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Letters

Comparison of different 3Y-TZP substrates for the manufacture of all-ceramic micro end mills with respect to the cutting edge radius and the tool wear

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ABSTRACT

In micro milling, size effects such as the ratio of uncut chip thickness to cutting edge radius result to high mechanical stresses. The tools need to be able to withstand these, with as little tool wear as possible. Cemented carbides are currently the tool substrates of choice. Technical ceramics are highly wear resistant as well, but they are not yet used in micro milling. To utilize their potential in micro cutting processes, we previously identified Y-TZP as the best ceramic for this purpose. Compared to cemented carbide, they exhibit only marginal tool wear when micro milling PMMA.

To investigate whether the 3Y-TZP characteristics influence the performance of all-ceramic micro end mills, three different substrate materials were used to manufacture tools that were tested by micro milling of PMMA. Further varied factors were the feed per tooth and the spindle speed. The initial cutting edge sharpness of the tools and the tool wear were used to quantify the results. One substrate was found to result in lower cutting edge radii and a more stable manufacturing process than the others. Also, a feed per tooth dependent wear behavior was observed.

1. Introduction

Micro milling, a scaled down version of the conventional milling process [1], is a very flexible micro manufacturing method [2]. However, size effects occur due to the scaling of geometrical aspects. For example, the cutting edges cannot be produced infinitely sharp, and thus the ratio of uncut chip thickness to cutting edge radius rises [3]. This leads to ploughing, high specific cutting forces and increased tool wear [4]. Cemented carbides are usually used as high performance tool substrates. Their small grain sizes also allow very sharp cutting edges to be produced [5], reducing the ratio of uncut chip thickness to cutting edge radius and therefore the amount of ploughing [6]. Technical ceramics have proven to be highly wear resistant in conventional machining [7]. They are available in submicron grain sizes, too [8]. While the grain sizes are not as small as those of cemented carbides, sharp cutting edges can still be produced.

Ceramic tool substrates are not used in micro milling thus far, which is why we want to research their use. In previous studies, we investigated grinding as a manufacturing method, different ceramic substrates and micro milled structures in different workpiece materials. The Y-TZP micro end mills performed best among the ceramic substrates in terms of both tool sharpness and tool wear in the milling trials [9]. In comparison to cemented carbide tools, significant improvements were achieved when micro milling polymethylmethacrylate (PMMA). In PMMA, tool wear was reduced, with lower and more stable process forces and improved surface quality of the micro milled structures.

With the micro tool substrate and the workpiece material defined, we wanted to investigate whether Y-TZP substrates whether Y-TZP substrates with identical composition from different suppliers had an effect on the tool geometry/sharpness and micro milling performance. Differences in the manufacturing process could result in different specifications of the tool blanks. Factors for this are the raw powders used for ceramic sintering and the sintering process itself. In this study, we therefore deployed micro end mills ground from three different Y-TZP substrates in PMMA. We compared the initial cutting edge sharpness of the tools and the tool wear after the micro milling trials to quantify the results.

2. Materials and methods

The tool substrates used to grind the all-ceramic micro end mills all were 3Y-TZP (zirconia stabilized with 3 mol% of yttria), though their individual specification/ mechanical properties differ

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as displayed in Table 1. From the tool blanks, all-ceramic end-mills were ground on our custom setup using an ultra precision lathe. The effective tool diameter of the single edged tools was 50 μm, with axial rake and helix angles of zero degrees. Further details of the grinding setup and process, and the tool geometry can be found in [10]. The tools were applied on a 3-axis high precision CNC machine in our laboratory, see [9]. The machine tool has stepper motor actuated axes (resolution 20 nm, two sided positioning accuracy < 1.5 μm) and an air bearing main spindle capable of speeds up to 50.000 min^{-1}. The PMMA workpieces were glued onto a sample holder and mounted on the XY-table of the machine tool. After face milling, meandering slots of 25 mm length were milled for a total feed length of 2 m. The parameters of the micro milling trials are shown in Table 1. In addition to the tool substrates, the feed per tooth and the spindle speed were varied in two steps. The design of experiments was conducted fully factorial, with one design repetition and randomized runs. The effects were analyzed via ANOVA with a p-value threshold of 0.05.

An atomic force microscope (AFM) was used to characterize the sharpness of the tools. From the measured data, the cutting edge radius in the area of the axial infeed was derived before and after the tool was used. More information on the measurement methodology and data analysis can be found in [11]. In addition to the AFM measurements, the micro end mills were also imaged using a scanning electron microscope (SEM). Prior to imaging (but after the AFM measurements) they were sputter-coated with a thin gold coating (about 20 nm thickness), which has no influence on the micro milling process. Thus, a quantitative as well as qualitative characterization of the tool wear is possible.

3. Results and discussion

Concerning tool wear, the spindle/cutting speed did not have any influence. This might be related to the absolute cutting speeds still being far lower than those commonly used in macro machining. However, this is a limitation set in place by the maximum spindle speed of 50.000 min^{-1}. Only the substrates themselves and the feed per tooth showed significant effects and are thus shown. The mean cutting edge radii of the micro end mills before the experiments are shown in Fig. 1 along with the individual tool values.

The influence of the tool substrates is clearly visible. S1 provides the sharpest cutting edges of about 400 nm. This is about half the cutting edge radius of the other substrates. S2 and S3 exhibit an average radius of 900 nm and 1000 nm, respectively. In addition, S1 also resulted in the lowest standard deviation. While the error bars of S1 and S2 are nearly identical, the individual values for S1 are very close together (aside from two outliers). This is likely a result of the combination of low grain size and high fracture toughness in comparison to the other substrates. A more stable cutting edge can thus be achieved due to less breakouts during grinding. For S2, the individual values are strongly scattered around the mean. S3 shows a completely different behavior: The standard deviation is quite large because the individual cutting edge radii are clustered in two spots. The lower cluster is at around 750 nm and the upper one at 1400 nm. This could be due to the higher hardness and lower fracture toughness of S3 leading to more grain breakouts and thus a higher cutting edge radius. The SEM image of a tool made from S3 in Fig. 3 shows a visibly larger cutting edge radius, that seems almost chamfered instead of a clean edge between rake and flank face. Overall, the tools made from S2 and S3 have large cutting edge radii. For S3, stable production is not possible due to the stochastic behavior of the cutting edge radii. In contrast, the tools made from S1 have the sharpest cutting edges and can be manufactured with a stable mean cutting edge radius.

Fig. 2 displays the increase in cutting edge radius after micro milling as percentage of the initial cutting edge radius for both feed per tooth values. Choosing the 'specific' increase over the absolute one compensates for the difference in initial cutting edge radius of the substrates, allowing to differentiate the results more accurately (for reference, the absolute increase ranges from 250 nm – 750 nm). All tools show a mean increase in cutting edge radius up to about 75%. However, for S1 at f_z = 1 μm the increase is

Table 1
Experimental parameters and properties.

machining conditions	
feed per tooth	1 μm 2.5 μm
spindle speed	30.000 min^{-1} 50.000 min^{-1}
depth of cut	10 μm
feed travel	2 m
workpiece material	PMMA
micro tools	
tool substrate	3Y-TZP
tool diameter	50 μm
substrate properties	
	S1/ S2/ S3
grain size	0.5 μm/ 1 μm/ 0.4 μm
hardness (HV30)	1291/ 1156/ 1380
K_{Ic} in $MPam^{0.5}$	7.54/ 7.26/ 6.78
compressive strength in MPa	2100/ 2500/ 2200
Young's modulus	200 GPa

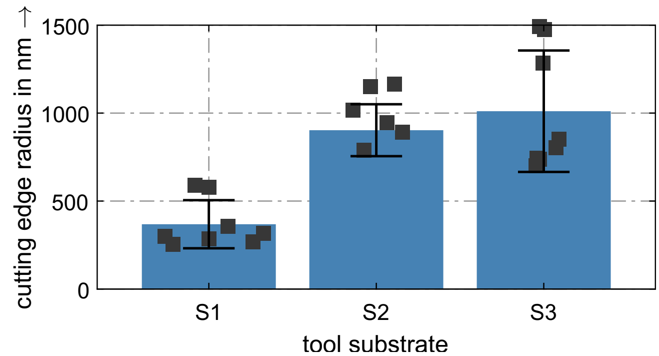

Fig. 1. Cutting edge radius of the micro end mills made from the three substrates before the experiments.

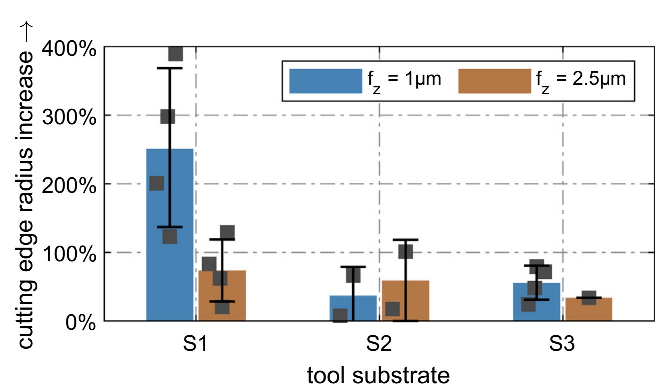

Fig. 2. Influence of the tool substrate and the feed per tooth on the cutting edge radius of the micro end mills. Displayed as percentage change of the original radius (model p-value 0.013).

significantly higher at about 250%, with a very high scatter of the values. As such, an influence of the feed per tooth is only present for the tools made from S1, which had lower absolute cutting edge radii to begin with. It seems that the cutting behavior changes when going from the lower feed per tooth to the higher one if sufficiently sharp tools are used. This could be related to ploughing processes/ the ratio of uncut chip thickness versus cutting edge radius: The cutting edge radii of S2 and S3 are closer to the feed per tooth than those of S1, and the process thus is ploughing dominated. For S1 the process changes from ploughing dominated to regular chip formation when going from the lower feed per tooth to the higher one. This suggests that a threshold instead of a gradual transition is present for the ratio of uncut chip thickness to cutting edge radius, that determines whether ploughing occurs or not. Further investigations are needed to confirm this, though.

The results from the cutting edge radii before and after the experiments can also be observed in the SEM images of the tools in Fig. 3. These show the tools of the experiments with f_z = 2.5 µm. Comparing the tools before the experiments, the larger cutting edge radii for all tool edges of S3 are obvious. For S1 and S2, the difference is much more subtle. For S2, the cutting edge seems slightly more rounded afterwards, while for S1 the cutting edges appear smooth. As expected from the change in cutting edge radii, no major wear can be observed on the tools after the experiments. Only the cutting edge corner seems to be somewhat more worn than before the experiments. This cannot be accurately determined by the SEM images, though.

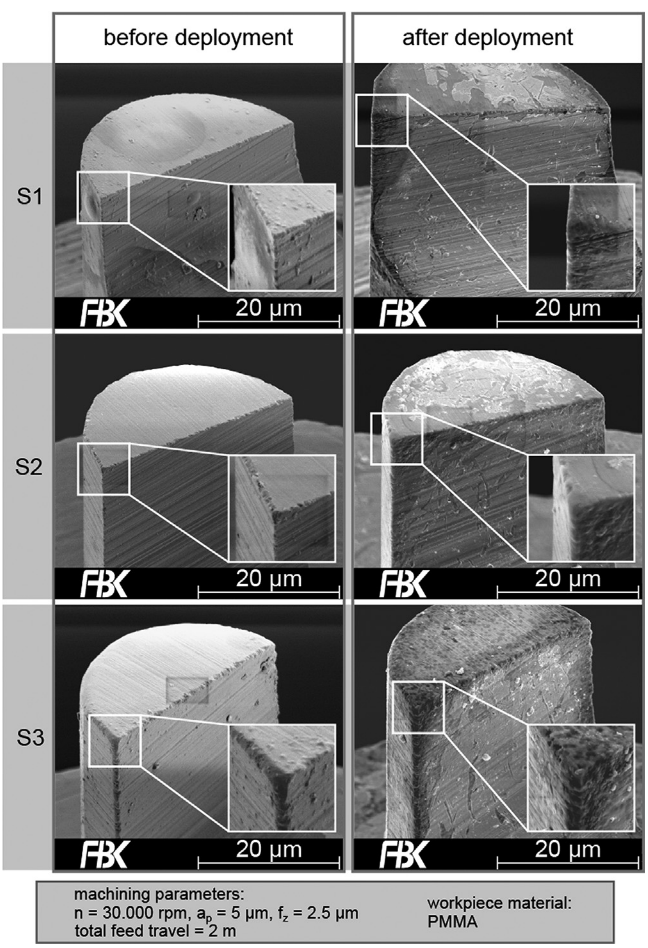

Fig. 3. SEM images of the micro end mills before and after the experiments.

4. Conclusion

In this investigation we examined the cutting edge radius and tool wear of all-ceramic micro end mills made from three 3Y-TZP substrates with identical composition, but from different suppliers and with different specification. Based on the characterization of the cutting edge topographies, we were able to identify large differences in the achievable cutting edge sharpness and the standard deviation of the mean radius. Substrate S1 was found to repeatably produce the micro end mills with the lowest cutting edge radii, likely due to its low grain size and high fracture toughness. In the micro milling experiments, these sharp tools showed a wear behavior dependent on the feed per tooth: For the lower feed per tooth, the cutting edge radius rose significantly. For the higher feed, the increase in radius was in line with the other tools. Furthermore, the SEM images of the tools confirmed the results of the changes in cutting edge radius after the experiments. Based on these findings, substrate S1 will be used for future tool production. The feed per tooth dependent behavior of the tools will be investigated in further experiments.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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[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."

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