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Tool Wear Modeling through Shape Mapping Method in Micro End Milling

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Abstract

The micro end milling process is widely used in industry because of its versatility and efficiency. Micro end milling with fine grained carbide end mills is an economical way to machine micro-components which have high aspect ratio features. Tool wear on the cutting edges of micro end mills is an important issue affecting the cutting forces, surface roughness and tool geometry. In this study Ti6Al4V was selected as a work piece material because of its wide range of applications in biomedical, electronics, optics, aerospace industry, etc. due to their superior mechanical, chemical and high temperature properties. A flank wear model for micro end milling cutter is established based on shape mapping method.In this study radial wear is considered as a characteristic parameter, which was measured based on the variation of slot profile. Thus a series of slots, which can represent the worn tool information are formed on the work piece after every 50mm length of slot is cut. In most of the tool wear study in micro end milling process, tool wear was monitored by directly investigating on tool which is a time consuming process. Where as in this study tool wear monitored based on the profile of the slot.The experimental work were carried out on a micro machining center (Mikrotools DT110, Singapore) using micro end mill with 1000µm diameter made of Tungsten carbide (WC) with AlTiN coating. The characteristic parameters of these slots, are measured using ALICONA 3D optical Profilometer to investigate the radial wear. A mathematical model was developed to predict flank wear width as a function of redial wear, effective rake angle and clearanceangle. The comparison between the predicted and measured flank wear has shown that the 20% deviation occur from experimental results.

Keywords: Micro end milling, Tool flank wear, Radial wear, Shape mapping, Effective rake angle.

1.INTRODUCTION

Nowadays, there have been increasing demands for micro components in many industries such as electronics, optics, aerospace, and medicine and biotechnology. Micro end-milling, one of the mechanical micromachining methods, that utilizes end mill cutter typically vary in diameter from 100 to 1000 µm and have edge radii that vary from 1 to 10 µm[1] .The tool wear is a very complex phenomenon with many variables and different wear mechanisms like adhesion,abrasion, melting or delamination.Tool wear in cutting process is defined as the amount of loss of tool material on the contact surface due to the interaction between thecutter and work piece. The very high temperature and pressure on the toolsurface and cutting edge may lead to development of different wear patterns under different cutting conditions [2].The tool wear leadsdirectly to the increase of cutting force, cutting temperature, andadverse effects on dimensional tolerance and surface quality of the product, etc.Many of the researchers and manufacturers have studied on end milling operations to design better tools, with including the effect of tool wear. LijingXie et al. [3] proposed the differential wear rate model to estimate tool wear and an estimating method for tool wear profile progress in cutting process.Oraby et al. [4] developed a model for wear and tool life determination using non-linear regression analysis techniques in terms of the variation of a ratio of force components acting at the tool tip.Kim and Kim [5] have suggested an orthogonal cutting model that considers the cutting edge radius and elastic recovery and then quantified these two effects.

Yellowley [6] developed a mechanistic force model to predict the cutting forces for worn milling cutters. In this model simulated the cutting action by dividing the cutting zone into orthogonal cutting disks and employing radial and tangential force parameters as constants.Sun. et al.[7] investigated the relationship between cutting force and flank wear of solid carbide tool and they developed the model of cutting force in end milling considering the effect of flank wear. Vogler et al. [8] have developed a chip-thickness computation algorithm, and showed the effect of minimum chip thickness on machining.Liu et al. [1]extracted the minimum chip thickness from the machined surface profile and also, they could predict the machined surface roughness by using the actual chip thickness byusing the surface generation mechanism. Fang and Liu [9] have developed the relation for the calculation of the average effective rake angle. In this paper, the rake surface will be defined not in terms of the averageeffective rake angle but by the partial effective rake angle.Zhangand Zhou [10] investigated the modelling of tool wear based on shape mapping from theoretically and experimentally aspects in the milling process for ball end milling cutter. Zhanget al. [11]have developed the tool wear estimation based on shape mapping and proposed the relationship between redial wear and tool flank wear in end milling process. Kim et al. [12], determined experimentally that when the feed per tooth is comparable with the edge radius of the tool, as is often the case in micro milling processes, the chip formation process becomes intermittent and the

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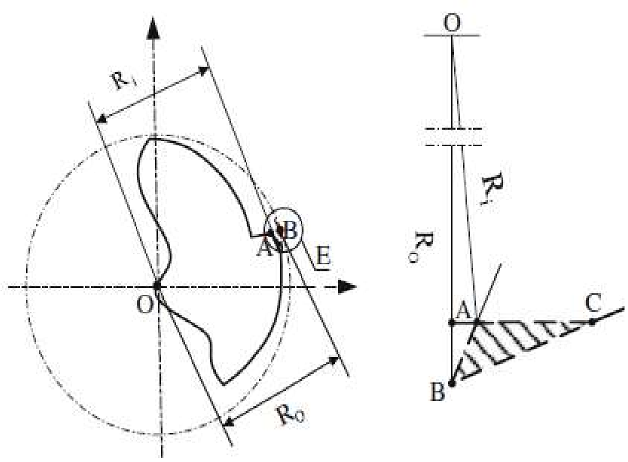
conventional understandingthat a chip is formed with every tooth pass is no longer valid. In this paper tool wear measured by shape mapping method. Redial wear measured on the optical profilometer, flank wear was estimated based on the proposed modeland compared with actual value. It was found that the error occurred less than 20%.

2.THEORY OF SHAPE MAPPING

During the machining process, cutter radius of the tool will become worn out. This characteristic to retain thetool wear information on a metal material, which has low influence on tool wear, by using milling slots. Shape mapping is defined to map the worn tool shape onthe material, by using milling cutter.After each slot cutting compare these slots with reference slot.Worn cutter can be shown as in Fig. 1 figure1a is a main diagram and Fig. 1b is a detail diagram. In Fig. 1, RO is the unworn cutter radius, Riis the worn cutter radius, area ΔABC is cutter wear part, and ACis the cutter flank wear extent.



(a) Main diagram (b) detailed diagram of E

Fig. 1. Relation between tool wear and cutter radius [11]

In this paper, a new approach to acquire tool wear is proposed based on shape mapping for establishing tool wear model during micro milling operation. These machined slots are analyzed to get the relationship between the redial wear and tool flank wear. The machined slots are measured on the profilometer to acquire redial tool wear of each slots. Reference slots and each slotswhich are machined by worn cutter are compared tomonitor tool condition after machining each slot. After each experiment the tool gets worn out and this will reflect on the slot produced. By comparing the width of the slot machined by the worn tool with the reference slot will give information about radial wear. In this paper radial wear is considered as the characteristic parameter. To establish the relationship between the machined slots and tool flank wear, a cutter edge wear detail diagram is shown in Fig.2. In this VB is flank wear, ΔR is radialwear, α isnominal rake angle, and β is clearance angle.Considering the triangle ABC in Fig.1. a relation between radial and flank wear can be established.Following assumptions have been taken to derive the formula as: Assume that machining is Orthogonal, only 2-D deformation considered. Both relationships are shown in the following equation:

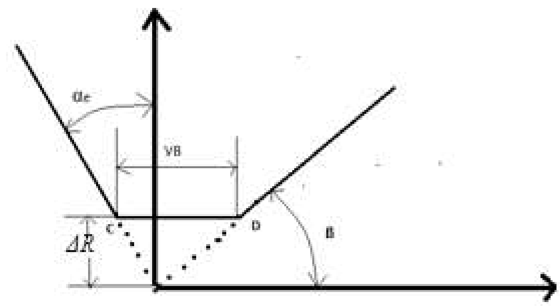


Fig.2.Sketch of radial section wear and flank wear

$$VB=\Delta R.\tan(90-\beta) - \Delta R.\tan\alpha_e$$

$$VB=\Delta R\,[\tan(90-\beta)-\tan\alpha_e] \quad (1)$$

Where αe is the partial effective rake angle. Thus, flank wear can be calculated by equation(1)provided that the radial section wear ΔR is fixed for a particular position.In most of the tool wear study in micro end milling process, tool wear was monitored by directly investigating on tool which is a time consuming process. Where as in this study tool wear monitored based on the profile of the slot. Methodology used in this study is given below:

Step 1: Mount the experimental workpiece on the machine tool by using standard fixture.

Step 2: Start machining with a new milling cutter. Initially cut the slot, which is called as reference slot, it will be used to compare with the slots produced by the same tool after subsequent machining.

Step 3: Find out width of the reference slot

Step 4: Mill workpiece using the same cutter.The cutter will wear out and it will reflect on the slot profile.

Step 5: Measure width of the slot

Step 6: Find out radial wear by taking the difference between slot width (W_t) and reference slot width (W_r) as shown-

$Wr > Wt$, radial wear width$(\Delta R) = \frac{Wr-Wt}{2}$

Step 7: Find out flank wear from equation (1)

Step 8: Measure actual value of flank wear using 3D optical profilometer.

Step 9: Find out the error between actual value and predicted value

Step 10: Repeat the same procedure as (step 4 to step 9 until the tool gets worn out).

2.1 Partial Effective Rake Angle-

Inmicro machining the uncut chip thicknessvalue that are equal in magnitude or less than the edge radius, the rake angle that affects the machining process is morenegative than the nominal rake angle. In micro machining whenever uncut chip thickness is less than the cutting edge radius of the tool, chip flows around the edge radius instead of tool rake face. Hence it is necessary to consider the effective rake angle for accurate analysis of the machining process in such situations.It has been found that there exists a minimum chipthickness below which no chip will form, unlike inconventional end-milling processes [1].Lee et al. [13] have established relation for the calculation of the average effective rake angle. According to Fig. 2, if the ordinate of a particularpoint within the chip is less than the height of the tangent point between the rake surface and the arc of the cutter's edge (h_{lim}), then the partial effective rake angle (α_e) at that particular position is defined as the inclination angle of the tangent to the arc of the cutter's edge at that particular point. In this case, the partial effective rake angle at an arbitrary point can be obtained by using the equation presented as-

$$\alpha_e = \begin{cases} -\frac{\pi}{2} + \cos^{-1}\left(1-\frac{h}{\rho}\right), & if\,h \le h_{lim} \\ \alpha, & if\,h > h_{lim} \end{cases} \qquad (2)$$

$$h_{lim} = \rho\,(1+\sin(\alpha)) \qquad (3)$$

Where ρ and $\alpha$are the edge radius and nominal rake angle of the tool (Fig. 3), respectively.In this study minimum uncut chip thickness was considered to be approximately 25 - 33% of the cutting edge radius.

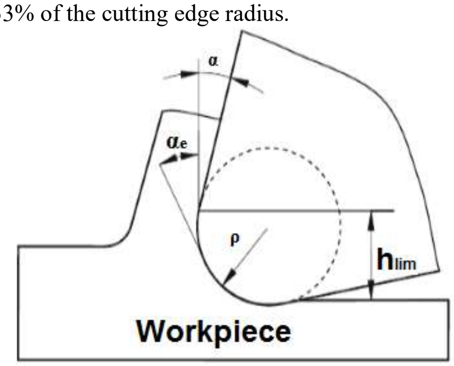
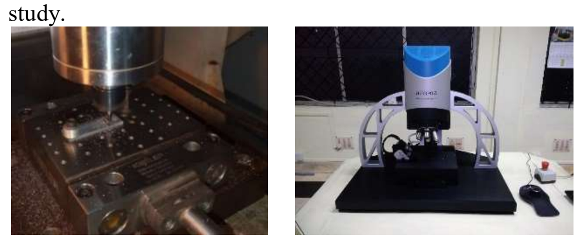


Fig.3.Effective rake angle [13]

2.2 Experimental setup and procedure

In order to verify the developed tool wear, experiments were conducted on a micro machining center (Mikrotools DT110, Singapore) using micro end mill with 1000µm diameter made of Tungsten carbide (WC) with AlTiNcoating (Fig. 4). In this study radial wear is one of the input parameter to find out flank wear as given in the equation 1. Radial wear was measured based on the variation of slot profile as machining progresses. Initial slot which was machined by the fresh tool was taken as the reference slot. Subsequent slots machined by the same tool will be influence by the condition of the tool. After every 50 mm length of cut slot profile was measured and compared with the reference slot. This difference in slot profile will give radial wear of the tool. An optical 3D profilometer (Fig. 4(b)) was used to measure the profile of the slot. Table 1 shows the cutting parameters used in this study.



(a) (b)

Fig.4.Experimental setup (a) Micro machining centre (b) 3D Optical profiler

Table 1
Experimental condition

Speed (rpm)	Feed (mm/min)	Depth of cut (µm)	Length of slot (mm)
5000	50	100	50

3. RESULTS AND DISCUSSION

In order to verify the reliability of the established tool wear model, machining experiments are conducted.Radial wear is as an input parameter to compute the flank wear from the equation (1). Predicted flank wear value from the model is compared to the measured value in the result and discussion. Fig. 5 shows that flank wear after every 50mm length of cut.Width of flank wear at the end of every 50 mm length of cut can be seen from Table 2. The maximum error between the predicted tool wear and the actual tool wear is 2.23µm. Maximum flank tool wear corresponding to 1000mm slot length is 21.233µm. The predicted flank wear using the proposed model have been verified with experimentally measured results as shown in Table 3.It was found thatprediction error is within 20%. The proposed tool wear modeling method and the tool wear estimation method can be expand to other work piece material and milling cutter material for establishing tool wear model. The established tool wear model based on shape mapping can be used to predict tool wear of different position at cutting edge of flat end milling cutter. So machining error can be compensated according to the predicted tool wear at the different positions. This is very convenient and helpful for machining error compensation.

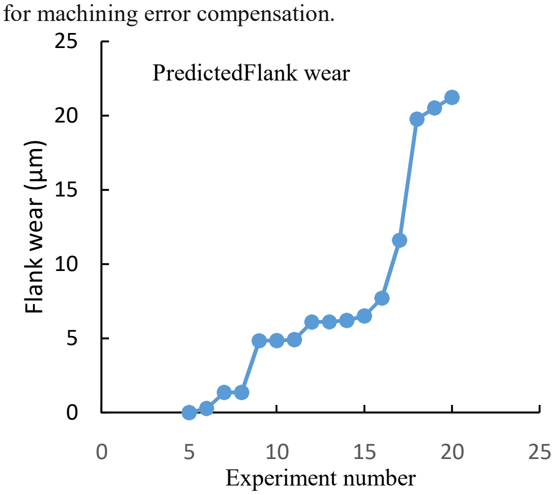


Fig. 5Flank wear vs. number of experiment

Table 2
Estimated data of redial and flank wear

Experiment no.	Slot length(mm)	Redial wear(μm)	Flank wear(μm)
1-4	50-200	-	-
5	250	0.0002	0.0014
6	300	0.0298	0.2804
7	350	0.1448	1.3624
8	400	0.1448	1.3624
9	450	0.5145	4.8410
10	500	0.5155	4.8502
11	550	0.5221	4.9166
12	600	0.6485	6.1019
13	650	0.6498	6.1141
14	700	0.6501	6.2110
15	750	0.6550	6.5110
16	800	0.7550	7.7110
17	850	1.2334	11.6050
18	900	2.1010	19.7610
19	950	2.1811	20.5220
20	1000	2.6817	21.2330

Table 3
Comparison of result

Slot length(mm)	Estimated flank wear (μm)	Actualflank wear(μm)	% Error
600	6.1019	8.1725	24.28
800	7.7110	9.9101	22.11
1000	21.2330	23.1284	12.51

4. CONCLUSIONS

A tool wear model, based on the concept of the shape mapping that can precisely predict the flank wear in micro end milling waspresented. Based on estimated value and experimental measuredvalue, following conclusion can be drawn:

(1) Developed a tool wear model to predict flank wear during micro end milling using shape mapping method. Proposedmodel was validated with the experimental result.

(2) It was found from Fig.5 that, flank wear width increases drastically after 800mm length of cut. Similar trend was found in experimental result also. From Table 3it can be noticed that after 800mm length of cut flank wear is 7.7110μm and after 1000mm length of cut flank wear was drastically increased to 21.2330μm.

(3) Based on the comparison between predicted and experimental value, it was found that the prediction error is within 20%.

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