obtained through cutting experiments and constant C was determined to compensate for the value determined by the properties of the material. Then they were multiplied by K and Y in expressions (2)–(5) to make up for the experimental and theoretical values.

Accordingly, in the micro cutting that takes into account the tool edge radius, the principle cutting force and thrust cutting force can be represented as expressions (6) and (7). They are expressed in the form in which the frictional force of con-

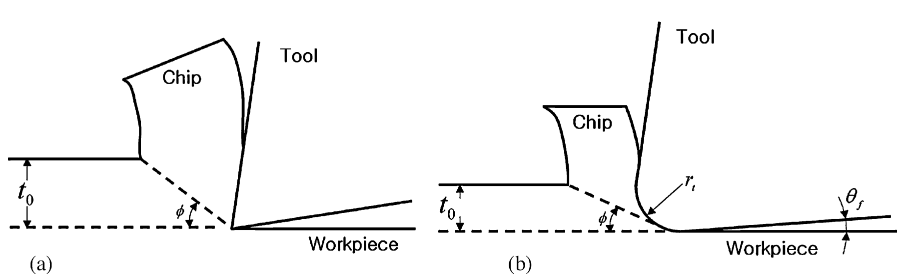

Fig. 1. Difference of conventional macro (a) and micro cutting (b).