International Journal of Machine Tools & Manufacture 105 (2016) 23–31

Contents lists available at ScienceDirect

International Journal of Machine Tools & Manufacture

journal homepage: www.elsevier.com/locate/ijmactool

A generic instantaneous undeformed chip thickness model for the cutting force modeling in micromilling

Kexuan Li [a,b], Kunpeng Zhu [b,c,*], Tao Mei [b]

[a] Department of Precision Machinery and Precision Instrumentation, University of Science and Technology of China, Hefei 230026, China
[b] Institute of Advanced Manufacturing Technology, Hefei Institutes of Physical Science, Chinese Academy of Science, Huihong Building, Changwu Middle Road 801, Changzhou, 213164 Jiangsu, China
[c] School of Logistics Engineering, Wuhan University of Technology, Heping Road 1178#, Wuhan, 430063 Hubei, China

ARTICLE INFO

Article history:
Received 27 October 2015
Received in revised form
6 March 2016
Accepted 7 March 2016
Available online 9 March 2016

Keywords:
Micromilling
Chip thickness
Tool runout
Cutting force

ABSTRACT

The precise modeling of the instantaneous undeformed chip thickness is one of the key issues in the mechanics of micromilling. While most current models noticed the influences of the tool tip trochoidal trajectory and tool runout, they took account only the workpiece removed by immediate passing tooth but not more preceded teeth. These lead to inaccuracy when the single edge cutting occurred, which has been identified to be a prevalent phenomenon in micromilling operation. In this paper, the actual cutting area in micromilling is derived, and then a generic instantaneous undeformed chip thickness model is proposed by considering the cutting trajectory of all passing teeth in one cycle. Additionally, this study derives a criterion that could determine the single-edge-cutting phenomenon in multi-tooth micromilling from the geometric relations. The accuracy of the model is verified by the real experimental data and the result are shown superior to known models.

1. Introduction

With the fast increasing demand of the miniature components and products in the fields such as aerospace, medical equipment and electronic communication device, the manufacturing methods of micro- and meso-scale parts become the research hotspot in these years [1–3]. Micromilling process, one of micro machining methods, has wide applications in micro and ultra-precision devices for its prominent capabilities in versatile material processing and complex 3D surface machining [4,5]. In addition, it can process high aspect ratios of parts [6], and has more excellent economic efficiency, and rapid process compared to micro electro-mechanical systems method [7]. Thus, micromilling technology has been one of the main machining technologies for complex micro parts.

In general, Micromilling means the machining of the characteristic dimensions between 1 μm and 1 mm, and the milling cutters with the diameter below 1 mm [3]. Cutting force is one of the most fundamental and important aspect for understanding the mechanics of micromilling [8,9]. Meanwhile, the precise estimation of instantaneous undeformed chip thickness is the key to the modeling of cutting force [10,11]. Due to the large tool size and high feed rate in conventional milling, the instantaneous undeformed chip thickness often is calculated by considering the approximate circular trajectory of the tool tip [12]. However, with the dramatic decrease of tool diameter and feed rate, the calculation method of the instantaneous undeformed chip thickness in conventional milling is not suitable for micromilling, and any small error will cause the instantaneous undeformed chip thickness to change larger proportion in micromilling process.

To meet this need, many researchers have modified the conventional instantaneous undeformed chip thickness model by considering the important influence factors in micromilling. Bao and Tansel [13] calculated the instantaneous undeformed chip thickness for two teeth micromilling operation by considering the trochoidal trajectory of the tool tip while the tool rotated and moved forward continuously. Tool runout was also considered in their later research [14] and the average error of maximum cutting force between the simulation by using the proposed model and experimental data was around 21%. Li et al. [15] proposed a new instantaneous undeformed chip thickness algorithm for micromilling operation by considering the combination of an exact trochoidal trajectory of the tool tip and tool runout, and the average peak of cutting forces between computational by using the proposed model and experimental cutting forces was around 10%. Afazov et al. [16] compared the changes of the instantaneous undeformed chip

* Corresponding author at: Institute of Advanced Manufacturing Technology, Hefei Institutes of Physical Science, Chinese Academy of Science, Huihong Building, Changwu Middle Road 801, Changzhou 213164, Jiangsu, China. Tel.: +86 519 8633 9823; fax: +86 519-86339709. The author is also with School of Logistics Engineering, Wuhan University of Technology, Heping Road, 1178#, Wuhan 430063, Hubei, China.
E-mail address: kunpengz@hotmail.com (K. Zhu).

http://dx.doi.org/10.1016/j.ijmachtools.2016.03.002
0890-6955/

thickness between different tool runout lengths for two teeth micromilling operation by simulation, and discovered that the tool runout have very large effect on instantaneous undeformed chip thickness at low feed rate. Malekian et al. [10] and Jun et al. [17] introduced elastic recovery of the machined workpiece and dynamic characteristics of the micromilling tool to instantaneous undeformed chip thickness model, and obtained a precise prediction of cutting force in micromilling operation. Rodríguez and Labarga [18] established instantaneous undeformed chip thickness model for two teeth micromilling operation by considering tool runout, too deflection, size effect, and asymmetric cutting. Then the cutting forces were simulated, and showed satisfactory agreement with those data from micromilling experiments. Scholars have done a lot of research on calculation of the instantaneous undeformed chip thickness and achieved a lot of success, while most of studies were limited to two-tooth micromilling and many factors were neglected in determination of the instantaneous undeformed chip thickness.

Among all the influence factors of the instantaneous undeformed chip thickness, tool runout is one of most important factors because of the ratio of tool runout to feed per tooth is much larger in micromilling. However, tool runout parameters are not easy to measure especially the tool runout angle. In micromilling, the cutter has a taper that connects the cutting edges of a smaller diameter to a shank of a larger diameter and this design introduces additional runout at the cutting edges. Therefore, the total runout can no longer be estimated at the tool shank and the values of tool runout parameters are more difficult to predict and control compared to macroscale tools [19]. In previous researches of micromilling, the tool runout parameters were immediate measured by dial indicator [16,18], capacitive sensor [20] or microscope [7,19,21]. Because of the small tool size, there were some measuring errors especially the runout angle in the methods. In conventional milling, some researches had used the methods that the analysis of the cutting force signals for determination of tool runout parameters. Wan et al. [22] determined the tool runout parameters by the minimum error between the prediction and measurement of cutting force. Ko et al. [23] selected the tool runout parameters that minimize the sum of the respective standard deviations of the cutting force coefficients during one cutter revolution. In micromilling, the cutting edge radius of the cutter is comparable in size to the instantaneous undeformed chip thickness in micromilling and the minimum chip thickness becomes an important parameter. The specific energy will non-linear increase with a decrement in the instantaneous undeformed chip thickness when it is less than the minimum chip thickness [3,24]. Thus there would be some error if the traditional methods were used directly to determine the tool runout parameters.

In this study, the real cutting areas are derived by including tool runout and a generic instantaneous undeformed chip thickness model is then proposed. Different from previous studies where only the immediate passing tooth is studied, the model considers the influence of the workpiece removed by all the previously passing teeth in one cycle. The influences of trochoidal trajectory of the tool tip and tool runout are also investigated. At the same time, a function for determining the single-edge-cutting phenomenon is derived. Then, the instantaneous undeformed chip thickness model generalizes the previous studies and an iterative algorithm is applied to estimate runout parameters with verifications from experiments.

2. The generic instantaneous undeformed chip thickness model of micromilling

2.1. The previous models and insufficiency

The conventional instantaneous undeformed chip thickness model can be expressed in ideal conditions, i.e., in absence of trochoidal trajectory of the tool tip, tool runout and deflection, it can be approximately expressed in the formula (1).

$$h(\theta) = f_t \sin(\theta) \tag{1}$$

where $h(\theta)$ is the instantaneous undeformed chip thickness (mm) at an instantaneous angle position θ (rad) of a milling tooth, and f_t is the feed per tooth (mm/tooth). However, due to the rapid decreases of the tool diameter and feed rate, the conventional computation model of instantaneous undeformed chip thickness cannot precise describe the actual instantaneous undeformed chip thickness of micromilling.

In the celebrated study, Bao and Tansel investigated the instantaneous undeformed chip thickness of micromilling operation [13,14]. They put forward the model based on the intersection between the current cutting edge's trajectory and the following one's. Li et al. [15] improved the computational accuracy of Bao and Tansel's model by iterative algorithm, while the results agreed with [13,14]. The simulation of the model [14] is shown in Fig. 1. It can be seen that tooth 1 can cut to the workpiece at only partially

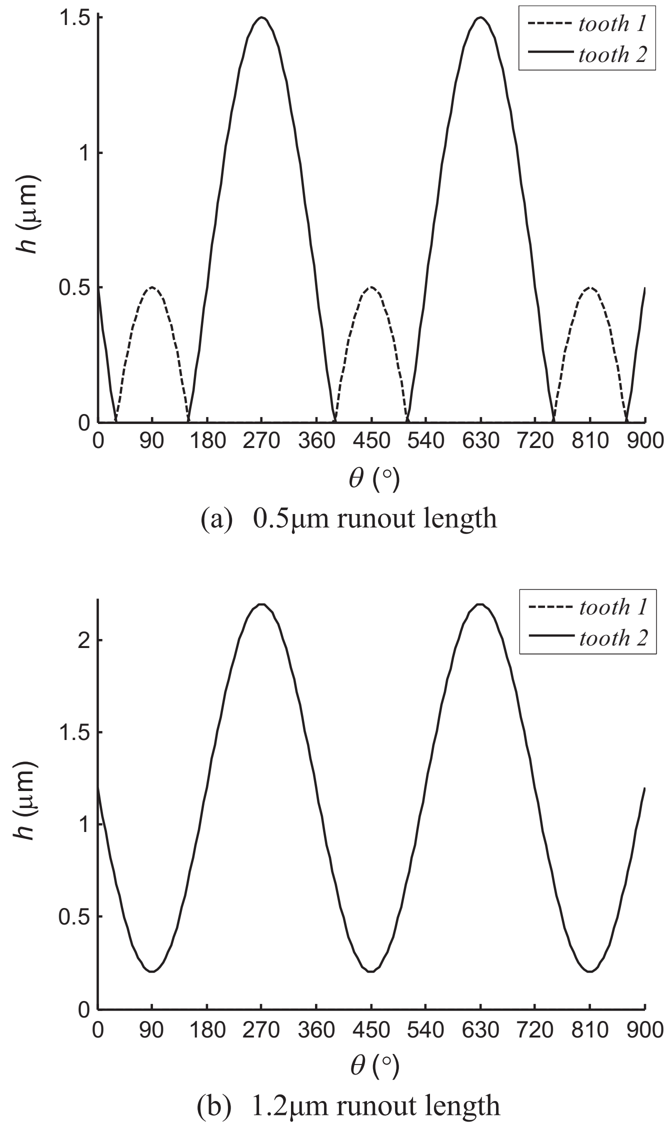

Fig. 1. Instantaneous undeformed chip thickness (h) simulate results according to the approach in [14]; simulation parameters: two teeth micromilling tool, 0.8 mm tool diameter, 1 μm/tooth feed per tooth and 60° tool runout angle (a) 0.5 μm runout length (b) 1.2 μm runout length.