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Micro milling of brass and commercially pure titanium with all-ceramic micro end mills made from four different ceramic tool substrates

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Micro milling is a micro manufacturing process that can be used to manufacture e.g. molds for micro forming processes or for prototyping of micro parts. The commonly used tools are micro end mills made from cemented carbide. As an alternative tool substrate, technical ceramics can be used. In previous studies, we successfully manufactured all-ceramic micro end mills made from four different ceramics: Alumina, yttria stabilized tetragonal zirconia polycrystal (Y-TZP), zirconia toughened alumina and silicon nitride. To evaluate their performance and select the most promising tool substrate, we deployed the different tools for machining of brass and commercially pure titanium, grade 2 (Ti2). The geometric accuracy of the micro milled structures, their roughness values, the process forces during micro milling and the tool wear after micro milling were examined.

The results show that the micro end mills made of Y-TZP achieved the best results in both the easy to cut brass as well as the harder to cut Ti2. They were able to machine the Ti2 specimen without tool breakage, although they exhibited a high amount of tool wear. The alumina-based ceramics immediately broke off when machining Ti2. The silicon nitride tools milled high quality structures in Ti2 at the beginning but suffered sudden tool breakages after a few millimeters of travel.

Micro milling, ceramic tools, tool substrates, tool wear, cutting forces

1. Introduction

As one of the principal micro manufacturing processes, micro milling has been extensively researched and can produce three dimensional components in a wide range of materials [1]. Examples for micro components are e.g. micro molds and dies for biomedical components such as micro pumps or lab-on-a-chip systems [2]. Ultra small micro end mills are usually made of fine-grained cemented carbide, commonly single edged to increase tool stiffness [3]. The cutting edge radius of the tools directly influences the minimum chip thickness, below which ploughing becomes more dominant than cutting. To increase surface quality and avoid ploughing, a lower minimum chip thickness and/or a sharper cutting edge, is beneficial [4].

Technical ceramics offer high hardness and abrasion resistance even at high temperatures, and are available with fine-grained structures allowing for sharp cutting edges [5]. Technical ceramics have successfully been tested by Bäcker et al. as substrates for all-ceramic end mills in conventional cutting processes [6]. However, they were not able to manufacture tools with diameters below 2 mm due the limits in their grinding setup accuracy. Also, all-ceramic end mills with diameters below 200 µm are commercially not available or not being researched.

To investigate the potential of all-ceramic micro end mills, we previously manufactured end mills with 100 µm diameter made of four different ceramics as tool substrates (alumina (Al_2O_3), yttria stabilized tetragonal zirconia polycrystal (Y-TZP/zirconia), zirconia toughened alumina (ZTA) and silicon nitride (Si_3N_4)). In our study, we found that the deviations from the target geometry of the alumina-based tools were very large, likely making them unsuitable as tool substrates. Sharp cutting edges were realized with zirconia, with the silicon nitride tools exhibiting a sort of 'chamfered' cutting edge [7].

In this study, we deploy the manufactured tools in easy-to-cut brass and hard-to-cut commercially pure titanium, grade 2 (Ti2) [8], to compare them and choose the most suitable ceramic substrate for micro milling. For this, the surface quality and roughness of the machined slots, the tool wear and the process forces were considered.

2. Experimental setup

The micro milling experiments were conducted on a high precision CNC 3-axis machine tool, see Figure 1, that is mounted on a passive vibration isolated granite base. The machining table is mounted on the stacked X-Y axes, which utilize air bearings and are driven by stepper motors with a resolution of 0.1 µm and positioning accuracy below 1 µm. The machine tool's air bearing spindle is vertically mounted on the Z-axis guided by cross-roller bearings. Available spindle speeds range from 10 000 rpm to 50 000 rpm. The sample holder with the glued-on workpiece was bolted onto a Kistler[1] type 9119AA1 dynamometer used to measure the cutting forces.

Workpiece materials were brass (CuZn40Pb2) and Ti2. The

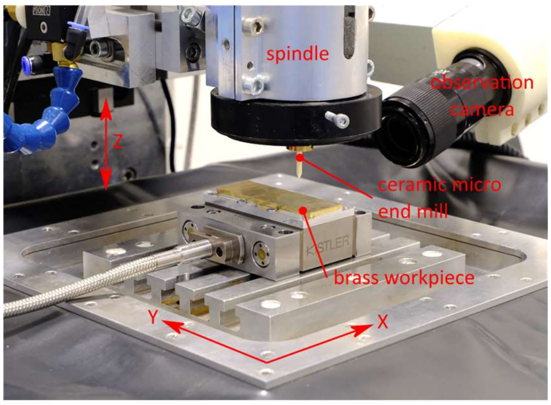

Figure 1: High precision CNC 3-axis machine tool used for the milling trials.

75 mm x 25 mm large samples were face-milled prior to the experiments. Based on previous experiments with cemented carbide tools, the cutting parameters were set as follows: Spindle speed n = 30 000 rpm, feed per tooth f_z = 1.2 µm, depth of cut a_p = 5 µm [9]. Four 25 mm long slots were machined for each tool in brass. For Ti2, slots were machined until tool failure. For each ceramic tool substrate, three tools were deployed in brass, and, due to the amount of tool breakages and wear, only two tools in Ti2.

The tools used were ground with a special grinding setup on an ultra-precision lathe, see [7] for more detailed information. The micro end mills were 100 µm in diameter, single edged with a rake angle of 0°, orthogonal clearance angle of 20° and a minor cutting edge angle of 12°. The tool geometry at the flank face allows feed per tooth values of up to 2 µm, without the back of the flank face touching the workpiece. The four tool substrates are listed in Table 1 below, with a summary of all the information regarding the milling trials.

Table 1: Experimental parameters of the milling trials.

machining condition	spindle speed	30 000 rpm
	feed per tooth	1.2 µm
	depth of cut	5 µm
	feed travel	100 mm
micro end mill specification	tool substrate	Al_2O_3
		ZTA
		Y-TZP
		Si_3N_4
	tool diameter	100 µm
	rake angle	0°
	orthogonal clearance angle	20°
	minor cutting edge angle	12°
workpiece material	brass	CuZn40Pb2
	cp-titanium	grade 2

After the milling experiments, the tools and the micro milled structures were imaged by scanning electron microscopy (SEM) with a FEI[1] Quanta 600 FEG.

In addition to the SEM images, the surface topography of the micro milled structures was analysed utilizing a Nanofocus[1] OEM confocal microscope with a 60x lens (NA = 0.9). Data processing was done with DigitalSurf[1] MountainsMap. In the software, the profile roughness values R_a (gaussian filter, λ_c = 8 µm) were calculated along the centre of the slot, as well as the areal roughness values S_a, for an area covering 90 % of the slot width and 260 µm in length.

The cutting forces measured with the dynamometer were amplified with three Kistler[1] type 5011 charge amplifiers and digitized with a National Instruments[1] USB-6210 data acquisition device. The sampling rate for all three channels was set to 12 kHz. The post process filtering and analysis was done in National Instruments[1] DIAdem: To eliminate noise from the AC mains and possible crosstalk above the dynamometer's resonant frequency, a bandpass filter (8th order Bessel filter, phase corrected) from 250 Hz to 3 500 Hz was employed. After filtering, the active cutting force was computed by vector addition of the forces in X- and Y-direction. The effective active cutting force was then calculated with a moving root mean square (RMS) average with a windowing size of ± 500 revolutions (calculated from an FFT analysis).

3. Micro milling experiments in brass

Figure 2 displays one of each tool after deployment in brass, as well as the milled structures. The tools show no signs of wear, their shape with the large, visible grain breakouts around the entire tool tip is identical to the one before deployment [7]. However, even though brass is very easy to cut, one alumina and one ZTA tool suffered a catastrophic tool failure, where a large part of the cutting edge broke off after a few millimeters of travel. The milled slots show a lot of adhesions and even substructures, but are still of better quality than expected, considering the tool shape. The slot milled with the alumina tool on the bottom left of Figure 2 shows heavy smearing and adhesions. A possible explanation for this might be the dull cutting edge of the micro end mill. The cutting process was dominated by ploughing, and due to the low shear strength of brass the ploughed material was smeared across the slot bottom. This is especially evident at the slot sides, where the uncut chip thickness is very low. The amount of ploughed material in front of the cutting edge might also lead to an increased effective tool diameter, which would explain the increase in slot width versus the ZTA tool.

The slot milled with the ZTA tool does show only few adhesions and no signs of smeared material. However, due to the grain breakouts at the cutting edge, a substructure appears at the sides of the slot. Two distinct steps can be discerned in the SEM image. It appears that the cutting edge was sharp enough to cut the material and avoid ploughing, but the actual cutting edge was moved slightly inward from the nominal position. Substructures also appeared in the trials with one alumina and another ZTA tool.

Comparing the silicon nitride and zirconia tools in Figure 3, top, to the alumina and ZTA tools in Figure 2, top, the difference in shape becomes apparent. Both former tools have the correct tool shape and no large breakouts at the tool tip. However, the silicon nitride tool's cutting edge corners are visibly rounded due to some grain breakouts, with a cutting edge radius in the range of one to two micrometers, judging from the SEM images. In contrast, the cutting edges of the zirconia tool are sharper, with a radius below one micrometer. Because of the better tool shape and sharpness, a much better quality of the micro milled

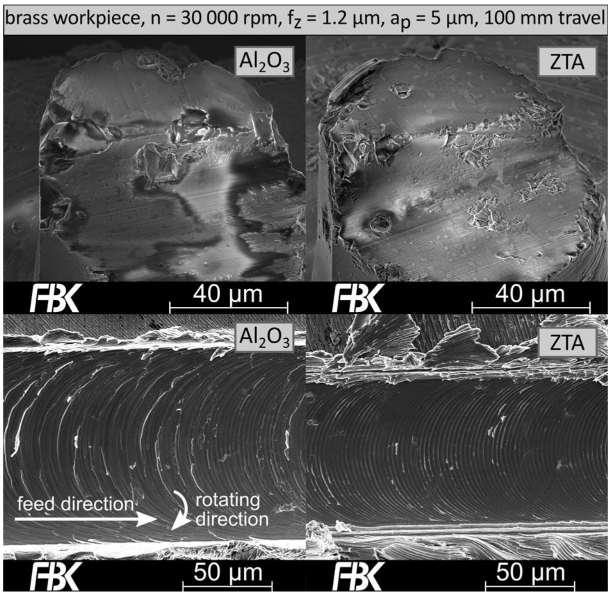

Figure 2: Alumina and ZTA micro end mills (top) and milled slots (bottom), each after milling trials in brass.

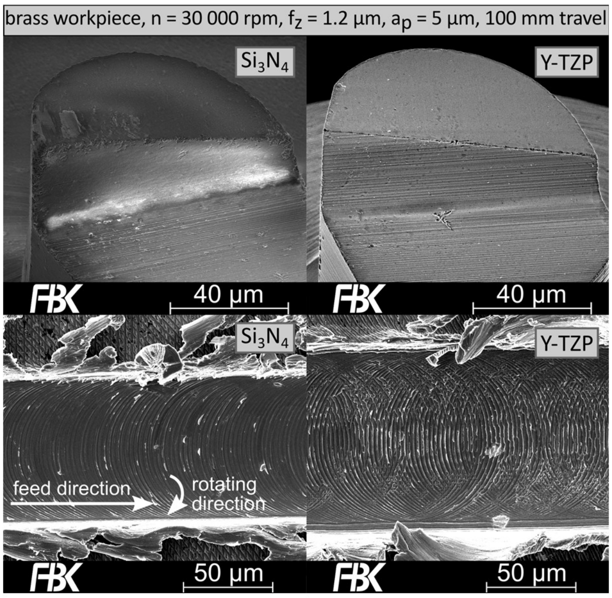

Figure 3: Silicon nitride and zirconia micro end mills (top) and milled slots (bottom), each after milling trials in brass.

structures was expected. This can be seen in the bottom images of the slots in Figure 3, where the milling kinematics are clearly identifiable. Again, comparing the milled slots to the ones manufactured with the alumina and ZTA tools, no smearing and adhesions or substructures appear. This can be attributed to the sharper cutting edges of the silicon nitride and zirconia tool. In fact, the slot milled with the zirconia tool in the bottom right image shows C and D milling tracks that only occur with the sharp zirconia tools, but not for the slightly duller silicon nitride tools. Similarly to the alumina and ZTA tools, the tool shape is unchanged after deployment with no tool wear observed.

In addition to the qualitative evaluation, Figure 4 displays the roughness values for the brass trials as a mean value over all three tools tested for each substrate. For the measurements, the first slot of each trial run was imaged at 12.5 mm travel. The roughness values are in the same range, apart from the silicon nitride tools. Both the R_a and S_a values are lower than for the other tools. This could be attributed to cutting edge sharpness: The silicon nitride tools are sharper than the alumina and ZTA tools, and thus have less or no ploughing. Yet they are duller than the zirconia tools, resulting in more shallow milling marks at the slot bottom due to the higher cutting edge radius. That effectively 'smoothens out' the generated surface as the waviness of the milling kinematics is reduced. The C and D tracks in Figure 3, bottom right, likely are the reason for the higher R_a values of the zirconia tools.

Overall, the alumina and ZTA tools did mill the entire feed travel, apart from one tool of each substrate which had a large

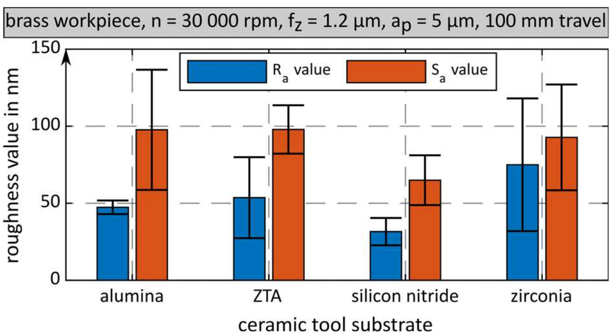

Figure 4: Roughness values R_a and S_a for the slots milled in brass versus the ceramic tool substrates (average over three trials).

part of the cutting edge corner brake off after a few millimeters of travel. The milled slots exhibit adhesions and smearing due to severe ploughing and substructures dependent on the exact cutting edge shape of the tool. The silicon nitride and zirconia tools produce better quality structures, with the silicon nitride tools having the lowest roughness. The zirconia tools are the sharpest in the trials, resulting in C and D tracks on the slot bottoms, and therefore increased roughness.

4. Milling experiments in Ti2

From the milling trials in brass, in which one alumina and ZTA tool already broke off, it was not expected that the tools would be able to mill Ti2. This proved to be correct, as all four tools (two of each material) broke of immediately after workpiece contact. The low fracture toughness, the dull cutting edges and the incomplete tool shape, stemming from the large grain sizes of the substrates, in combination with the hard to cut Ti2 resulted in too much load. Thus, it can be concluded that alumina and ZTA substrates with grain sizes larger than 1 µm to 2 µm are not well suited for micro milling.

The difficulty of machining Ti2 was also apparent for the silicon nitride and zirconia tools. The silicon nitride tools reached a feed travel of only 1.5 mm and 7.5 mm, respectively, before suffering a sudden tool breakage. Figure 4, top left, exemplarily shows the slot milled with the first silicon nitride tool shortly before the tool failure occurred. There is heavy smearing next to the left side wall, which was milled in back cutting and represents the up milled side of the slot. Adhesions can be seen over the entire slot width, but no geometric deviations from rapid tool wear can be seen. Judging by the amount of smears, it seems that the rounded cutting edge of the silicon tools as seen in Figure 3, top left, results in a large amount of ploughing when milling Ti2. The slot at the tool failure point is unremarkable as well for both tools, suggesting the tool substrate cannot tolerate the cyclical loads, resulting in a sudden tool failure without prior indications.

The zirconia substrate did not fail for both tools deployed, but suffered severe tool wear, as can be seen in Figure 5, top right. The wear of the tool can be visually tracked by examining the milled slots: In the first slot in Figure 5 bottom left, the tool wear was minimal; while in the last slot in Figure 5, bottom right, the tool was mostly cutting with built-up edges (BUEs) and only a

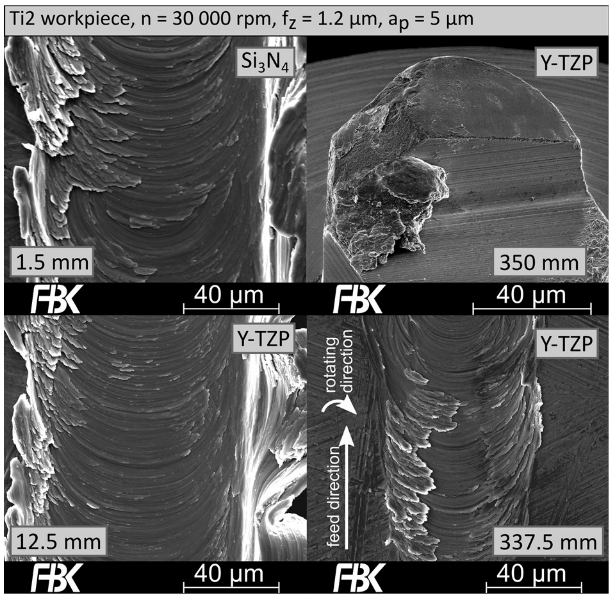

Figure 5: Slots and micro end mill after milling trials in Ti2: Slot milled with silicon nitride tool before tool failure (top left), slots milled with Y-TZP tool (bottom), and Y-TZP tool (top right).

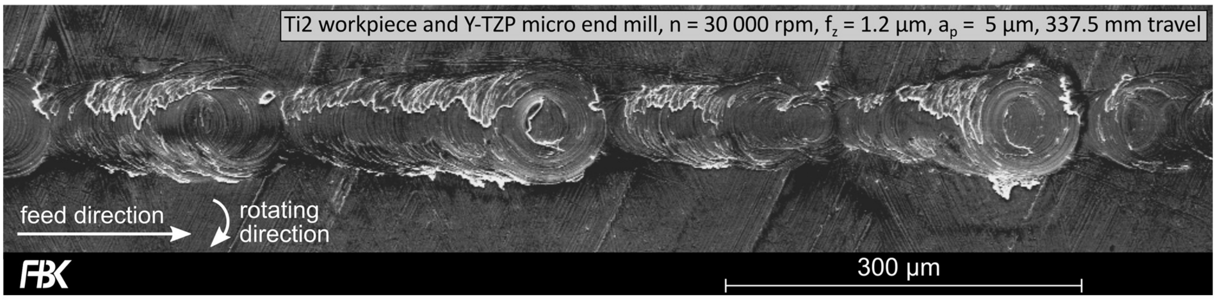

Figure 6: Cyclic built-up edge formation and collapse during micro milling of Ti2 with the worn Y-TZP tool.

very narrow slot was manufactured. The formation and collapse of the BUEs is depicted in Figure 6, where multiple BUE cycles can be identified. On the resulting cutting edge of the worn zirconia tool in Figure 5, top right, a large BUE can be identified that did not shear off. The approximate 45° angle of the resulting cutting edge explains the 'cone' shape of the structures in Figure 6, too. With no BUE attached to the tool tip, the tool barely contacts the workpiece at the most inward point of the cutting edge in a ploughing manner. Over multiple revolutions, enough material accumulates at the top part of the cutting edge corner to form a BUE. This then assumes the role of the cutting edge, removing more material and enlarging itself along the 45° angled cutting edge. Thus, the milled structure widens and on the BUE's collapse the 'cone' ends. At that point, the tool only contacts the workpiece at the most inward point of the cutting edge again, and the cycle repeats itself.

In addition to the visual tracking of the tool wear through the deteriorating structure quality, this can also be seen in the measured cutting forces. Figure 7 shows the root mean square of the active force during the zirconia milling trial, with the average force per slot indicated by the orange markers. The forces decline in a linear manner, along with the increasing tool wear which results in less material being removed. The beginning of the tool wear in slot one can also be identified, as well as the start of the cyclic BUE formation after slot 8 and 9 by the sudden force drops. The increase in cutting force in the last slot coincides with the BUE formations shown in Figure 6, which removed more material than in the previous slots.

Overall, milling of Ti2 with the zirconia tools is not feasible. Comparing the results for silicon nitride and zirconia, the trials showed that a higher fracture toughness is preferrable to avoid sudden tool failure, even at the cost of reduced hardness and higher tool wear. This is especially true for micro milling, where tool breakages are far more common than in conventional milling, e.g. due to the small diameters and unproportionally reduced torsional section moduli [10]. As it allows for a much more stable process with its predictable wear behavior, zirconia will be chosen as the tool substrate for all-ceramic micro end mills for future manufacture and deployment.

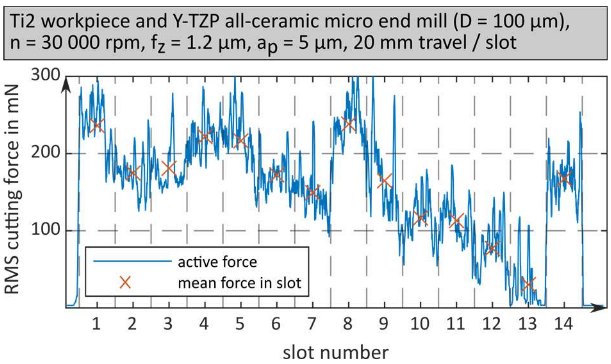

Figure 7: Moving average RMS cutting force from the Ti2 milling trials with the Y-TZP tool.

5. Conclusion and outlook

In this study, all-ceramic micro end mills made from four different ceramic substrates were used for milling trials in brass and Ti2 to evaluate their performance and choose the most suitable one. In the milling trials with brass, the alumina and ZTA tools showed low quality structures in the slot bottoms, and suffered immediate tool breakages in the Ti2 trials. Therefore, these materials are not well suited for micro end mills.

The silicon nitride and zirconia tools showed promise in the brass trials, but the silicon nitride tools suffered sudden tool breakages without warning in the Ti2 trials. The zirconia tools did not break in the Ti2 trials, but exhibited severe tool wear. While neither of the ceramic substrates is suited for micro milling of Ti2, zirconia allows for a much more stable process than the silicon nitride tools and was thus chosen as tool substrate for further studies.

In future studies, zirconia micro end mills will be deployed in different workpiece materials and the structure quality and the tool wear will be compared to cemented carbide tools.

Acknowledgements

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

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