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Error Detection and Correction Methodology for Laser Milling Processes on Biocompatible Ceramic Materials

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Abstract

This paper shows the work done on the correction of laser milled geometries on biocompatible ceramic material for medical prostheses. After the exposition of the error detection and correction methodology to be followed after the machining of a geometrical feature, the experimental procedure for the application of the methodology is detailed. Finally, the obtained results are exposed and discussed. The results show that the error detection methodology is able to properly identify the defective zones and define a laser milling process for their correction, in order to obtain a geometry within the defined tolerances in comparison to the theoretical one.

1. Introduction

The application of ceramic materials as zircon dioxide (ZrO_2) as the base for medical prostheses has become broadened due to their inertness and biocompatibility [1]. Besides the machining of the prosthesis bodies, micromanufacturing processes have been successfully applied for the modification of the prosthesis interfaces in order to improve their interaction with biological tissues and overall oseointegration [2]. While mechanical micromanufacturing processes have been applied for the preparation of prosthesis surfaces, their application range is limited due to the high tool wear generated during the machining of the ceramic materials [3].

In order to avoid these problems related to tool wear, mechanical machining processes can be applied to semi-sintered parts but, due to the shrinkage generated during the final sintering process, the final part can lose the desired accuracy or even get cracked due to the non-totally homogeneous shrinkage [4]. This way, the application of laser ablation processes to already sintered parts can help obtaining the desired part accuracy while avoiding the problems related to mechanical micromachining processes.

However, the laser ablation processes can show several instabilities due to different sources such as poor surface quality (scratches and defects), inhomogeneities on the workpiece material, lifting of the material during machining or unsteady laser source energy output. These problems may lead to geometrical deviations on the machined workpieces in comparison to the desired theoretical geometries. Due to the long processing times and high operational costs related to ultrafast laser ablation processes, the generation of these defects can make the process non-competitive in comparison to the traditionally employed manufacturing processes. In order to avoid them, devices and adaptive process methodologies have been developed, mainly linked to macro-machining laser process as laser welding [5]. However, in the case of ultrafast laser ablation processes, more sensitive devices with very high dynamics are required. This way, for the definition of an adaptive process control scheme, a considerable work for the monitoring of the process state and parameters should be carried out. Furthermore, the monitoring data would require extensive analysis so decisions could be defined for the correction of the process parameters. These points lead to very complex equipment and methodologies that could be applied for the real-time process control during ultrafast laser ablation operations [6].

Nevertheless, a control that would focus on the final geometry of a machined part would not require such a real-time control along the whole machining process. Thus, the present work, instead of defining an adaptive process control scheme, proposes the use of an error detection and correction methodology on the laser milling of ceramic prostheses in order that a defect minimization scheme can be incorporated into it.

2. Error detection and correction methodology

The material removal rates obtained during the ultrafast laser ablation processes are comparatively low regarding other manufacturing processes. This way, the focus of the error detection and correction methodology would be the control of key geometrical features (final shape) instead to the whole process for the manufacturing of a complex geometry.

The overall structure of the error identification and correction methodology proposed on the present work is shown in Figure 1. After the machining of a key geometrical feature, it is measured so it can be compared to the theoretical geometry. Once this comparison is carried out, a decision can be made on continuing with the defined process if the machined feature is inside the defined tolerances, scrap the part if the generated errors are not recoverable or, if it can be corrected, define a new machining loop for the correction of the feature and, this way, generate the desired geometry.

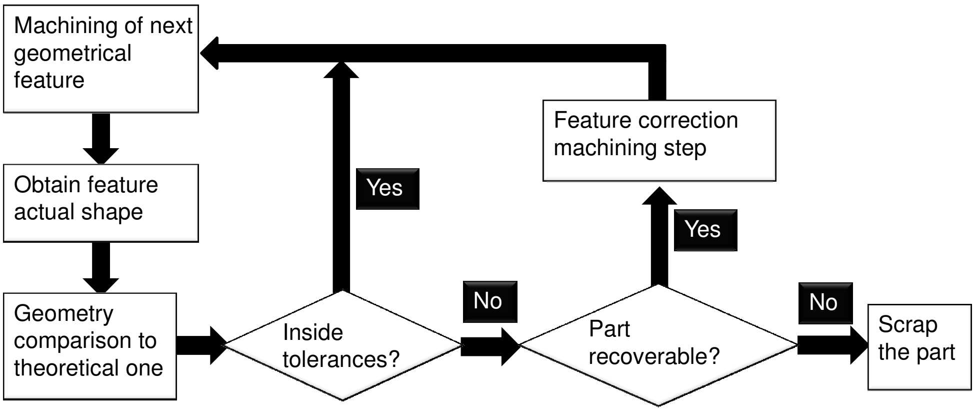


Figure 1: Diagram for the error detection and correction methodology.

The generation of the machining step for the correction of the defects is founded on the difference between the actual and the theoretical geometries for a given feature. Once this difference is calculated, it is divided into simple square areas and a mean height error value is calculated for each of them. The comparison of this height error with the geometrical accuracy defined for the part will identify the areas that require a correction step. Based on this, the (X,Y,Z) location of an area that would require the correction step is stored into a file, also including the desired depth for the correction. By processing the information for the location and depth for each correction, the identification of how many correction steps (based on the square areas) would be required is carried out. Finally, a NC code file is automatically generated, containing the location for each correction step and the call to a parameterized laser milling cycle already coded on the laser ablation machine

3. Experimental procedure

The tests have been carried out on an in-house developed laser ablation machine (Figure 2). This machine is equipped with a Picosecond LUMERA Hyper rapid 25 laser beam source. The laser scanning is carried out by the movement of the X-Y stages, leading to low speeds in comparison to galvanometric heads. Nevertheless, this speed limitation should not be an issue regarding the evaluation of the error correction methodology presented here.

The laser pulse characteristics employed for the laser milling trials were based on experimental tests done on sintered zirconia: wavelength (λ) 1064 nm, repetition rate (f) 250 kHz, power (P) 6,94 W, pulse duration (τ_H) 10 ps, scanning speed (v_s) 5 mm·s^{-1} and a focal diameter (d_w) of 20 µm. All of the machining work was carried out at standard atmospheric conditions without any gas assistance.

Figure 2: The in-house developed ultrafast laser ablation machine IK-Laser.

The error detection and correction methodology has been applied to the laser milling of simple geometries (square cavities of 0.5 mm side and 50 µm depth). In order to evaluate the capability of the methodology presented on this paper, artificial geometrical defects were introduced into the theoretical geometries. The tests were carried out on already sintered yttria stabilized zirconia blocks. The sintering steps can be seen in Table 1, which was carried out following instructions from the provider.

Table 1: Steps followed for the sintering of the yttria stabilized zirconia blocks.

Sequence	**Time**
Preheating rate up to 900 ºC (8 ºC·min^{-1})	110 min
Holding time at 900 ºC	30 min
Preheating time to final temperature of 1500 ºC (9 ºC·min^{-1})	75 min
Holding time at 1500 ºC	120 min
Cooling rate down to 900 ºC (4 ºC·min^{-1})	150 min
Holding time at 900 ºC	20 min
Cooling rate down to 200 ºC (4 ºC·min^{-1})	175 min
Total time	11 h 20 min

As commented above, the correction of the geometrical deviations is founded on the difference between the actual and the theoretical geometries so, numerical values for the geometries would be required in order to obtain this difference. This way, the laser milled geometries were measured employing a Sensofar PLu Neox imaging confocal microscope. Since the workpieces have to be taken away from the laser ablation machine in order to make these measurements, the repeatability of the workpiece clamping on the machine has to be guaranteed in order to ensure the correction process. Thus, a zero-point clamping system (Erowa FTS) with a clamping repeatability < 2 µm was used for the fixation of the workpieces to the machine.

The defect correction is carried out by laser milling of elemental square areas with the same size (30 µm side) as the ones the geometry difference was divided into. The employed laser milling strategy for the error correction is based on the machining of several layers on the Z direction until the desired correction depth is achieved. The depth of each layer on the Z direction was 10 µm so several layers were required for obtaining the desired correction depth. Each Z layer was machined by overlapping several laser scanning paths (Figure 3). The overlapping value employed was 10 µm, requiring 3 scanning paths in order to generate the desired cavity size.

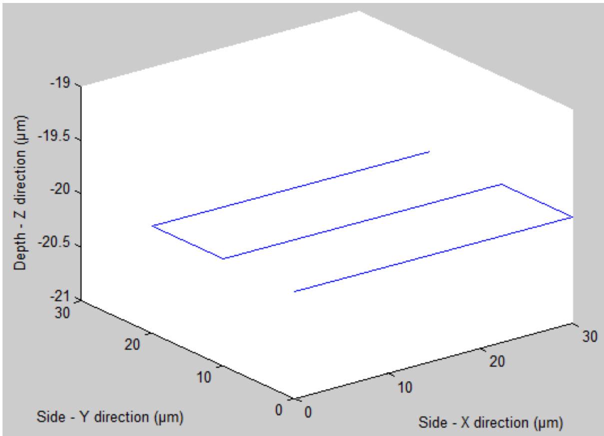


Figure 3: Laser trajectory for each Z level of the defect correction process.

4. Results and Discussion

Top images from the laser milled cavities have been obtained by Scanning Electron Microscopy (SEM) employing a Zeiss Evo 40. Figure 4 shows the top image of a laser milled cavity with an artificially introduced defect (un-machined corner) can be seen in Figure 4. After measuring the cavity with the imaging confocal microscope, the measurement data is exported and treated by comparing it to the theoretical geometry, obtaining this way the difference between both. The measurement data, the theoretical geometry and the obtained difference can be seen in Figure 5, both on 3D and top representations.

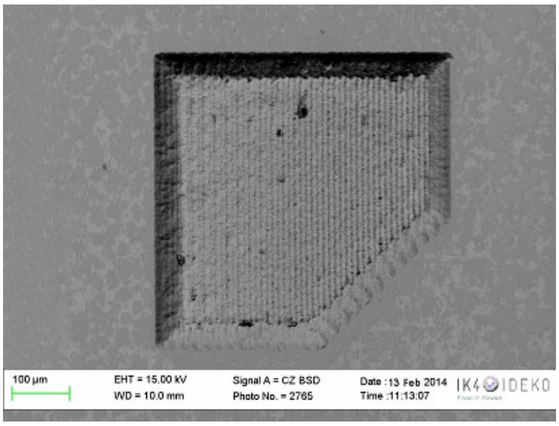
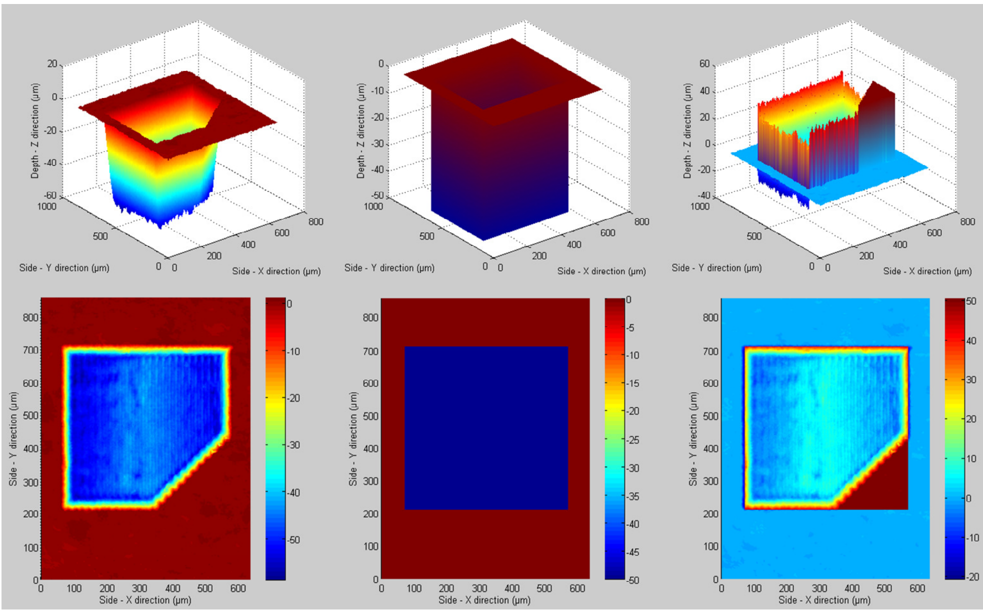


Figure 4: Top image of the laser milled cavity with the artificial defect



a) b) c)

Figure 5: Top and 3D representation of a) laser milled cavity measurement data, b) theoretical geometry and c) difference between both

After the difference between the theoretical and the actual geometry is calculated, it is divided into elemental square areas. The top and 3D representations of the difference before and after the discretization can be seen in Figure 6. By the evaluation of the mean height of each area in comparison to the defined manufacturing tolerance (15 µm), the elemental areas that will later be corrected are identified.

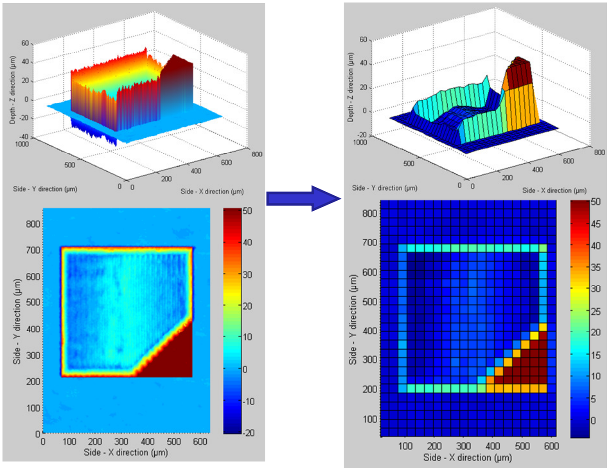


Figure 6: Top and 3D representation of the difference between the actual and theoretical data before and after its discretization.

After the elemental areas that will require the later correction are identified, the (X,Y,Z,) location for each of them is identified and the required layers in the Z direction to obtain the desired geometry are calculated. Finally, the data for the machining of each of these layers is written into a NC code file in order to introduce it on the control of the ultrafast laser ablation machine and carry out the correction of the defective geometry. An example of the NC code for the machining of one of the layers from one elemental area can be seen in Figure 7.

```
$X_ORIG=151.994+$OFFSETX
$Y_ORIG=158.8971+$OFFSETY
$Z_ORIG=-25.3+$OFFSETZ
$DEPTH=0.025
CALL ZRO2_CORRECTION_CYCLE
```

Figure 7: Example of the NC code generated for the correction of an area

The top image of the cavity shown in Figure 4 can be seen in Figure 8 after the error detection and identification methodology has been applied. The top representation of the machined cavity before and after the methodology has been applied can be seen in Figure 9. As it can be seen, the artificially introduced error is identified and correction steps are created for this zone. Furthermore, some correction steps are created for the upper side of the cavity due to the slope of the theoretically vertical wall.

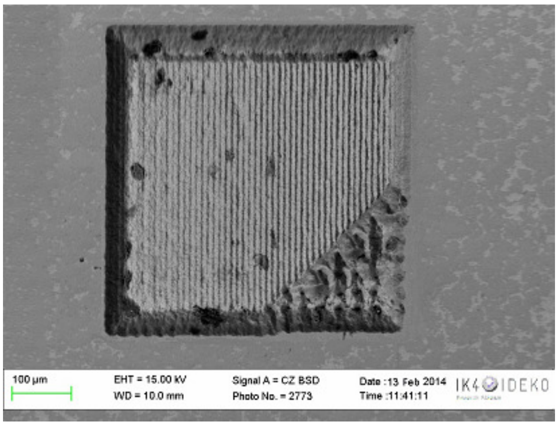


Figure 8: Top image of the laser milled cavity after the correction of the artificial defect

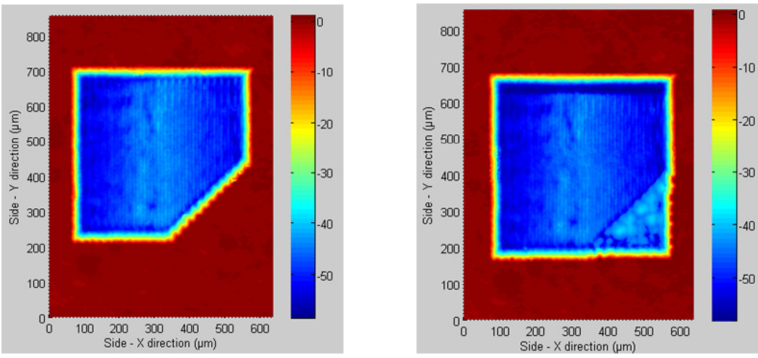


Figure 9: Top representation of the machined geometry before and after the correction of the artificial defect.

Nevertheless, as it can be seen in Figure 9, the depth of the zones machined by the correction methodology is different. In the case of the upper zone of the cavity, where the slope of the vertical walls has been corrected, the final depth is slightly higher (5-10 µm) than the theoretical depth of the cavity. On the contrary, the depth on the corner where the artificial defect was located is lower (10-15 µm) than the theoretical depth. This indicates that the laser milling process employed for the correction of the defective zones should be optimized in order to obtain an homogeneous depth within the whole cavity.

Besides, the vertical walls created on the zone where the artificial defect was located do not match perfectly the walls from the original geometry, showing a slight offset (5-10 µm) with them. This point is related to the location of the 'discretization grid' concerning the original geometry and should be further analysed in order to obtain a better dimensional quality on corrected geometries.

5. Conclusions

The analysis of the obtained results can lead to the next conclusions:

- The imaging confocal microscopy allows for the proper characterization of the laser milled geometries in order to obtain numerical values for their treatment.
- The comparison between the theoretical and the actual laser milled geometries allows for the precise identification of the defective zones and the later application of the correction methodology.
- The proposed error detection and correction methodology is capable of generating a NC code file that would define the machining process for the correction of the defective geometries in order to obtain the desired geometry.
- The offsetting of the discretization grid employed for the evaluation of the errors on the geometry should be analysed in order to generate better dimensional accuracy on the corrected geometries.
- The laser milling process employed for the correction of the defective geometries requires an optimization in order to obtain the desired quality on the laser milled geometries.

6. Acknowledgements

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