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Cutting Edge Preparation of Micro Milling Tools

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Abstract

Micro milling is commonly used industrially for the production of precision components. Premature tool wear is usually the reason for a short tool life of cemented carbide end mills. An approach to improve the tool wear behavior is the defined cutting edge preparation. In this contribution, experimental investigations on the formation of cutting edge geometry during immersed tumbling of micro milling tools are presented and discussed. It could be shown that it is possible to prepare end mills with a diameter $D = 1\, \text{mm}$ and to generate edge radii of $4.0\, \mu\text{m} \leq r \leq 31.2\, \mu\text{m}$. Investigations about the correlations between the cutting edge geometry and the tool wear behavior in micro milling operations showed decreased flank and crater wear as a result of an appropriate cutting edge preparation.

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Keyword: Immersed Tumbling; Micro Milling; Cutting Edge Geometry

1. Introduction

Precision components e. g. for die and mould fabrication can be produced with micro milling in different kinds of materials with high geometrical flexibility. Due to high dynamic loads and different wear mechanisms the cutting edge geometry changes during the tool life of micro milling tools. Tool wear is usually the reason for the failure of cemented carbide end mills with nominal diameters of $D \leq 1\, \text{mm}$. The wear behavior leads to unpredictable tool life and quality of the workpieces [1, 2].

An approach to improve the tool wear performance is a defined cutting edge preparation [3, 4, 5]. Fundamental understanding of the manufacturing process is necessary in order to optimize micro milling tools with a cutting edge geometry preparation. Immersed tumbling is an appropriate process for the cutting edge preparation of rotationally symmetrical cutting tools also with small diameters [2].

In the following, experimental investigations on the formation of the cutting edge geometry during immersed tumbling of micro milling tools are presented and discussed.

Further investigations obtain basic knowledge about the correlations between the cutting edge geometry and the tool wear behavior in micro milling operations.

Nomenclature

- $a_e$: width of cut
- $a_p$: depth of cut
- $D$: diameter
- $d_G$: grain diameter
- $d_K$: grain size
- $f_z$: feed per tooth
- $h$: uncut chip thickness
- $h_{\text{min}}$: minimum chip thickness
- $n_W$: number of workpieces
- $L_{\text{Cut}}$: cutting length
- $n$: rotational speed
- $n_{\text{H}}$: rotational speed of the workpiece holder
- $n_{\text{R}}$: rotational speed of the rotor
- $R_s$: chipping of the cutting edge
2. Cutting Edge Preparation

For the cutting edge preparation of rotationally symmetric cutting tools even with small diameters immersed tumbling is an appropriate process [2]. In this production process the workpieces are fixed on holders and immersed in an abrasive lapping medium. The material removal is the result of the relative movement between the workpiece and the abrasive lapping medium. The cutting processes are mainly caused by ploughing and furrowing due to impacts and rolling of the abrasive grains on the workpiece surface.

For the experiments examining the formation of the cutting edge geometry of micro milling tools a machine DF 3 Tools made by the company OTEC PRÄZISIONSFINISH GMBH, Straubenhardt, Germany was used. The machine is shown in Figure 1 schematically.

This machine has two independent drives. The main drive moves the rotor with a rotational speed up to \( n_R = 50 \text{ rpm} \). The second drive rotates the holder of the workpiece holders as well as the workpieces themselves using a planetary gear. The rotational speed of the workpiece holder can be up to \( n_H = 200 \text{ rpm} \). The machine is equipped with three holders. Each holder can again be equipped with up to six workpiece holders. The second drive allows the independent control of the rotational speed as well as the rotational direction of the rotor and the holders. The workpieces can be immersed in the work bowl using a linear unit. To control the depth of the immersion \( T_I \) the workpiece tip is measured using laser sensors.

For the investigations two flute end mills made by the company Walter AG, Tübingen, Germany, with a diameter of \( D = 1 \text{ mm} \) were used. These were uncoated and made of fine grain carbide with a grain size of \( 0.8 \mu\text{m} \leq d_K \leq 1.3 \mu\text{m} \). The fine grain carbide has a Vickers hardness of \( HV 10 = 1716 \text{ kN mm}^{-2} \) and a density of \( \rho = 14.5 \text{ kg dm}^{-3} \). As part of the analysis these end mills were machined using various lapping media and varying the processing time \( t_B \) from \( t_B = 0 \text{ min} \) to \( t_B = 16 \text{ min} \).

The lapping media with the product names HSC 1/300, QZ 0.5-0.8, H 4/400 and M 4/400 were used. HSC 1/300 is a mixture of 30 % silicon carbide (SiC) with a grain diameter of \( d_G = 200 \mu\text{m} \) and 70 % walnut shell granulate with a grain diameter \( 0.8 \text{ mm} \leq d_K \leq 1.3 \text{ mm} \). This lapping medium is particularly suitable for the preparation of cutting tools made of high speed steel (HSS) and cemented carbide. QZ 0.5-0.8 is aluminium oxide with grain diameters of \( 0.5 \text{ mm} \leq d_K \leq 0.8 \text{ mm} \). This medium is particularly suitable for the edge preparation of cutting tools with a high material removal rate and the generation of relatively large edge radii \( r_\mu \). H 4/400 consists of a mixture of walnut shell granulate with a grain diameter of \( 0.4 \text{ mm} \leq d_K \leq 0.8 \text{ mm} \) and a polishing paste containing diamond particles. This lapping medium is suitable for polishing, light deburring and edge rounding. M 4/400 consists of corn with a particle size of \( 1 \text{ mm} \leq d_K \leq 3 \text{ mm} \). This lapping medium type is new and still in the testing phase [6].

In Figure 2 the results of the cutting edge preparation are given. Cutting edge radius \( r_\mu \) in dependence of the processing time \( t_B \) is given in chart a. The maximum chipping of the cutting edge \( R_{\text{s,max}} \) in dependence of the processing time \( t_B \) is given in chart b. During the experiments, the radius \( r_\mu \) and the maximum chipping of the cutting edge \( R_{\text{s,max}} \) was measured using an optical measurement device InfiniteFocus of the company A LICONA IMAGING GMBH, Graz, Austria. The results are shown in Figure 2.

The experimental results in Figure 2 show that the highest cutting edge radii could be reached using of the lapping medium QZ 0.5-0.8. In that case the cutting edge radius \( r_\mu \) is \( r_\mu = 19.5 \mu\text{m} \) after a processing time of \( t_B = 4 \text{ min} \) and \( r_\mu = 31.2 \mu\text{m} \) after a processing time of \( t_B = 16 \text{ min} \). When using the lapping medium HSC 1/300 the cutting edge radius \( r_\mu \) is \( r_\mu = 11.1 \mu\text{m} \) after a processing time of \( t_B = 4 \text{ min} \) and \( r_\mu \approx 22.2 \mu\text{m} \) after a processing time of \( t_B = 16 \text{ min} \).

Very low and smooth radii could be manufactured using the lapping media H 4/400 and M 4/400. For example, when using the lapping medium H 4/400 the cutting edge radius \( r_\mu \) is \( r_\mu = 5.1 \mu\text{m} \) after a processing time of \( t_B = 4 \text{ min} \) and only \( r_\mu = 9.7 \mu\text{m} \) after a processing time of \( t_B = 16 \text{ min} \). Further, the chipping of the cutting edge and the surface roughness were analyzed taking the processing time \( t_B \) and the cutting edge radii \( r_\mu \) into account. Those investigations showed that the processing time \( t_B \) is mainly responsible for the size of the cutting edge radius \( r_\mu \). The choice of the lapping medium determines the chipping of the cutting edge.

\begin{align*}
  t_B & \quad \text{processing time} \\
  T_I & \quad \text{depth of immersion} \\
  \text{VB}_{\text{max}} & \quad \text{maximum of the width of flank wear land} \\
  v_c & \quad \text{cutting speed}
\end{align*}
Fig. 2. Results of the cutting edge preparation

Using this knowledge four groups of three tools each were prepared by immersed tumbling. The results in Table 1 show the possibility to control the size of the cutting edge radius \( r_\varepsilon \) independently of the chipping of the cutting edge \( R_{s,\text{max}} \). These tools were used for the subsequent investigations in micro milling operations presented in the following.

### Table 1. Different cutting edge geometries manufactured by immersed tumbling

| Tool Group | Processing Time | Lapping Medium | Cutting Edge | \( r_\varepsilon \) | \( R_{s,\text{max}} \) |
|------------|----------------|----------------|--------------|-----------------|-----------------|
| Unprepared | \( t_B = 0.0 \) min | - | - | 2.0 \( \mu \)m | 0.5 \( \mu \)m |
| Tool Group 1 | \( t_B = 0.5 \) min | HSC 1/300 | - | 4.0 \( \mu \)m | 0.4 \( \mu \)m |
| Tool Group 2 | \( t_B = 4.0 \) min | H 4/400 | - | 4.0 \( \mu \)m | 0.3 \( \mu \)m |
| Tool Group 3 | \( t_B = 12 \) min | HSC 1/300 | - | 8.0 \( \mu \)m | 0.4 \( \mu \)m |
| Tool Group 4 | \( t_B = 18 \) min | H 4/400 | - | 8.0 \( \mu \)m | 0.3 \( \mu \)m |

3. Micro Milling with Different Cutting Edge Geometries

Experimental investigations were carried out to analyze the influence of the cutting edge geometry on the wear behavior of the micro milling tools. Therefore a 3-axes micro milling machine tool, WISSNER GAMMA 303 HP was used. This machine has two spindles. For the experiments a spindle PRECISE SC3062 (Figure 3, 2) with a maximum rotational speed of \( n = 60.000 \) rpm was used. The position accuracy of this machine and the true running accuracy of the used spindle is 2 \( \mu \)m. The machine tool is equipped with a camera system for direct detection of tool wear and with a piezoelectric dynamometer for the indirect tool condition assessment.
The camera system consists of a compact μEye UI-1480RE-C-HQ CCD camera with a Pentax H1214-M C-mount lens and a diode ring light, which directs the light in a steep angle in front of the lens. The system provides the possibility to capture the cutting edge and to measure the width of flank wear land VB. It is particularly suitable to be integrated into the machine tool due to its compact dimensions, enabling wear detection without unclamping the tools. In Figure 4 the wear detection using the camera system (1) and the measurement of the width of flank wear land VB (2) is shown.

The cutting part of the end mill can automatically be positioned into the focal plane of the lens using a NC routine. However, the rotational alignment of each flute still has to be performed manually. The horizontal measurement range of the camera-lens-combination is 2 mm. It displays a measuring zone of 2 mm x 2 mm at a maximum resolution of 2,560 x 1,920 Pixel. The results of analysis of the maximum of the width of flank wear land VB$_{\text{max}}$ are shown in Figure 5.

**Fig. 3. Test stand WISSNER GAMMA 303 HP**
1. Headstock, 2. Spindle No. 1, 3. Spindle No. 2, 4. Machine table, 5. 3-component dynamometer, 6. Camera system, 7. Light control, 8. Charge amplifier, 9. A/D-converter, 10. Force measurement computer, 11. Wear measurement computer

**Fig. 4. Wear detection, (1) capturing of the cutting edge (2) Measurement of the width of flank wear land VB**

**Fig. 5. Max. width of flank wear land VB$_{\text{max}}$ in dependence of the cutting length L$_{\text{cut}}$**
The results in Figure 5 (a) show the comparison of all end mills regarding the growth of the maximum width of flank wear land $V_{B_{\text{max}}}$ in dependence of the cutting length $L_{\text{cut}}$.

After a cutting length of $L_{\text{cut}} = 10$ m the unprepared tools showed on average a maximum width of flank wear land of $V_{B_{\text{max}}} = 63$ µm. The results had a high dispersion. The width of flank wear land was in the range of 51 µm ≤ $V_{B_{\text{max}}} ≤ 75$ µm. The wear is accordingly determined stochastically when unprepared end mills are in use. The end mills of the group T. 1 showed on average a maximum width of flank wear land of $V_{B_{\text{max}}} = 61$ µm. The end mills of group T. 2 with cutting edge radius of $r_{t} = 4$ µm and a significantly reduced chipping of the edge $R_{c}$ showed a 10 % decreased width of the flank wear land $V_{B_{\text{max}}}$ in comparison to the unprepared tools. Overall the end mills of the group T. 4 showed the lowest maximum width of flank wear land of $V_{B_{\text{max}}}$. After a cutting length of $L_{\text{cut}} = 10$ m on average a maximum width of flank wear land of $V_{B_{\text{max}}} = 55$ µm was measured. An increase of the width of flank wear land $V_{B_{\text{max}}}$ for the use of unprepared end mills (Figure 5, b) in comparison to the use of end mills with a cutting edge radius of $r_{t} = 8$ µm (Figure 5, c) can be observed. This shows that a defined cutting edge preparation additionally offers the possibility to decrease the variance of the tool wear up to 92 %. These results show that the chipping of the cutting edge $R_{c}$ has a greater influence in comparison to the size of the cutting edge radius $r_{t}$.

The SEM images in Table 2 show that, in addition to the wear land on the flank of the tools, also apparent crater wear can be observed at the cutting edges of the unprepared end mills. Crater wear deteriorates the stability of the cutting edge and can cause sudden chipping or breakage of the cutting edges. The end mills which were machined by immersed tumbling showed no crater wear after the same cutting length $L_{\text{cut}}$, see Table 2.

| Cutting Edge: | Cutting Edge: | Process Parameters: | Process Parameters: | Width of Flank Wear: | Width of Flank Wear: |
|-------------|-------------|-------------------|-------------------|-------------------|-------------------|
| $t_{c}$     | $t_{c}$     | $l_{c}$          | $l_{c}$          | $V_{c}$          | $V_{c}$          |
| 2 µm        | 4 µm        | 40 m min$^{-1}$  | 40 m min$^{-1}$  | 100 µm           | 100 µm           |
| $R_{c_{\text{max}}}$ | $R_{c_{\text{max}}}$ | $v_{c}$          | $v_{c}$          | $V_{B_{\text{min}}}$ | $V_{B_{\text{min}}}$ |
| 0.5 µm      | 0.3 µm      | 5.9 µm           | 5.9 µm           | 68 µm            | 68 µm            |

4. Conclusion

Premature tool wear is usually the reason for a short tool life of the cemented carbide end mills. In addition the wear behavior leads to unpredictable tool life and workpiece quality. An approach to improve the tool wear behavior is the defined cutting edge preparation.

In this contribution, experimental investigations regarding the formation of the cutting edge geometry during an immersed tumbling process are presented. Therefore two flute end mills with a diameter of $D = 1$ mm were machined by the use of various Lapping media. It was found that the processing time $t_{p}$ is mainly responsible for the size of the cutting edge radius $r_{t}$. The lapping medium defines the chipping of the edge. During the experiments cutting edge radii in the range of $4.0 \mu m \leq r_{t} \leq 31.2 \mu m$ with a maximum chipping of the cutting edge in the range of $0.2 \mu m \leq R_{c_{\text{max}}} \leq 0.5 \mu m$ were manufactured.

Moreover, end mills with various cutting edge geometries were tested in milling experiments to obtain basic knowledge about the correlations between the edge geometry and the tool wear. Therefore the wear land on the flank was analyzed over a cutting length of $L_{\text{cut}} = 10$ m. It was found that the end mills with a cutting edge radius of $r_{t} = 8 \mu m$ and a maximum chipping of the cutting edge $R_{c_{\text{max}}} = 0.3 \mu m$ showed overall the lowest maximum width of flank wear land $V_{B_{\text{max}}}$. In comparison to unprepared end mills the maximum width of flank wear land $V_{B_{\text{max}}}$ could be reduced by 14 % and the variance of the results could be reduced up to 92 %. Additionally, the tools which were prepared by immersed tumbling showed no tendency for crater wear.

These results are valid for non-coated tools. Various coatings are often used to improve the tool wear behavior of micro milling tools. An additional coating leads to an increase of the cutting edge radius $r_{t}$ and thus to an increase of the minimum chip thickness $h_{\text{min}}$. This relationship needs to be examined and taken into account particular for coatings on micro milling end mills. In this context, the correlation between the cutting edge geometry and the process forces is of high interest. The increase of the cutting edge radius $r_{t}$ can cause an increasing process force. This increasing of the process force is the result of ploughing effects when the uncut chip thickness $h$ is less than the minimum chip thickness $h_{\text{min}}$ [7, 8] and the main reason for unpredictable tool breakage.

Further investigations will examine the influence of the tool diameter $D$ and the processing speed in the immersed tumbling process. Furthermore analyzes regarding the correlations between the cutting edge geometry and the process forces, run out, burr formation, manufacturing results and the process parameters in micro milling operations are planned.

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