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An experimental analysis of laser machining for dental implants

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Abstract

In the recent years, the scientific progress in both technological and medical sectors has led to an evolution of materials and fabrication techniques used for dental prosthetics. This paper proposes laser subtractive process to manufacture dental implants and explores the behavior of a CO_2 laser beam effects on biocompatible materials, namely zirconia and PMMA. The aims of the experiments are the study of CO_2 laser beam effects on biocompatible materials and the creation of a mathematical model to relate the process parameters with groove geometry and surface finish.

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Keywords: Biomanufacturing; Laser Machining; Subtractive process; Dental implants; Ceramics; Polymers

1. Introduction

Dental prosthetic is defined as a manufactured product, realized by a dental technician, used to replace the original teeth lost or compromised for functional or aesthetic reasons. Dental prosthetics must meet several requirements:

- functionality: the prosthesis must re-establish proper chewing and joint functions;
- resistance: the prosthesis must resist to the masticatory load and to the wear of mouth liquids;
- safety: the prosthesis must be made with non-toxic materials and without sharp angles, not to damage mouth tissues;
- aesthetics: the artificial teeth should be as similar as possible to the natural one, so as not to affect the correct patient's facial profile.

The dental sector is characterized by a great propensity towards innovation, in particular as regards materials for dental prostheses. From the original metal implants, in recent years plenty of heterogeneous materials, such as ceramics, glass-ceramics, resins, Polymethylmethacrylate (PMMA), have been introduced in dental prosthesis manufacturing. For obtaining metal implants through the lost wax casting process, also wax prosthesis are used as a transient product.

Among traditional methods, the just mentioned lost wax casting is one of the principal used for manufacturing dental implants. Also milling is used for producing various parts of the prosthesis in different materials. In particular, 4 or 5-axis machines are used in dentistry, to allow the prosthetic machining from all angles. As for welding processes, brazing and laser welding are used in the dental field. Additive manufacturing or rapid prototyping methods include ceramic stereolithography (CSL).

2. Laser machining for orthodontic prosthetic devices

Besides of the above-mentioned techniques for processing materials suitable for dental prosthetics manufacturing, a new method, consisting in the laser subtractive process, can be outlined.

2.1 State of the art

Laser machining on bio-compatible materials is a wide research area and several industrial applications are currently proposed. Despite of the increasing production of customized orthodontic and prosthetic devices, laser machining in implant dentistry still deserves much consideration. Laser applications in this area are relegated to the development of systems that modify existing implants, manufacture the infrastructure of fixed partial dentures [1,2] and to improve mechanical

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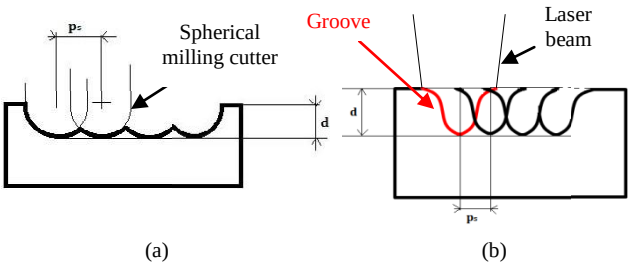
properties of cast titanium [3], a widely used material to restore the dental volume and the implant in its entirety.

Çelen and Özden consider the long-term mechanical adaptation of titanium alloy implants to impact the osseointegration process and to prevent stress shielding effect of dental implant surfaces that originate from the mismatch between bone and implant [1]. Watanabe et al. [3] investigate mechanical strength, surface hardness and wear resistance of cast titanium treated with Nd:YAG laser in order to generate residual compressive stresses, deeper than conventional milling, that inhibit the propagation of fatigue cracks. In a pioneering work, Minamizato investigates the modification of cast zirconia by laser micro-drilling for dental root implantation [2]. Initially, zirconia is used in bilayered structures for prostheses, with a framework that gives mechanical resistance and a porcelain layer that provides translucency to the restoration due to a good aesthetic factor. Unfortunately, clinical reports on zirconia-based restorations have indicated a high rate of short-term failures related to cohesive fracture of the porcelain layer [4], which constitutes a weak link from a mechanical point of view, introducing the risk of chipping. Therefore, manufacturers have recently introduced monolithic prostheses, which are fully composed of zirconia, without any veneer porcelain to extinguishing chipping and fracturing of the veneering porcelain [5] and dental restorations of monolithic full-contour crowns or complete arch implant rehabilitation (monolithic restoration) [6]. In addition to the mechanical and optical properties, monolithic zirconia has become an alternative material to pure titanium or titanium alloy for its inexpensive costs due to mass production in commercial solid bulks or disks [7].

2.2 The proposed laser subtractive process for dental implant manufacturing

Typically, laser machining has always been used as an additive process in the sintering phase. In this work, its application as a subtractive process is presented. By generating a high concentration of energy density, the heat focuses on an extremely small superficial portion. The material molecules, thanks to a vibrational motion, overheat till the cutting temperature. Thus, the laser beam serves as a milling cutter, used in the traditional milling process. The two methods are compared in Fig.1, where a milling cutter and a laser beam are represented in removing a depth portion of material d with a step between subsequent passes of p_s.



(a) (b)

Fig. 1. Comparison between milling (a) and laser (b) subtractive processes.

In general, biomaterials used in monolithic restoration as zirconia and PMMA are particularly suitable for material removal by subtractive processes, whose consist in to machining a bulk to obtain the customized 3D model of single teeth or dental implants. The area to be machined is removed with a number of closely spaced steps of spherical cutting tool or closely spaced parallel grooves of laser beam energy. Subtractive methods overtake transforming methods, as traditional slip casting, hot pressing and injection moulding, because of the customization costs of prosthetic implants. In conventional milling, the mechanical contact of the spherical tool with the sculptured surface of the tooth determinates the process resolution. It depends on process parameters, as feed rates and number of passes, which involves low material removal rate and high tool wear costs.

Among the well-known competitive advantages of laser micromachining, the following are relevant for processing dental implants [8]:

1. Non-contact process. The material is directly molted, ablated and vaporized due to the rapid heating produced by high energy density associated with the focused laser spot. Energy transfer from the laser to the material eliminates mechanical force/impingement of abrasive particles, tool wear, machine vibration, industrial effluents typical of subtractive techniques as conventional milling. In addition, the lack of cutting forces allows to quickly position and not to clamp the workpiece for faster operations by not skilled operators like dentists and orthodontists.
2. Thermal property. The efficiency of laser machining mainly depends on the thermal and on the optical properties of the material. This makes it suitable for machining hard or brittle materials such as structural ceramics with low thermal diffusivity and conductivity, where milling suffers from excessive tool wear.
3. Operation flexibility. In combination with a multi-axis positioning system or robot, lasers can be used without tool changes for different operations and different materials. Both the high speed and the flexibility of the fabrication process make laser systems an effective tool for 3D machining of cavities. As opposed to milling machine, the laser can obtain very small details or radii, including complex shapes and sharp corners.

On the other hand, the choice of such a process involves a cost-benefits analysis, since laser system are expensive and the possible presence of cracks, inclusions or burrs can affect the cutting quality.

2.3 Aim of the present work

On the basis of the previous considerations, the aim of this work is to experimentally analyse the potential of the laser subtractive process as a new method for the creation of dental implants. The motivation is to offer a competitive advantage over conventional materials by means of the increasing efficiency of the applications for groove fabrication on biomaterials. The sector is so promising that, even in the industrial reality, researches in this field are currently being conducted, developing new laser milling machines.

The rest of the paper is organized as follows: direct comparison on laser subtractive process modeling previously developed by one of the authors is discussed in section 3; the experimental plan used in the work is presented in section 4; the experimental results obtained on different materials are given in section 5; lastly, in section 6, the conclusions are drawn.

3. Process model for PMMA

According to [9,10], using a CO_2 laser to achieve material removal on polymers, PMMA is rapidly heated, molten and then vaporized by the laser beam and the process resolution increases with the energy density of the focused laser spot. The same model is adapted to current materials to predict the groove width W_{Groove} and depth D_{Groove}, as represented in Fig.2, calculated in the model proposed in [9] as follows:

$$W_{groove} = \Phi_{spot}[1 - c_1 \exp(c_2(\varepsilon - \varepsilon_{th}))] \quad (1)$$

$$D_{groove} = c_3\, \varepsilon - c_4 \quad (2)$$

with $c_3 = 2k\alpha/\rho W_{Groove}$ $c_4 = 4kQ_{th}/\rho W_{Groove}{}^2$

where Φ_{spot} is the spot diameter, ε is the energy density acting on the irradiated area, defined as the ratio between the incident laser power P_{in} and the scanning speed v, ε_{th} is the energy density threshold value, c_1 is a factor considered to be 1 in [9], c_2 is an experimental constant, k is a constant related to the chemical binding energy of PMMA, α is the absorptance, ρ is the material density of the material, Q_{th} is the threshold energy.

The groove width varies with the focal length and is lower limited by the spot diameter. The groove depth is directly proportional to the incident laser power and inversely proportional to the cutting speed.

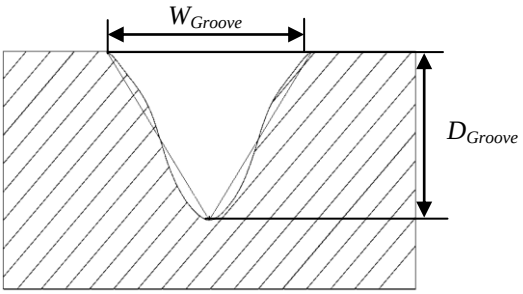


Fig. 2. Geometrical definition of the groove width and depth.

Still on the same research [9], experiments were then conducted to analyse the correlation between groove profile, beam speed and power. The results showed an effective correspondence between the proposed model and the collected data.

The depth D_{layer} of a layer, removed by machining multiple parallel grooves with partially superimposed profiles, is given by:

$$D_{layer} = D_{Groove} - R_T/2 \quad (3)$$

with $R_T = p_s/2 \cot\theta/2$ (4)

where R_T is the roughness of the machined surface, p_s is the scanning step representing the spacing between each groove and θ is the angle of the triangular pass model. From the model, the layer depth can be noted to linearly depend on R_T and p_s.

4. Methodology

The aim of the experimental tests is to preliminary analyze the effect of laser beam during the interaction with materials mainly used in dental implants. The method of investigation adopted in the present work consists of three steps, described below:

1. Laser machining, executed through a CW CO_2 laser source ranging from 0W up to 30W, shown in Fig.3;
2. Profile detection, performed through an optical sensor;
3. Groove analysis, conducted with an optical microscope.

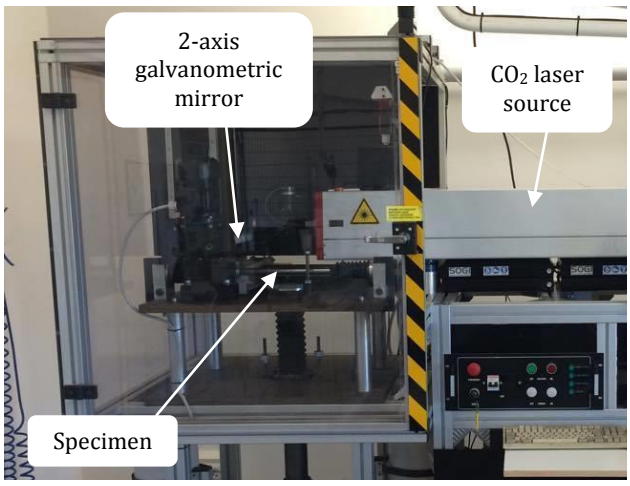


Fig. 3. Laser equipment used in the experiments from Quanta System, model QuickMark 50.

4.1 Material selection

The experiments were performed on samples materials most used in dentistry, including composite resin and different types of Zirconia, PMMA and wax. Two materials were selected for the present paper, specifically Zirconia and PMMA. In Table 1, some properties of these two materials are reported. Wax is not included because of the low accuracy caused by softening with the spot size tested.

Table 1. Characteristics of the materials used in the experiments.

	Melting temperature [°C]	Vaporization temperature [°C]	Specific heat [J/kg K]	Density (10^{-3}) [g/mm^3]	Hardness [MPa]
Zirconia	2533	4300	425	5.757	1250
PMMA	110-160	133	1465	1.183	195

4.2 Experimental

The following process parameters have been considered in experiments: focal distance *f*, laser power *W*, scanning speed *v*. A preliminary parameter analysis was conducted to determine the range of variation of each parameter. Within these ranges, the values reported in Table 2 were chosen to perform test scanning speed. Table 2 summarizes the obtained values.

Table 2. Processing parameters for Zirconia and PMMA.

Focal distance (*f*) [mm]		Laser power (*W*) [W]		Scanning speed (*v*) [mm/s]	
Zirconia	PMMA	Zirconia	PMMA	Zirconia	PMMA
180	160	20.8	20.8	16	20
200	180	22.5	22.5	20	65
	200	24.2	24.2	25	110
		27.1	27.1	33	155
		28.3	28.3	50	200

5. Discussion

The tests performed can be classified into two phases, the former relating the execution of single passes to obtain individual grooves on different materials, and the latter inherent the execution of multiple passes for the creation of multiple parallel grooves.

5.1 Single pass

Based on the identified parameters and their values, 75 grooves were performed for each material (3 focal distances; 5 laser powers; 5 scanning speeds). The profile of each groove was detected by the optical sensor. For the sake of brevity, one profile for each material is reported in Fig.4. The profiles are depicted with a blue curve, while the dotted green line represents a reference model, approximated to a Gaussian curve centered in zero and considering a width of ±3σ.

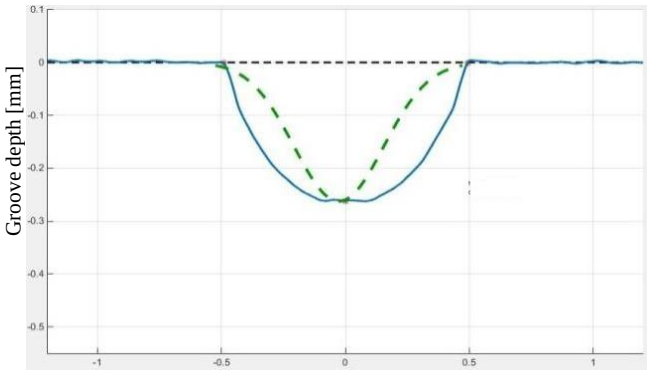
For PMMA, the groove profile can be noted to be similar to a Gaussian curve. This phenomenon is related to instant vaporization polymers are subject to. Assuming that the laser beam has a Gaussian-type energy distribution, and thus also the temperature, the material removal follows these isotherms. Conversely, for Zirconia the removal by fracture cannot form a Gaussian; experimentally a semi-circular shape was detected. Results on single scan for the two materials photographed by the optical microscope are shown in Fig. 5.

Figs. 6 and 7 give groove width respectively for PMMA and Zirconia. From the analysis of these curves, it can be noticed that that for both materials groove width doesn't depend on laser power or forward speed individually, but on their ratio, called energy density. An increase of the energy density causes ever more extensive machining. Furthermore, for increasing in focal distances, the groove width decreases.

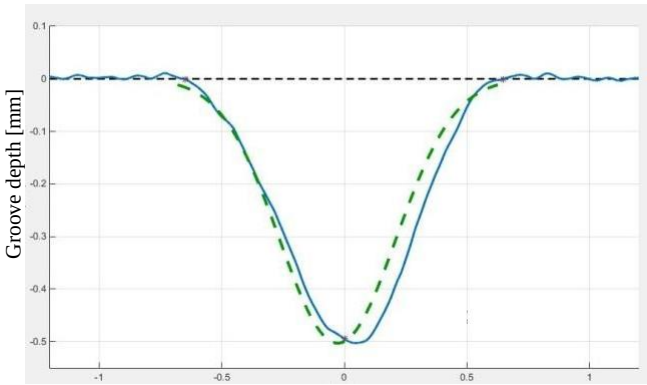
Figs. 8 and 9 show the results obtained for groove depth respectively for PMMA and Zirconia the groove depth can be noted to depend on the energy density. An increase on the energy density causes an increasingly deep groove.

In Figs. 6 and 8 continuous lines represent the model for PMMA shown in Section 3. An exponential mathematical model for Eq.(1) and a linear one for Eq.(2) were used to derive the values of model parameters for each focal distance, by means of the best-fit method. Table 3 shows these evaluations. Data can be noted to be slightly more dispersed for low energy density, as the machined polymer is a non-conductive material and thermophysical phenomena are involved. The theoretical model thus proves to be adherent to the reality the higher the energy density is.

As the process model is not presented for Zirconia, in Figs. 7 and 9 continuous lines represent raw data interpolation. The results obtained experimentally could be a first introductory step for setting, also for this material, a groove width and depth mathematical model, which can be noted to have a linear trend with energy density.

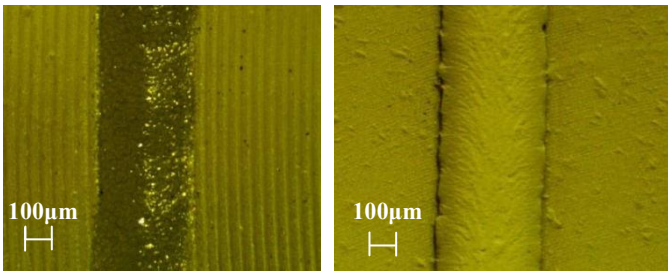


(a)



(b)

Fig. 4. Groove profiles obtained on: (a) PMMA (f=180mm; W= 22.5 W v=20 mm/s); (b) Zirconia (f=180mm; W= 28.3 W, v=20 mm/s).



(a) (b)

Fig. 5. Single scan captured with optical microscope. Groove on: (a) PMMA (f=180mm; W= 22.5 W v=20 mm/s); (b) Zirconia (f=180mm; W= 28.3 W, v=20 mm/s).

Table 3. Evaluation of model parameters for Eq.(1) and Eq. (2) for the considered focal distances.

f [mm]	Φ_{spot} [mm]	ε_{th} [J/m]	c_1	c_2	c_3	c_4
160	1.0	10	0.5966	-0.0010	0.0009	-0.0029
180	1.5	25	0.5174	-0.0010	0.0005	0.0170
200	2.1	50	0.5083	-0.0010	0.0002	-0.0021

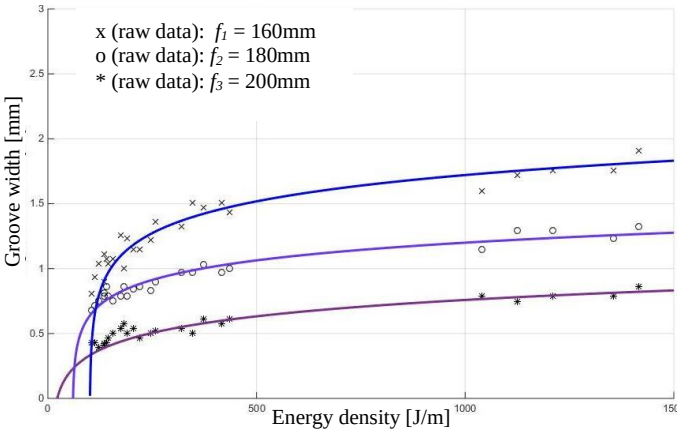


Fig. 6. Profile width vs. energy density for PMMA, with continuous lines representing the model (Dark Blue: f_1 = 160mm; light blue: f_2 = 180mm; purple: f_3 = 200mm)

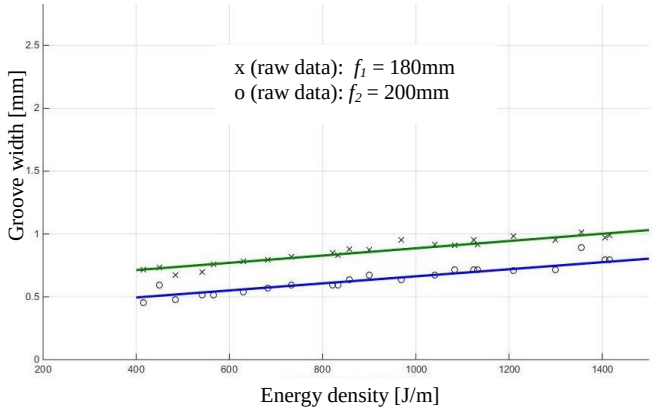


Fig.7. Profile width vs. energy density for Zirconia. Best fit curves of the experimental data in coloured font. (Green: f_1 = 180mm; blue: f_2 = 200mm)

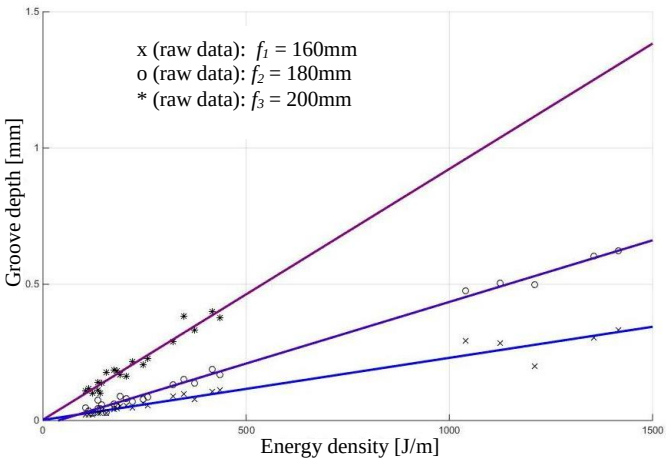


Fig.8. Profile depth vs. energy density for PMMA. , with continuous lines representing the model (Dark Blue: f_1 = 160mm; light blue: f_2 = 180mm; purple: f_3 = 200mm)

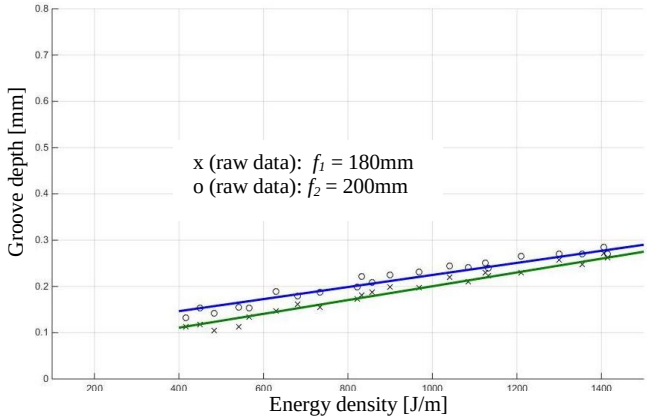


Fig.9. Profile depth vs. energy density for Zirconia. Best fit curves of the experimental data in coloured font. (Green: f_1 = 180mm; blue: f_2 = 200mm)

5.2 Multiple passes

Multiple grooves were obtained with a scan spacing p_s ranging from 0.4 to 0.8 mm. Results on multiple scans are following reported for PMMA (Fig.10) and for Zirconia (Fig.11) for one of the p_s values that were tested.

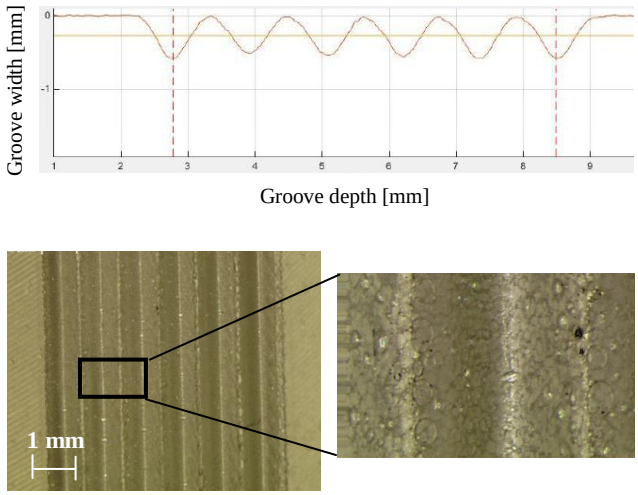


Fig. 10. Multiple scans on PMMA with f=200 mm, W=27.1 W, v=110 mm/s and p_s=0.8 mm.

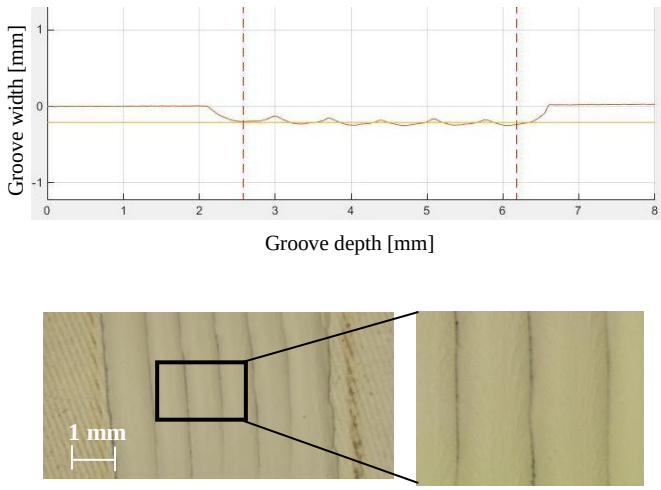


Fig. 11. Multiple scans on Zirconia with f=180 mm, W=27.1 W, v=25 mm/s and p_s=0.8 mm.

By analyzing the scans obtained in subsequent passes, the groove depth becomes increasingly greater. In fact, at first pass the removal capability is focused on a larger area, then, being equal the material removal rate, the removal capability focuses on an ever-smaller surface to decrease p_s.

Tests with multiple scans were aimed to evaluate the surface roughness obtainable by varying the scanning step and to compare these real values of roughness R_a to the ideal ones R_T, calculated according to the theoretical model presented in Section 3 (Eq. 4). The ideal roughness value comes from the alignment of different profile curves, for a distance equal to the scanning step. The curves represent the approximation of the profile corresponding to the single scan with the same focal distance, scanning speed and power used in multiple scans.

In the case of PMMA, curves are approximate to Gaussian profiles with a ±3σ standard deviation as width and with a depth coming from the mean value of multiple passes depth. The theoretical roughness is compared to the actual roughness for different scanning step in the case of PMMA in Fig.12. The results demonstrate the adherence of the theoretical model to the reality as roughness values are always similar. Therefore, it can be stated that the PMMA has predictable and in-line behavior.

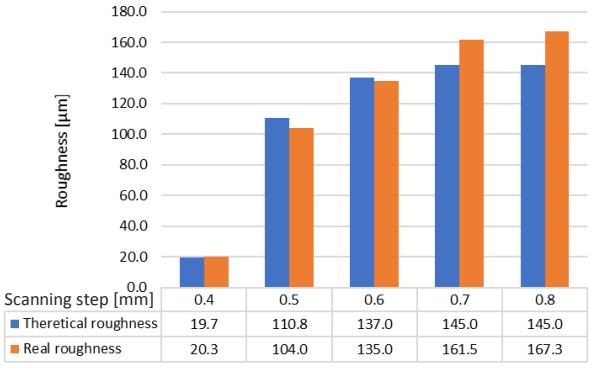


Fig. 12. Comparison of theoretical and real values of roughness for PMMA.

In the case of Zirconia, the hypothesis that the removed portion in ceramic materials assumes a semicircular shape was considered and the radius was established based on geometric considerations. As shown in Fig.13, for low scanning steps, the actual roughness is higher than the theoretical one, but for higher scanning steps, the mutual influence between the individual grooves, not predictable analytically, results in lower values of real roughness compared to the ideal ones.

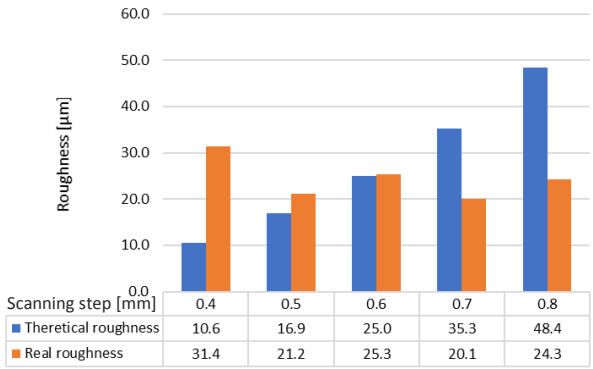


Fig. 13: Comparison of theoretical and real values of roughness for Zirconia.

To conclude, in the case of PMMA machining the process can be kept under control, while for Zirconia external factors interfere with the predicted theoretical trend. By comparing real values of roughness for the two materials PMMA can be noted to produce a higher surface quality for p_s = 0.4. However, for higher steps, roughness grows sharply so much so that Zirconia results to have a better quality.

6. Conclusions

This paper proposes a preliminary experimental analysis to examine the application of the laser subtractive process for the fabrication of dental prosthetics. Different materials were processed, such as PMMA and Zirconia, which resulted qualitatively better in the surface finish. The results have demonstrated that this technique could be successfully implemented for this purpose. Although the work here presented is a preliminary analysis with the aim on assessment of effects of laser subtractive on different materials, it provides useful results to interpret the phenomenon and to set model constants for an estimation of groove geometry in function of process parameters.

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