Effect of high spindle speeds on micro end milling of commercially pure titanium

Sonja Kieren-Ehses¹, Martin Bohley¹, Tobias Mayer¹, Benjamin Kirsch¹, Jan C. Aurich¹

¹TU Kaiserslautern; Institute for Manufacturing Technology and Production Systems
sonja.kieren-ehses@mv.uni-kl.de

Micro milling is a highly flexible and efficient manufacturing process. Limitations arise when micro milling commercially pure titanium due to built-up edge formation, especially at spindle speeds between 80 krpm and 160 krpm (D = 50 μm). These negative characteristics of the micro milling process may be reduced when using higher spindle speeds. Therefore, an air bearing spindle with spindle speeds up to 350 krpm was applied in the presented study. With these higher spindle speeds, it was possible to achieve cutting speeds comparable to conventional milling when micro milling with tools of 50 μm in diameter. It was shown, that at spindle speeds higher than 290 krpm, the formation of built-up edges decreases. The slot bottom shows the typical milling kinematic with C- and D-marks. Thus, it is possible to increase the feed rate by high spindle speeds without using a higher feed per tooth and risking premature tool breakage. Also, the precision of the process is maintained as built-up edge formation can be avoided. This enables the use of micro milling as a highly efficient process for the production of individual and mass products with micro features.

1. Introduction

Driven by medical technology, there is an increasing demand for personalized micro products such as titanium implants [1]. To produce these individual products, an efficient and flexible manufacturing process with low set-up costs is required, such as micro milling. However, the process speed is limited by the feed rate, that also is linked to the spindle speed in terms of feed per tooth. In addition, the increase of the feed per tooth is limited by the stiffness of the tools, especially at small tool diameters. Micro milling is also characterized by high friction and high temperatures in the contact zone. Thus, during cutting of commercially pure (cp) titanium with spindle speeds between 80 krpm (krpm = 10⁵ min⁻¹) and 160 krpm (D = 50 μm) a strong built-up edge (BUE) formation limits the efficiency and the precision of the process. BUEs may improve the surface roughness as long as the BUE is not too large, but they result in higher process forces [2]. However, BUEs lead to the deposition of material on the surface. This is accompanied by larger peak-to-valley differences of the surface compared to surfaces machined without BUE formation [3]. Deposits of the BUE at the slot bottom occur mainly next to the side walls [4]. BUE formation may be reduced at higher cutting speeds by exceeding the recrystallization temperature at the cutting edge [5]. Therefore, spindle speeds up to 330 krpm were applied in the present study and the influences on surface roughness and topography, the manufacturing accuracy and the process forces were investigated.

2. Experiments

2.1. Experimental setup

For analyzing the influence of spindle speeds up to 330 krpm, an air bearing spindle was implemented into a precision milling machine. With this air bearing spindle (ABL² AW350A-101-BN), spindle speeds between 30 krpm and 350 krpm can be achieved. The spindle is adapted to the precision milling machine by a 3R° chuck. This allows a quick change between different spindles, for example when different collet chuck diameters or other ranges of spindle speeds are demanded. The precision milling machine consists of three linear axes (X, Y and Z). The working table is mounted on the X- and Y-axes (ball screw bearing; travel 100 mm x 100 mm). The main spindle is mounted on the cross roller bearing Z-axis with a travel of 60 mm.

On the working table, a dynamometer is mounted for force measurements (Kistler³, MiniDyn Typ 9119AA1; sensitivity < 2 mN, natural frequency < 6 kHz). The workpiece (cp-titanium grade 2) is fixed on a workpiece holder which is mounted on the dynamometer (see Figure 1).

Figure 1: Experimental setup and micro end mill

The tools used in the experiments were single edged (see Figure 1) made of cemented carbide (WC+Doping 91%, Co 9%). The grain size of the cemented carbide is 0.3 μm and the hardness 1950 HV30. To minimize the imbalance of the tool-spindle-system, the collet diameter of the spindle is only 2 mm. The diameter of the micro end mill is 50 μm, manufactured by a two-step grinding process for micro end mills, developed at the Institute for Manufacturing Technology and Production Systems, TU Kaiserslautern [6].

2.2 Cutting parameters

In this research, slots were milled with spindle speeds between 30 krpm and 330 krpm (cutting speed vc between 4.7 m/min and 51.8 m/min). For each series of tests, the spindle speed was varied between 30 krpm and 330 krpm in
steps of 10 krpm (30 different speeds per series). A total of three test series were carried out. A new micro milling tool was used for every test series. For each spindle speed examined, two slots with a length of 10 mm each were milled per test series. Due to the resulting short feed travel of 600 mm per tool, wear of the tools is limited to a minimum. The parameters feed per tooth \( f_z = 1 \mu m \) and depth of cut \( a_v = 5 \mu m \) were kept constant.

After setting the spindle speed to the current value, a dwell time of 5 minutes before milling guaranteed a stable bearing temperature without a change in cutting depth due to axial spindle growth. To detect the workpiece surface in Z-direction, an electric contact was used. For each spindle speed, this procedure (dwell time, workpiece detection) has to be repeated due to the spindle growth depending on the spindle speed.

2.3. Measurement technology

To analyze the run-out of the spindle at each respective spindle speed, a spindle analyzer by Lion Precision\(^1\) was used. The spindle analyzer consists of three capacitive sensors (X-, Y- and Z-direction). The sensors have a sample rate of 15 kHz and an accuracy of approximately 12.7 nm. Each spindle speed was measured for 1 s. To derive the radial run-out, the root mean square (RMS) of the vector addition of the values in X- and Y-direction was calculated. To determine the axial deviation, the RMS of the Z values was calculated.

To detect the forces in X-, Y- and Z-direction, a multicomponent dynamometer was used during the experiments. The frequency of the AC power supply voltage and the spindle frequencies were filtered using a symmetrical bandstop filter (AC voltage 50 Hz ± 5 Hz and spindle frequencies: spindle speed \( n \)/60 Hz ± 25 Hz). The effective cutting force was computed by the root mean square (RMS) of the filtered data. Then, the effective active force is determined by vector addition of the RMS values in X- and Y-direction. The passive force corresponds to the RMS in Z-direction.

The surface roughness was examined via a Nanofocus\(^1\) OEM confocal microscope with a 60x magnification objective lens (numerical aperture: 0.9; measuring field: 260 \( \mu m \times 260 \mu m \)). For each spindle speed, a field of 260 \( \mu m \) x 500 \( \mu m \) was evaluated in the middle of each slot after a feed travel of 5 mm. The arithmetic mean roughness \( R_a \) was determined in the middle of the groove for a length of 400 \( \mu m \) and filtered using a Gaussian filter with \( \lambda_0 = 8 \mu m \). The arithmetic mean height \( Sa \) of the surface was examined for a field with a length of 495 \( \mu m \) and a width of 90 % of the slot width. Additionally, the slot width was measured in these images.

3. Results and discussion

As an air bearing spindle is a highly dynamic part with an ever-changing spindle run-out over the whole rotational speed bandwidth, it is crucial to determine the radial and axial run-out before conducting the experiments. Then, it is possible to relate the spindle behavior with the resulting surface roughness and the process forces, and to calculate the deviation of the milled slot width from the nominal slot width. This contributes to a deeper insight in the process behavior.

3.1. Spindle run-out

Figure 2 shows the radial run-out of the spindle-tool system depending on the spindle speed (blue graph). As can be seen, the maximum run-out was detected as 28 \( \mu m \), blurring the scale. Hence, a second graph is depicted, detailing the scale from 0 \( \mu m \) to 2.5 \( \mu m \) (red graph). For spindle speeds between 30 krpm and 240 krpm and > 300 krpm, the run-out is between 0.8 \( \mu m \) and 2.5 \( \mu m \). These values do not have a negative influence on the process. Due to the high values in the range between 240 krpm and 300 krpm, these spindle speeds should be avoided. The axial run-out is for all spindle speeds lower than 0.7 \( \mu m \) and thus can be neglected. A low axial and radial run-out of the spindle is important when micro milling. A high radial run-out leads to a larger circle diameter of the major cutting edge and thus a larger effective tool diameter. Very high run-out values can lead to tool breakage due to run-out and tool diameter in the same order.

3.2. Surface topography and surface roughness

Regarding the slot bottoms after micro milling, surfaces could be detected where, as expected, the milling kinematic is reflected. However, surfaces influenced by the formation of BUEs could be identified. The resulting surfaces can be categorized into three different types: A, B and C. The occurrence of these three types depends on the spindle speed. Which type corresponds to which spindle speed is marked in Figure 4. Green color corresponds to type A, yellow to type B and red to type C. For type A, the slot bottom is characterized by C- and D-tracks (see Figure 3, type A). This type primarily occurred at low spindle speeds (30 krpm - 50 krpm, see Figure 4) caused by lower temperatures in the cutting zone at low cutting speeds [7]. Type A surfaces show the kinematic of face milling at the slot bottom and are not influenced by BUE formation. At higher spindle speeds (> 60 krpm), there is an increasing influence of BUE formation. During micro-milling, friction and prevailing temperatures in the contact between tool and workpiece can result in thermal softening of the workpiece and even melting with recrystallization. Thus, micro milling of titanium is characterized by BUE formation. Figure 3 type B and C show two different slot bottom topographies that occur as a result of BUE formation. Type B is characterized by adhesions, especially next to the side walls. Additionally, there are areas visible with holes smaller than the tool diameter, caused by a BUE at the minor cutting edge. Both phenomena suggest, that BUEs have formed which build and disintegrate over and over again. BUEs change the micro geometry of the minor cutting edge during milling and hence result in irregular, non-predictable slot bottoms. Type C is completely different from type A and B. While, as mentioned before, the slot bottom is also

![Figure 2: Radial run-out (RMS) and scaled radial run-out (RMS) depending on the spindle speed n](image-url)
Adhesions type

Figure 4: Amount of the encountered surface structure types depending on the spindle speed

influenced by BUE formations as for type B, the surface of type C is comparably flat and has a regular but undefined structure over the complete slot bottom caused by a large BUE at the major and minor cutting edge.

Figure 3: One example of each of the three types of slot bottom topography that have occurred during micro milling at different spindle speeds

Type A appears continuously at spindle speeds between 30 krpm and 50 krpm and sometimes at spindle speeds between 50 krpm and 120 krpm or higher than 260 krpm. Type A topographies occur when the cutting edges of the tool machine the surface and no BUE is formed. Due to the defined geometry of the cutting edges, the Sa values (112 nm ± 37 nm) are comparable with the simulated value. Deviations, for example at 30 krpm, occur due to slight adhesions at the minor cutting edges which result in locally deeper C- or D-tracks (see Figure 3 type A). There are also spindle speeds with different types at once. For example, at a spindle speed of 60 krpm (type A and B) or 150 krpm (type B and C). The different types result in high standard deviations due to the large differences of the Sa values depending on the type of slot bottom topography.

Regarding the Ra values (see Figure 6), the differences between the spindle speeds or the surface topography types is not as big as they are described by the Sa values. The reason is the position of the Ra measurement position at the slot bottom. For Sa, the whole slot bottom is considered, for Ra just one line in the middle of the slot. Thus, the adhesions next to the side walls are ignored. Additionally, Ra is a filtered value. As a consequence, for example the holes of type B are filtered out. Regarding type B, the surface is smeared due to the BUE, leading to small Ra values. This results in even smaller values compared to the simulated value of 35 μm [8]. Irregular small adhesions at the surface (type C) lead to high Ra values and standard deviations. Same with type A: Small Adhesions that deposit at the slot bottom. Here no BUE is formed. The results show, that the characteristics of the surface and the associated surface roughnesses depend on the chosen spindle speed.

Figure 5: Sa values depending on the spindle speed

3.3. Comparison of nominal and resulting workpiece geometry

For all micro milled slots of each series, one micro end mill was used without reclamping to keep the clamping error constant for each test series. Due to the high clamping error of up to 5 μm it cannot be neglected when micro milling with tool diameters ≤ 50 μm. Without reclamping, only the dynamic behavior of the tool-spindle-system influences the effective tool diameter. Based on the measurements of the radial run-out of the tool-
spindle-system the maximum deviation between the measured slot widths and the nominal value of 50 µm from 30 krpm to 240 krpm should be 2.5 µm. Figure 7 shows the measured slot widths. Additionally, the nominal slot width of 50 µm is marked. For some spindle speeds, the measured slot width deviates significantly from the nominal one, up to 30 µm. As the maximum deviation should be 2.5 µm based on the measured run-out, there is no direct correlation of the run-out and the slot width. However, the comparison of the slot width and the slot bottom type shows a correlation. Small measured widths have occurred for type A surfaces, very high widths for type C surfaces. Type B surfaces are accompanied with medium slot width deviations. This can be explained by BUE formation. At type A no BUE occurs and thus the effective diameter of the tool determines the slot width. Type B is characterized by a BUE which led to the mentioned deeper, circle-like areas. This is caused by a BUE at the minor cutting edge and not at the major cutting edge. A BUE at the major cutting edge additionally occurs at the type C surfaces. The bigger BUE moves and leads to type C surfaces. Furthermore, the BUE at the major cutting edge results in a larger effective tool diameter and thus in a wider slot.

![Figure 7: Slot width depending on the spindle speed](image)

Regarding the slot depth, no significant correlation can be observed. The slot depths vary between 4.5 µm and 5.5 µm over the examined spindle speed range. This depth variation depends on the formation of BUEs. A BUE that is formed during machining results in higher actual depths of cut and hence slightly deeper slots. When the tool exhibits a BUE during surface detection and then is ripped off during machining, the actual depth of cut and hence the groove depth is reduced.

### 3.4. Process forces

Figure 8 shows the active (standard deviation σa = 0.1 N) and passive (σp = 0.08 N) force depending on the spindle speed. The active force does not show a trend to higher or lower values over the whole spindle speed range considered.

![Figure 8: Passive and active forces depending on the spindle speed](image)

In contrast, the passive force increases with a rising spindle speed. The forces do not show a significant softening of the workpiece due to higher temperatures in the contact zone as suspected. Softening of the workpiece would lead to decreasing forces at rising spindle speeds. However, the BUE formation depending on the spindle speed and the increasing passive force suggests that a change in material cutting mechanisms occurs. The passive force increases due to material being squeezed under the cutting edges. This process is favored by a slight softening of the material which may indicate the beginning of material softening.

### 4. Conclusion and outlook

To increase the productivity of micro milling processes, spindles with higher spindle speeds are needed for higher feed velocities at constant feed per tooth. In this study, a spindle was used with speeds of up to 330 krpm. With the 50 µm diameter micro end mills used, cutting speeds between 4.7 m/min and 51.8 m/min were realized.

The influence of different spindle speeds on the surface topography and roughness, and the manufacturing accuracy when using micro end mills was analyzed regarding the process parameters. The resulting surface topography can be divided into three types depending on the applied spindle speed. For type A, the milling kinematic is reflected at the slot bottom, type B and C are a result of BUE formation. Depending on the type, high or low values of Sa and Ra occur. With regard to manufacturing accuracy, it could be shown that when a large BUE (type C) has formed, the slot width is drastically increased. At spindle speeds higher than 290 krpm, no influence of BUE formation resulting in type C surfaces is visible at the slot bottom. When machining with these spindle speeds (> 290 krpm), the surface roughness and quality, and the manufacturing accuracy are nearly the same compared to the surfaces machined with spindle speeds < 80 krpm, yet at almost thrice reduced machining times.

In further investigations, the wear of the micro end mills is going to be researched at spindle speeds lower than 80 krpm and higher than 290 krpm to determine whether the spindle speed influences the tool wear. In addition, investigations are carried out in which micro end mills with a diameter of 100 µm are used to achieve higher cutting speeds.

### Acknowledgements

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - project number 172116086 - SFB 926.

1 “Naming of specific manufacturers is done solely for the sake of completeness and does not necessarily imply an endorsement of the named companies nor that the products are necessarily the best for the purpose.”

### References