EVALUATION OF MACHINING STRATEGIES FOR THE MANUFACTURE OF DENTAL PROSTHESES IN ZIRCONIA USING THE CAD/CAM TECHNOLOGY

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ABSTRACT

The continuous use of the CAD/CAM technology in dentistry has offered new possibilities of materials and procedures for the manufacture of dental prosthesis. The present study aimed to evaluate the CNC machining of dental zirconia copings, as well as the surface quality of the workpieces. Two different milling sequences combined with two distinct cutting strategies were analysed. After establishing the best combination of strategy and machining sequence and prioritizing the surface finishing and the machining time of each sample, the tests were performed using varied feed rates. The combined use of the machining sequence, the strategies and the milling parameters had a strong effect on the final finishing and the productivity of the workpieces. The parameters used proved to be effective with the use of 3D offset strategy. The recommended feed rate for roughing and finishing surfaces was 1600 mm/min.

KEYWORDS: *Zirconia, CAD/CAM, CNC Milling, Prostheses, Dentistry*

I. INTRODUCTION

The use of new materials, including translucent and multicoloured zirconia, processed via CAD/CAM has brought new opportunities to the market for the production of dental restorations. The clinical and aesthetic outcomes of dental prosthetics have been constantly improving due to the combination of methods, materials and technologies.

The main objectives of the CAD/CAM systems are automation (mass customization) of the production process for dental prostheses and better quality and accuracy of fit in the mouth. Considering that each sequential step of the process will add a degree of inaccuracy to the final piece, which ranges from 50 to 75 microns [1-5], it is of utmost importance to consider the effects of each step on the quality and accuracy of the final workpiece.

There is an increasing demand for studies on CNC milling, involving the production of dental prostheses via CAM programming, strategies and zirconia cutting tools [6-8]. Mello et al. [9] evaluated the marginal adaptation of fixed dental prosthesis frameworks fabricated by CAD/CAM with three different systems of data acquisition. They demonstrated that CAD/CAM system has lower discrepancy when compared with the conventional method. Denkena et al. [10] investigated the impact of hard machining on the material properties to establish a correlation to failure. They showed that the uncut chip thickness plays an essential role in machining zirconia. Hamza and Sherif [11] conducted a study to evaluate the marginal fit of 5 different monolithic zirconia restorations milled with different CAD/CAM systems and concluded that the type of CAD/CAM used affects the marginal fit of the restoration.

The present study has been carried out using partially sintered ceramics [12-13], milling the restorations in a green zirconia block, which was sintered and shrank to the desired size and hardness. It is worth mentioning that for finalization of the prosthesis and subsequent placement in the mouth, the zirconia needs to be sintered, however, this procedure was not part of the present study.

Thus, the present work aimed at evaluating the machining of dental zirconia copings, as well as the surface quality of the workpieces. To this end, some machining tests were proposed using varied cutting parameters, strategies and sequences of the machining programs.

In addition to the introduction (section I), the structure of the article is given as follows. Section II presents the materials and methods used in this study. Section III shows the results and discussion, and finally the conclusion (section IV) and future work (section V) are presented.

II. MATERIALS AND METHODS

For the CNC machining, a partially sintered 3mol% yttria (Y_2O_3) stabilized zirconia (ZrO_2) block was used [14-16]. The material was a U16W zirconia disk (D98*16) manufactured by Upcera®. The specimens were milled using the DM5 milling machine (Tecnodrill®) with a power of 2500 W, spindle speed up to 36000 rpm and feed rate up to 12 m/min. Two spherical tools (Zirkonzahn®) were used; one with 3 mm in diameter and 3 cutting edges (FR021) and the other with 1 mm diameter and 2 cutting edges (FR061). A coping (CAD) obtained from a 3D scan reference model was used. Figure 1 illustrates the 3D model to be machined.

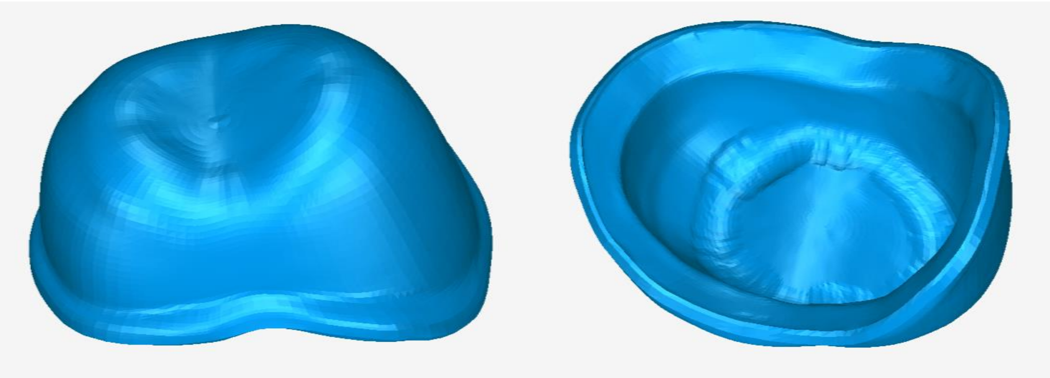


Figure 1. 3D model: (A) occlusal side and (B) internal cavity

The CAM programming process was carried out using the WorkNC® Dental software, which was developed to produce customized prototypes and prosthetics. With the shrinkage factor reported by the manufacturer (1.258), the software recalculates and measures the CAD model. Considering that the partially sintered material is highly brittle, the milling pressure and the tool force applied to the workpiece should be reduced, particularly along the borders. Therefore, the parameters and the machining sequence were alternated and combined in order to evaluate the productivity and the quality of the copings. This software offers two tool path distribution strategies: Raster (zig-zag) and 3D Offset (contour curves). The raster refers to move along one coordinate axis for machining. In 3D offset the cutter starts at the periphery and moves to the inner of the surface to be machined forming a cardioid-shaped pattern (Figure 2).

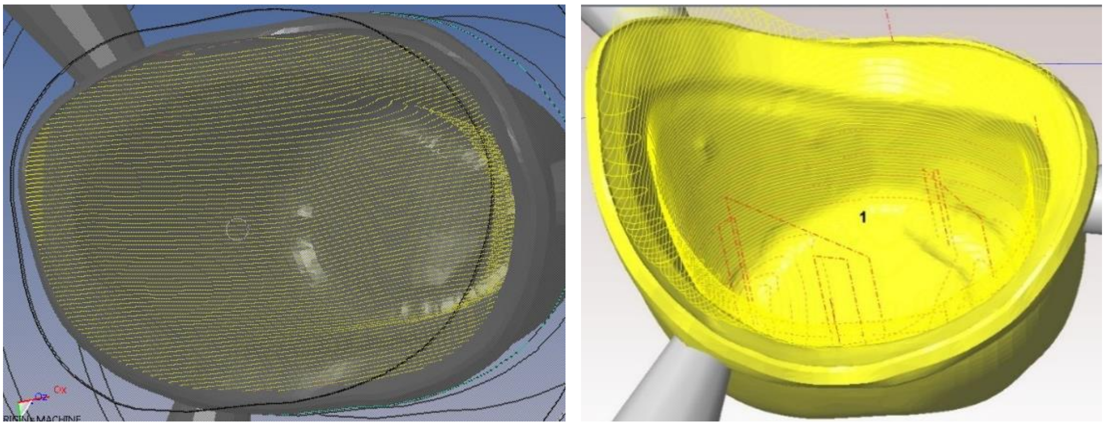


Figure 2. Tool path strategies: (A) Raster and (B) 3D Offset.

Since each side of the workpiece was machined twice by each milling tool, i.e. each tool was used to mill both the occlusal surface and the cavity of the coping, the machining sequence was also altered to determine its effect on the process. All machining tests were performed with the 3 mm (roughing) and the 1 mm tool (finishing), respectively. In sequence 1, the cavity was milled first (roughing and finishing) and then the occlusal side was milled. In sequence 2, the workpieces were completely roughed using the 3 mm cutting tool and, subsequently, both were finished using the 1 mm cutting tool (Table 1). For the evaluation of the machining tests, five workpieces obtained from each sequence/strategy combination were produced, totalling 20 samples.

Table 1. Machining tests*

		Steps
Machining sequence 1	1st milling	Cavity roughing
	2nd milling	Cavity finishing
	3rd milling	Occlusal roughing
	4th milling	Occlusal finishing
Machining sequence 2	1st milling	Occlusal roughing
	2nd milling	Lateral roughing
	3rd milling	Cavity finishing
	4th milling	Lateral finishing

*Both sequences were performed using two tool path strategies: Raster and 3D Offset.

The cutting parameters were set according to the manufacturer's recommendations: feed rate of 1200 mm/min, spindle speed of 30000 rpm, step over of 50% of the tool diameter. The depth of cut was 0.5 mm and 0.1 mm for the 3 mm and 1 mm tools, respectively.

Following the combination of machining strategy and sequence, prioritizing the surface finish and the machining time used for each workpiece, new tests were performed using varied tool feed rates, as shown in Table 4. Four samples were produced for each test group, totalling 20.

Table 2. Feed rates for the tests

Groups	**1**	**2**	**3**	**4**	**5**
Feed rate (mm/min)	800	1200	1600	2000	2400

III. Results and Discussion

For the surface quality of the workpiece, particularly in relation to the finishing obtained on the borders, the machining sequence had more influence than the strategy. The results showed that the machining performed with the 3D Offset strategy has given a better surface finish to the workpiece. These results are consistent with the expected outcomes due to the circular movement of the tool applied to the model, leaving a smoother and continuous surface, as observed in Figure 3.

In raster milling, the tool travels transversally to the border lines and produces cusps along the sealed borders, as shown in Figure 3. To reduce this effect, the step over was decreased by half. This procedure provided similar finish to the two workpieces, however with doubled time, affecting productivity.

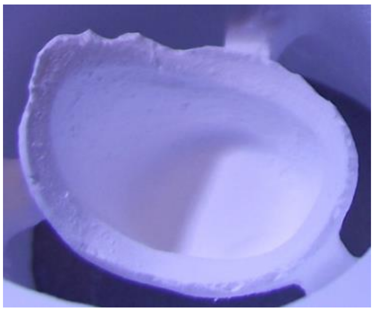
	Raster	3D Offset
Sequence 1		
Sequence 2		

Figure 3. Workpieces machined with two tool path distribution strategies

Nine out of ten workpieces that were milled in sequence 1 showed integrity and good finish. Only one workpiece milled with the raster strategy presented a cracked border and had to be discarded. With the use of the sequence 2, three workpieces submitted to raster strategy and two pieces to 3D offset strategy were broken, only half of the workpieces could be used. Therefore, the machining sequence 1 showed better results compared to sequence 2. This result can be explained by the removal of material during machining. In sequence 1, both roughing and finishing operations were performed in sequence on the side of the cavity, leaving a good amount of material, and therefore, strengthening the outside (occlusal side) of the coping. Partially sintered ceramic materials, especially those in the green state, are more resistant under compression than under traction. Thus, when the inner border is machined, a traction load is generated on the outer wall and if this border has been previously milled, this procedure may crack the workpiece. This defect occurred when both sides of the workpiece were submitted to roughing followed by internal finishing (sequence 2). Consequently, the external supporting material is removed and the coping becomes weak.

The results showed that the coping with better finish and integrity can be obtained by combining the machining sequence 1 with the 3D offset strategy. This combination provided 100% approval of the copings, which were milled in the initial conditions proposed by the present study. The same combination was used in tests with varied feed rates to evaluate the workpieces in every milling step.

When the feed rate was increased to 1600 mm/min (group 3) there were no damages to the workpieces, providing a convenient guideline for the maximum estimation of the surface quality and safety. The first border broke down with the 3 mm tool at 2000 mm/min (group 4), causing a little cracking on the border. However, some extra material was left for subsequent removal during finishing, considering that such small damage was not able to affect the workpiece. During the finishing process, two workpieces had their borders broken with the use of a 1 mm tool, affecting quality and making their use in clinical settings impossible (Figure 4). We can therefore assume that the roughing process can be performed in higher feed rate (up to 2000 mm/min), but it should be reduced during finishing (1600 mm/min).

Figure 4. Damages caused to the border of the workpiece during finishing

In group 5 (2400 mm/min), three workpieces were severely damaged during roughing; one of them was totally fractured and the remaining two presented cracks during finishing. This feed rate was considered too high for the process, combined with the step over and the depth of cut previously established.

IV. CONCLUSION

The results obtained from these experiments have made it possible to evaluate the behaviour of zirconia processed by CNC machining and the influence of the strategies and cutting parameters on the surface finishing. The milling strategies had a great effect on the quality and productivity of the workpieces. Since zirconia was only partially sintered, and therefore fragile, the machining process applied via 3D offset proved to be more efficient, as well as the milling sequence 1 – roughing and finishing each side of the workpiece and starting with the cavity surface. The feed rate can be increased to 33% of the reference value, which was 1200 mm/min. Therefore, it is possible to operate safely with feed rates up to 1600 mm/min, improving productivity and without compromising the quality of the workpieces.

V. FUTURE WORK

As future work it is suggested the study of tool diameter influence on the surface quality and machining time. It is also suggested the study of CNC machining employing different materials, as super high translucent zirconia.

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