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Modeling of cutting forces in micro end-milling

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ABSTRACT

Accurate modeling and prediction of cutting forces are important for process planning and optimization in micro end-milling process. In order to exactly predict the cutting forces, an innovative uncut chip thickness algorithm is proposed by considering the combination of the exact trochoidal trajectory of the tool tip and the cutting trajectory of all previously passing teeth, tool run-out, minimum chip thickness and the material's elastic recovery. The proposed uncut chip thickness algorithm also considers the variation of the entry and exit angles caused by tool run-out. To determine the cutting force coefficients, a finite element model (FEM) of orthogonal micro-cutting that considers strain hardening, strain rate sensitivity, thermal softening behavior, and temperature-dependent flow has been established. Based on the results from FEM analysis, the cutting force coefficients are identified and represented by a nonlinear equation of the uncut chip thickness, cutting edge radius and cutting velocity. The identified cutting force coefficients are integrated into a mechanistic cutting force model and used to simulate micro end-milling forces. The simulation results show a very satisfactory agreement with the experimental results.

1. Introduction

Micro-components and products with feature sizes that range from tens of micrometers to a few millimeters are widely used in many industries such as electronics, optics, aerospace, medicine and biotechnology to mention a few [1]. Research on micro machining processes of micro-components and products became a research hotspot [2]. Among the micro machining processes, micro end-milling has wide applications in ultra-precision devices for its prominent capabilities in versatile material processing and the ability to produce complex 3D shapes [3,4]. In micro end-milling processes, the diameters of the micro cutting tools vary from 0.05 mm to 1 mm [5]. As the size of the cutting tool decreases, the cutting process changes as compared to macro end-milling and some parameters that are ignored in macro-milling become significant in the micro end-milling process [6]. Due to limitations in the tool fabrication processes, the sharpness of the cutting tool cannot be improved proportionally to the decreases of the cutting tool diameter. The radius of the cutting edge is in the range of 0.5–5 μm which is comparable to or even larger than the feed per tooth. As a consequence, a large negative rake angle and elastic-plastic effects are taking place, and the formation of the chip depends on the minimum chip thickness [7]. When the uncut chip thickness becomes smaller than the minimum chip thickness, ploughing phenomena occur and no chip is formed. Moreover, the run-out in micro end-milling processes is approximately 1–5 μm leading to a process in which only one cutting edge is engaged during cutting [8]. These characteristics of the micro end-milling process lead to cutting process uncertainties and make it a challenging task to realize the desired process outputs.

The cutting force is one of the fundamental and most important parameters in the micro end-milling operation. The cutting forces generated in the process are correlated with tool wear and system stability [9,10]. In addition, the cutting force can be used as a key process variable to optimize the cutting conditions. Therefore, an accurate prediction of the cutting forces for different process parameters is essential to economically improve the machined part quality and extend tool life. There have been extensive research efforts on understanding the mechanics of micro end-milling processes and on developing cutting force models. Four different approaches, such as analytical, numerical, mechanistic, and the hybrid approach which combines the strength of the previous three approaches, have been used for modelling the cutting forces. Altintas et al. [11] presented an analytical cutting force

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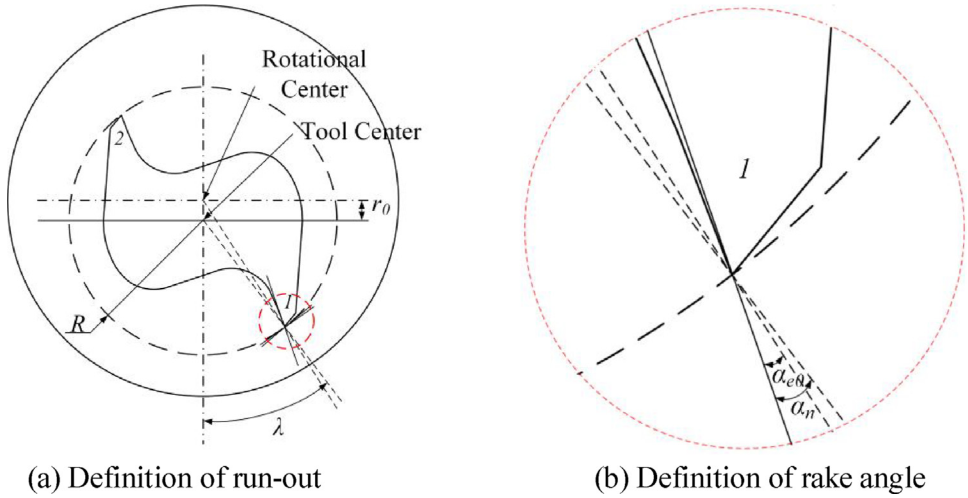

Fig. 1. The definition of run-out and tool geometric parameter definition.

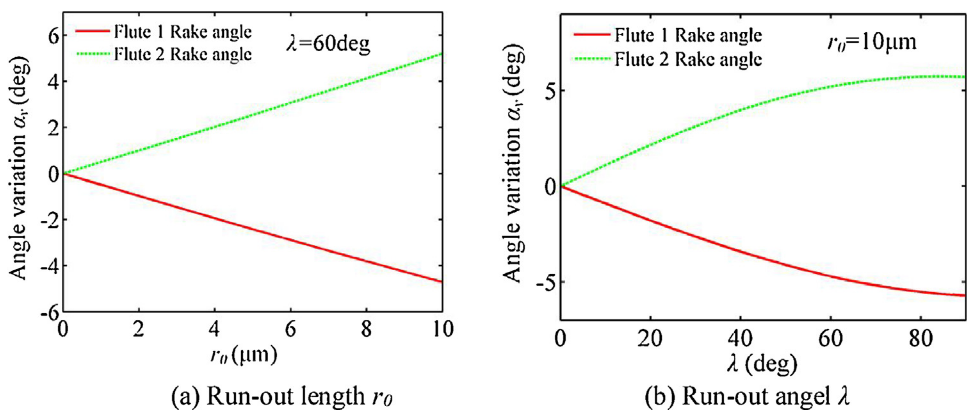

Fig. 2. Influence of r_0 and λ on rake angel.

model using the constitutive model of the material and a friction coefficient. The chip formation process was predicted with a slip-line field model which considered the effects of strain hardening, strain-rate and temperature on the flow stress of the material. In turn, Dhanorker et al. [12] developed a 3-D finite element method of micro end-milling for the prediction of chip formation, temperature, tool wear and cutting forces. The predicted results agreed with the experimental results very well. However, FEM requires a considerable amount of computational power to produce accurate results, especially when 3-D FEM is used to simulate the micro end-milling process, which makes FEM not a practical approach for industrial users [13].

The use of mechanistic cutting force models is associated with the ability of accurately defining the instantaneous uncut chip thickness and obtaining the cutting force coefficients for the corresponding cutting tool geometry, cutting parameters and workpiece material. A number of studies have been reported on the development of analytical instantaneous uncut chip thickness models for the micro end-milling process. Bao [14] calculated the instantaneous uncut chip thickness for micro end-milling operations which firstly included the tool run-out effect. Li et al. [15] improved the computational accuracy of Bao's model using an iterative algorithm to calculate the chip thickness considering the trochoidal trajectory of the tool tip, run-out and the minimum chip thickness effects. Malekian et al. [7] introduced the elastic recovery of the machined workpiece and the dynamic characteristics of the cutting tool to model the instantaneous uncut chip thickness. Rodriguez et al. [16] developed a cutting force model by considering the tool run-out and tool deflection. Experimental results on steel and aluminum showed a good correlation with the model. To predict the cutting force, an instantaneous uncut chip thickness model was established including the trochoidal trajectory of the cutting edge, tool run-out and dynamic modulation caused by the machine tool system vibrations [17]. Zhang et al. [18] proposed a comprehensive cutting force model for micro end milling processes. The effect of cutting edge radius size-effect, tool run-out, tool deflection and the exact trochoidal trajectory of the tool flute are considered in the proposed model. The actual instantaneous uncut chip thickness was evaluated by considering the theoretical instantaneous uncut chip thickness, the minimum uncut chip thickness and a certain critical chip thickness value governed by three types of material removal mechanisms. However, the results showed that the effects of the tool deflections on the cutting force are not very pronounced.

Numerous results have been reported on the calculation of the instantaneous uncut chip thickness and achieved reasonable success. While most of the research calculated the chip thickness only based on the intersection between the current cutting edge's trajectory and the following one's, the variation of the entry and exit angles caused by tool run-out was neglected. Another vital issue for building a mechanistic cutting force model is the evaluation of the cutting force coefficients. Conventionally, the cutting force coefficients are obtained using orthogonal and oblique cutting experiments [19] and milling trials [7,15,20] while neglecting the effects of the cutting conditions on the cutting force coefficients.