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Benchmark of tools for machining dental ceramics

A benchmark test carried out at the Faculty of Mechanical and Process Engineering at Augsburg University of Applied Sciences shows that when machining zirconium dioxide in dental technology, the choice of milling tools has a significant effect on the quality of the results and the efficiency of the processes. The production of dummy crowns with different wall strengths – also known as the Merlon test – demonstrates that only few tools can guarantee a consistently high quality. The finest structures could only be processed convincingly with the leading benchmark winner. The test results of the study also show that the coating of the tool is crucial for tool life and a high yield.

MADE IN GERMANY

Summary of the findings

The benchmark test of tools for the machining of zirconium dioxide carried out at Augsburg University of Applied Sciences in the context of a bachelor thesis signifies the following for the dental practice: With standard carbide tools acceptable results can only be accomplished for a short duration. In order to ensure the reliable production of prosthesis components or monolithic crowns and bridges made of zirconium dioxide, specialized material-specific tools should be used. In particular the tool life test shows that a consistently high quality can be achieved with the HC720DT-DIP®3S tool from Hufschmied Zerspanungssysteme GmbH, closely followed by the Dentsply Sirona tool. All in all, the test clearly shows that investing in high-quality tools tailored to the respective dental milling machine makes a decisive contribution to process reliability in prosthesis production.

Reference

The following text is based on the bachelor thesis „Influence of tool geometry on the machinability of dental ZrO2 ceramics" by Lena Wieland, Augsburg University of Applied Sciences, December 2019, first examiner Prof. Dr.-Ing. The text presents a selection, summary and interpretation of the findings of the benchmark test documented in the admission work. As a follow-up to the bachelor thesis, the benchmark test was also carried out under the same conditions for the tool supplied by the machine manufacturer. The results are included in the extended benchmark evaluation used here. The whitepaper does not use any scientific apparatus - please refer to the work of Ms. Wieland for a list of references.

The Faculty of Mechanical and Process Engineering at the Augsburg University of Applied Sciences offers Bachelor's degree courses in Mechanical Engineering (B.Eng.), Mechatronics (B.Eng.) and Environmental and Process Engineering (B.Eng.) as well as Master's degree courses in Applied Research (M.Sc.), Lightweight Construction and Fibre Composite Technology (M.Eng.), Environmental and Process Engineering (M.Eng.) and Part-time Technology Management (M.Eng.). The Faculty of Mechanical and Process Engineering understands research as „application-oriented research": With scientific methods, knowledge should be generated in order to create new products and processes or to further develop existing products and processes. This new knowledge is to benefit teaching. Research is not meant to be an objective in itself, but should benefit society, taking into account human dignity and the aspects of sustainability (resource efficiency). In addition to numerous projects, especially on topics of materials research, there are two cross-departmental projects on simulation in mechanical engineering and on composites in mechanical engineering.

The importance and properties of zirconium dioxide

In addition to the mechanical properties, biocompatibility and aesthetics are the focus of attention in artificial teeth. The ceramic veneer of a metallic substructure offers further potential for improvement, especially in the visible area, since the total opacity of the metallic material means that the appearance of a natural tooth cannot be achieved. All-ceramic solutions are the alternative. Here, in addition to the veneering of the crown, the framework constructions are also made of a ceramic material.

The development of the high-performance ceramic zirconium dioxide has made all-ceramic restorations commercially competitive. Due to its extremely good mechanical properties, zirconium dioxide is mainly used as a framework material in the front and side tooth area. In addition to its use as a framework for veneers, it can also be used as an all-ceramic. Such monolithic crowns or bridges do not have a veneer, but consist exclusively of zirconium dioxide. The originally white material can be coloured in the corresponding tooth colour.

Processing

When milling zirconium dioxide, a distinction is made between two processing concepts: the processing of ceramics that have already been sintered through and the processing of white bodies. In the first process, the ceramic material is available in its almost pore- and defect-free form due to the sintering process. The sintered, hot-isostatically pressed zirconium dioxide, also called hipped zirconium dioxide, already shows its very high final strength. Machining this so-called densely sintered, extremely hard material places very high demands on machine and tool, requires cooling and results in long process times and high tool wear. Therefore, the far more common process - and subject of the benchmark of the Augsburg University of Applied Sciences - is the machining of the so-called whiteblanks. The starting material is a pre-sintered zirconium dioxide block with a compression ratio of 55-70%. The much lower strength compared to the sintered through variant enables a faster, lighter and thus more cost-effective subtractive production. Cooling of the machining process is not necessary. The ZrO2 then acquires its final strength during the subsequent sintering process. This leads to a uniform shrinkage in all spatial directions of 25-30 %, which must already be taken into account and compensated for in the component design.

The benchmark test

Tools

The test compared coated carbide full-radius milling tools with 2.5 mm cutting edge diameter from ten manufacturers. Two of the manufacturers could only supply tools with 2.0 mm, two of the tools were uncoated. Important: All tools were declared suitable for zirconia machining by the respective manufacturers.

Machine

The test was carried out with a 5-axis milling and grinding centre developed for the dental technology market: Sirona inLab MC X5. Each of the circular blank machining operations took 6 to 8 hours and was completely automated and performed without human intervention.

Material

The material used is zirconium oxide rounds inCoris TZI C provided by the company Sirona. These discs have a diameter of 98.5 mm and a height of 16 mm. They are translucent, pre-coloured, pre-sintered zirconia.

Workpiece in the Merlon Fracture Test

30 reference bodies are milled out of each blank, which roughly resemble a crown and have crenellations of different material thicknesses: 0.1 mm, 0.2 mm, 0.3 mm, 0.4 mm and 0.5 mm. Of interest in this Merlon test (Merlon = French pinnacle), which is customary in the industry, is the quality of the pinnacle as well as of the bases. In the Merlon Fracture Test, a pinnacle is considered to be in order if less than 1/3 of the material has broken off during the milling process. The quality of the base, on the other hand, is characterised by the translucency. If you can see through it with the naked eye, the area is considered defective.

Figure 1: STL file of the Merlon test crown

Quality control

For the test, a method was developed to evaluate the measurements of the milled crowns with a Keyence digital microscope. A circular measuring line is chosen, which runs along the crenellations. A height coordinate can now be assigned to each point of this measuring line, resulting in the diagram in the lower part of figure 2.

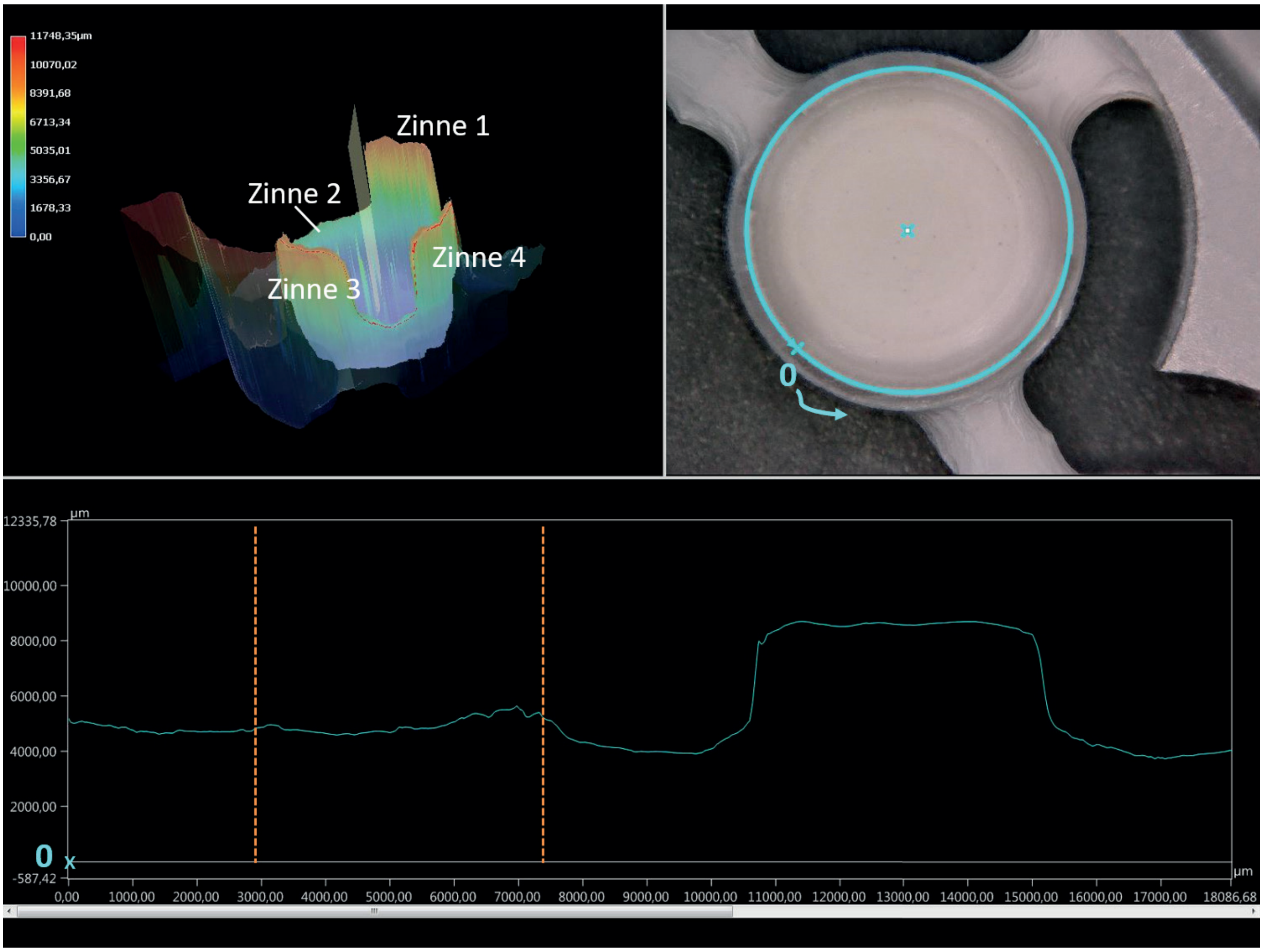


Figure 2: Measurement of a crown by circular measuring line

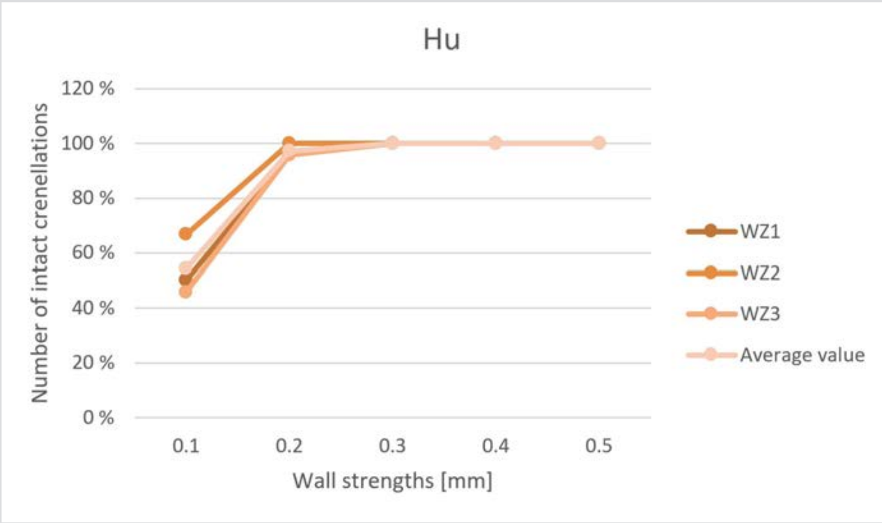
The X-axis corresponds to the course of the measuring line and thus the circumference of the measuring circle. The Y-axis shows the height values. The result is a diagram with more or less complete steps, which represent the four merlons of the crown. With the naked eye it is often difficult to judge whether the broken out area is more than 1/3 (corresponds to 33 %) of the merlons. By calculating the area below the graph in the area of the merlons, this decision criterion for passing the Merlon test can be clearly determined. This calculation has been implemented in a program that compares the measured data imported into Matlab with the „ideal battlement area" - first for one crown and then for the entire circular blank. In this way, the automated test can reliably differentiate between intact or defective blanks.

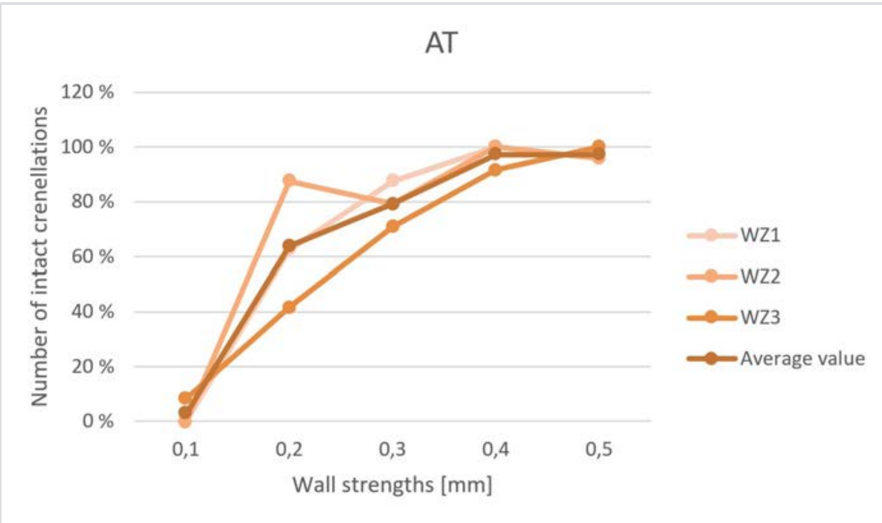
Test procedure

The milling of the blanks is repeated with three tools from each manufacturer. The six tools from the manufacturers with the best results are then subjected to a test of the service life behaviour. For this purpose, the machining process is carried out two additional times with one milling cutter already in use, so that one of the tools machines a total of three blanks. This is the tool life test, in which the effect of wear on the tool on the quality of the machining becomes visible.

Test result

The test results were assessed both with the naked eye and by means of the readings taken with the algorithm developed for this purpose - the algrorithm is better able to decide on the criterion „maximum 33 %" in case of doubt, especially in relation to material breakage. The assessment factors for success and failure are bases and crenellations. For each manufacturer, a diagram was prepared which shows the percentage of intact crenellations and bases for each of the five different wall thicknesses. The results for the three different tools of the test runs for each manufacturer are shown with differently coloured curves.





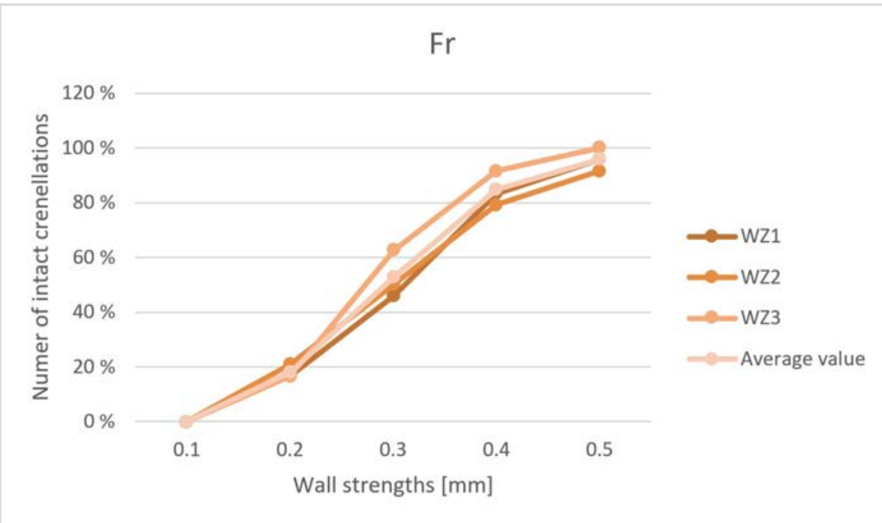


Figure 3: Three examples of the percentage evaluation: In the case of the benchmark winner Hufschmied, the results for all three tools are tightly correlated - unlike, for example, the competitor AT. While Hufschmied achieved an average success rate of 54 percent even for the 0.1 mm thin crenellations, others only achieved this with walls three times as thick (example Fr).

In order to be able to assess the quality of the machining process in a meaningful way, two variables are introduced as key indicators, according to which all manufacturers are compared: linear and quadratic performance. The former generally indicates the percentage of all crenellations or bottoms of a round blank that are in order. This is simply the average value of the intact merlons of the different wall thicknesses. The calculation of the quadratic performance is of more interest here, since it not only takes into account the number of defective heads and merlons, but also the respective merlon wall thickness in the evaluation.

With this method, the performance of a milling cutter is evaluated as significantly worse if crowns of larger wall thicknesses are defective. By contrast, if defects are only found on crenellations and bases with a wall thickness of 0.1 mm, this has a significantly lower negative effect on the performance.

The formula of the square performance P2 is

$$P2 = 1-[(1-W0.1[\%])*(0.1*10)2+(1-W0.2[\%])*(0.2*10)2+(1-W0.3[\%])*(0.3*10)2+(1-W0.4[\%])*(0.4*10)2+(1-W0.5[\%])*(0.5*10)2 / [(0.1*10)2+(0.2*10)2+(0.3*10)2+(0.4*10)2+(0.5*10)2]$$

W0,1 [%] represents the percentage of intact crenellations of a wall thickness of 0.1 mm.

Higher performance values indicate better machining of the ZrO2 blanks by the tool. The following table summarizes all calculated values of the quadratic and linear performance.

	Bases						Crenellations					
	Tool 3		Tool 2		Tool 1		Tool 3		Tool 2		Tool 1	
	P² [%]	P [%]	P² [%]	P [%]	P² [%]	P [%]	P² [%]	P [%]	P² [%]	P [%]	P² [%]	P [%]
Hu	100	100	100	97	100	97	99	88	99	93	99	89
DS	100	100	100	100	100	100	99	88	99	90	97	88
Dt	99	90	100	97	100	100	96	74	97	78	97	78
Fr	100	100	100	100	100	100	84	54	74	48	77	48
AT	100	100	100	100	100	100	87	63	92	73	92	69
AG	99	90	99	90	99	90	97	79	96	79	96	81
Zr	100	97	100	100	100	100	95	75	94	70	95	73
Ac	100	100	100	100	100	100	90	65	97	83	89	63
Ka	100	100	100	100	100	100	92	66	95	72	95	73
Zz	99	90	100	97	100	100	94	72	95	73	95	73

Figure 4: Results of the quadratic and linear performance

The classification of the milling tools was based on the average values of all three tools used. (Figure 5). To minimize roundoff errors in this case, the values in this table are given with two decimal digits. The clear result: The tools from Hufschmied Zerspanungssystem GmbH are the benchmark winners.

Tool life test

For further investigation, the best six manufacturers were selected whose tools showed an average square performance of at least 95 % in the crenellations tested. It is interesting to note that these include the two uncoated cutters AG and Zz. According to this, a coating does not seem to be essential for machining only a single blank, i.e. 30 crowns.

Without tool change, three more blanks were milled for the tool life test. Figure 6 shows the results of the tool life test. While the tools are still relatively close to each other in terms of performance when machining the bases, the results of the walls clearly separate the wheat from the chaff. The performance of the uncoated tools drops sharply from the second round blank onwards. There are also obvious differences in the quality of the coating and its wear behaviour. Only the Hufschmied tools show a consistent maximum performance during all three cycles.

	Average value			
	Bases		Crenellations	
	P² [%]	P [%]	P² [%]	P [%]
Hu	99.80	97.78	98.96	90.28
DS	100.00	100.00	98.36	88.61
Dt	99.60	95.56	96.82	76.67
Fr	100.00	100.00	78.16	50.28
AT	100.00	100.00	90.13	68.06
AG	99.09	90.00	96.26	79.72
Zr	99.90	98.89	94.62	72.50
Ac	100.00	100.00	92.05	70.56
Ka	100.00	100.00	94.09	70.28
Zz	99.60	95.56	94.90	72.22

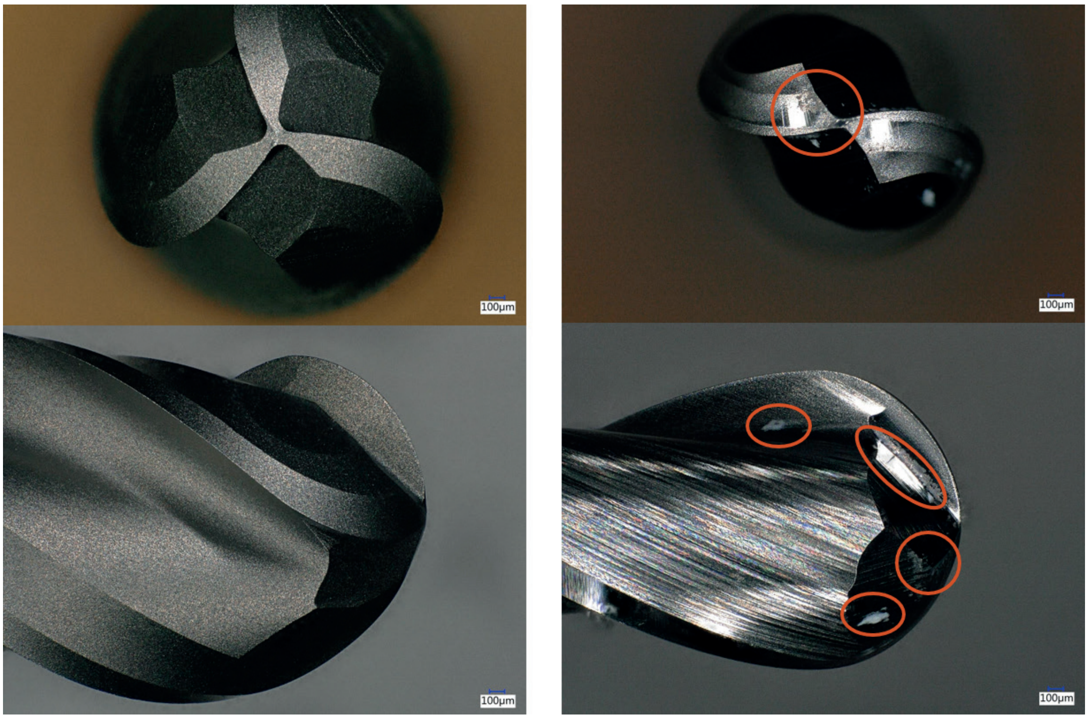
→ in ascending order →

	Average value	
	Bases	Crenellations
	P² [%]	P² [%]
Fr	100.00	78.16
AT	100.00	90.13
Ac	100.00	92.05
Ka	100.00	94.09
Zr	**99.90**	**94.62**
Zz	**99.60**	**94.90**
AG	**99.09**	**96.26**
Dt	**99.60**	**96.82**
DS*	**100.00**	**98.36**
Hu	**99.80**	**98.96**

Figure 5: Average values of the quadratic and linear performance determine the winner of the test.

	Walls			Bases		
	Cycle 1	Cycle 2	Cycle 3	Cycle 1	Cycle 2	Cycle 3
Hu	99%	99%	99%	100%	100%	100%
Ds	97%	99%	99%	100%	100%	100%
Dt	96%	94%	94%	99%	100%	99%
AG	97%	73%	16%	99%	96%	91%
Zr	94%	92%	90%	100%	100%	100%
ZZ	95%	65%	6%	100%	98%	92%

Figure 6: The results of the endurance test



Left: Cutter Hu after the 3rd operation
Right: Cutter Zz after the 3rd operation

Figure 7: Tool Hu and Zz after milling three blanks (image source: Hufschmied Zerspanungssysteme GmbH)

Figure 7 compares the milling tools from the company Hufschmied (left) and one of the uncoated tools Zz (right) after the entire series of tests. A clear difference in the condition of the tools can be seen here. While the tool on the left does not show any defective spots in the coating or in the geometry, the one on the right clearly shows signs of wear (marked in colour). The perfect condition of the benchmark winner from Hufschmied explains the consistently high quadratic performance in all three machining cycles.

From the available results, a clear correlation between the coating of the cutters and the tool life behavior can be deduced. Uncoated milling cutters can machine zirconia well for short periods of time, but the quality drops rapidly and dramatically with the number of milled blanks and crowns. In the dental practice, this means in order to achieve a continuous high performance, the tool must be equipped with a diamond coating, since damaged tools do not achieve high-quality machining results.

Conclusion

„With the benchmark of the Augsburg University of Applied Sciences we have the scientific confirmation that we have been successful with the development of a milling tool specifically for the machining of zirconium dioxide for dental applications. Decisive for the outstanding results in terms of machining quality and tool life are the cutting edge geometry of the HC720DT-DIP®3S, which is tailored specifically to the material, and combined with our proprietary diamond coating. Here, dental technology takes its lead from experience with industrial processes:A consistent and process-reliable production in dental technology is only possible with high-quality special tools", says Ralph Hufschmied, Managing Director of Hufschmied Zerspanungssysteme GmbH. „In addition to the adaptation of tools to the material to be machined, there is potential for optimization in our daily practice at the customer's site by taking into account the characteristics of milling machines and machining programs. This is confirmed by the good performance of the Dentsply-Sirona tool. Another consequence of the benchmark: Manufacturers of milling machines for dental technology can score points by providing optimized tools. We are happy to offer our know-how in cooperation with them.

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