EVALUATION OF SURFACE CHARACTERISTICS OF DENTAL GUIDES FABRICATED THROUGH 3D PRINTING

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In the field of medical devices and instruments, dental medicine uses a large category of devices and innovative materials intensively. Dental guides play a crucial role in the stability of implants, and the surface properties best lead to obtaining concrete results for their use. The present study focuses on the investigation of five types of 3D printed dental guides, manufactured by combining processing technologies with various materials: Selective Laser Melting (SLM), Stereolithography (SLA), Masked Stereolithography (MSLA) and Fused Deposition Modeling (FDM), focusing on their interfacial behavior and surface characteristics. Four main analyses were performed: contact angle measurements, surface free energy calculation, surface roughness profiling (to determine the micro-topographic characteristics), and SEM analysis. The results show significant differences in wettability and energy distribution, with resin-based samples produced by MSLA demonstrating hydrophilic behavior and smoother surface features, supporting enhanced cellular interaction and increased adhesion.

Keywords: 3D printing, dental guides, surface characterization.

1. Introduction

Biomedical engineering encompasses knowledge from several fields, such as materials science, physics, mechanics, electronics, and chemistry, in which information merges to streamline medical treatments and effectively support patients injured areas.

Recent materials and technologies have brought several extended benefits to many surgical specializations, from dentistry to neurosurgery and cardiovascular surgery, adding in addition to the classic equipment for monitoring, checking and

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treating patients, digital imaging devices, clinical data analysis systems and personalized medical treatments [1-4].

Current demands focus on technologies that assure a fast clinical and personalized response to each patient, with minimal invasive interventions, able to respond to complex clinical problems. Additive manufacturing techniques look to be the best option given by the engineering to these clinical demands, also due to their versatility related to the biomaterials used [5,6].

Additive manufacturing is an essential component in dental applications and the digitalization of dental interventions. Technologies such as stereolithography (SLA) and masked stereolithography (MSLA) allow the fabrication of complex geometries, highly detailed surfaces, and customized models that match the patient’s specific anatomy [7-13].

In dental medicine, the main factors that ensure proper treatment of patients include dental applications such as implants and prostheses, as well as surgical guides and other instruments used during implantation. These instruments are made by materials carefully selected and all of them are sterilized because they were identified as a factor for potential infections in dentistry. In the past, dental guides were initially hand-made from acrylic resins, a process that led to a considerable increase in production time, human error, and loss of fine anatomical details of shape and size. Digitally assisted manufacturing has marked a major improvement in accuracy and workflow efficiency [14-16]. While milling and 3D printing can provide comparable dimensional accuracy, additive manufacturing offers distinct advantages: reduced costs, flexibility in geometry, and the ability to produce guides directly in the dental office, without laboratory intermediaries [17-24].

The clinically favourable results of a surgical guide are based, in addition to accuracy and dimensional stability, on a few functional and surface properties appropriate for the oral environment. The series of significant surface properties that determine the efficiency of a surgical guide includes the wettability, the roughness, which actively contribute to biological interactions such as bacterial attachment, and contact of the sample with the patient's saliva and soft tissues [25-28]. From the point of view of the hydrophobicity of the surface of the analysed sample, a slightly hydrophilic character promotes a safer wetting and stabilization, and in correlation with a smooth surface, the adhesion of the guide increases significantly, while a hydrophilic character combined with a rough surface roughness can lead to stimulation of bacterial retention and instability during the implantation procedure [29].

According to the previously mentioned data in literature, the need to optimize surgical dental guides used in oral implantology through a dual approach: advanced manufacturing technologies and an in-depth understanding of the behaviour of materials at the microstructural and superficial level [30]. Thus, a considerable justification is exercised on the need to carry out comparative studies focused on the surface properties of dental guides manufactured by combining the types of various additive techniques with different materials, because they are a series of representative parameters for the clinical efficiency of the prototypes made to improve the dental implantation intervention.

The aim of the current study involved the evaluation of five distinct types of 3D-printed dental surgical guides, manufactured using a selection of additive manufacturing techniques and different biomaterials, following their surface properties.

2. Materials and Methods

The additive manufacturing techniques used to produce each dental guide are Selective Laser Melting (SLM), Stereolithography (SLA), Masked Stereolithography (MSLA), and Fused Deposition Modeling (FDM). The raw materials used for each manufacturing technique, and the thickness of each printed layer, are shown in Table 1.

The experimental samples were made at the Advanced Research Centre affiliated with the Carol Davila University of Medicine and Pharmacy in Bucharest.

Table 1

Fabrication methods and material specifications of the dental guide samples

Sample Code	Additive manufacturing technique	Material / type	Thickness of each printed layer (μm)	Printer Type
GD1	SLM	Ti6Al4V / powder	30–50	Metal laser melting system
GD2	SLA	Polymer / resin	50	Stereolithography laser printer
GD3	MSLA	Polymer / resin	50	LCD mask photopolymerization system
GD4	FDM	PEEK / filament	100	High-temperature FDM printer
GD5	FDM	PEEK / filament	200	High-temperature FDM printer

Each dental guide is unique because it was printed using a different additive manufacturing technique and material type, as is shown in Figure 1.

The SLA-based guide was printed using a biocompatible photopolymer resin, chosen for its precision and smooth surface finish [31]. The guide obtained through the MSLA technique was fabricated from a Next Dent biocompatible resin, a material widely used in dental applications due to its favourable processing characteristics and medical approval. Two guides were produced via fused deposition modelling (FDM), employing high-performance PEEK filaments with different thicknesses (100 µm and 200 µm), allowing for comparison of surface effects induced by the printing process. The fifth sample was obtained through selective laser melting (SLM) using Ti6Al4V powder, a raw material that is commonly used in dentistry for its mechanical robustness and long-term stability in the oral environment [32]. Despite sharing the same design model, the differences in manufacturing methods and material compositions were expected to generate variations in surface morphology, wettability, and interfacial energy.

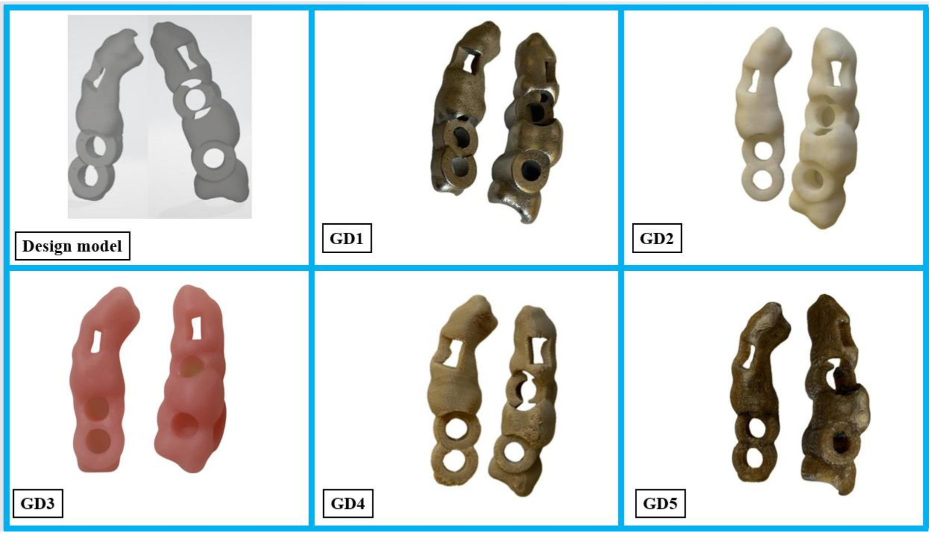


Fig. 1. Comparative visualization of 3D printed dental surgical guides fabricated using various additive Manufacturing Technologies: Design Model, GD1 / SLM–Titanium, GD2 / SLA–Resin, GD3 / MSLA–Biocompatible Resin, GD4 / FDM–PEEK 100 µm, GD5 / FDM–PEEK 200 µm.

2.1. Contact angle measurement

For the characterization of the surfaces of the surgical guides obtained by 3D printing, the KRÜSS DSA30 droplet shape analysis system, a reference equipment for measuring the contact angle, was used. This parameter provides essential clues about the hydrophobic or hydrophilic behavior of materials, but also about their ability to interact with biological fluids under real clinical conditions.

The applied method allows not only the quantification of the static contact angle, but also the deduction of the wetness of the surface, an essential aspect for the applicability of the guidelines in the clinical context, where the interaction with saliva, blood, or other biological fluids can influence the precision and stability of positioning during surgery.

2.2. Determination of free surface energy

The determination of the free surface energy for each of the five dental guides analyzed was made based on the values obtained from the measurement of the contact angle, applying a relationship established in the literature. The method used is based on the model proposed by Girifalco, which considers the interactions between solid and liquid that are proportional to the square root of the surface energies.

2.3. Roughness analysis

To characterize the roughness of the surfaces, three representative samples were selected from the dental surgical guides obtained by 3D printing, each corresponding to a different material used in the manufacturing process. Thus, experimental analyses were carried out on three types of materials. Within this characterization, the following printed guides were analyzed:

- guide obtained by selective laser melting (SLM), made of Ti6Al4V, with 30 μm layer thickness,
- guide obtained by masked stereolithography (MSLA), made of STOMA NextDent light-curing resin, with 50 μm layer thickness,
- guide obtained by fused deposition modeling (FDM), made of polyether-ether-ketone (PEEK) with 200 μm layer thickness.

This selection allowed for a pertinent comparative assessment, both in terms of the printing technology used and in terms of the specific surface behavior of each material.

2.4. Surface morphology analysis by SEM

In order to deepen and complete the results obtained by investigating the wettability, free energy released by the surface and profilometric roughness, the analysis of the morphological characteristics of the 3D printed dental guides was correlated to this series and performed, using scanning electron microscopy (SEM). These aspects are essential for determining he interfacial behavior of biomaterials, as any surface irregularity directly influences the stability, integration, and possibility of bacterial colonization.

The SEM analyses were performed using an ESEM Quattro S microscope (Thermo Fisher Scientific Inc., Waltham, MA, USA), operating in low vacuum mode at an acceleration voltage of 30.00 kV (Figure 2). A working distance of 10–13 mm was maintained, while magnifications ranged from 25× to 1000×, allowing for both general and detailed assessment of surface characteristics.

Fig. 2. 3D-printed dental guides for Scanning Electron Microscopy (SEM) analysis.

Through this multi-scale approach, the SEM evaluation provided complementary insights into the relationship between print resolution, material type (resin, PEEK, or Ti6Al4V alloy) and the resulting surface morphology. Structural comparison presented a tangible basis for observing manufacturing parameters with performance and punctual results, thus supporting the optimization of 3D-printed dental surgical guidelines for clinical use.

3. Results and discussion

The results obtained from these investigations allowed the performance of each surgical guide to be compared, providing an objective basis for determining which variant best fits the specific clinical and technical requirements and which model is less effective or appropriate in the context of use in medical practice. Thus, the advanced characterization allowed not only the qualitative validation of the prototypes, but also the optimization of the choice of material and manufacturing technology for future applications.

3.1. Assessment of the wettability of experimental samples

For surgical guides made by different 3D printing technologies, combined with different materials and obtained by using distinct working parameters, systematic determinations of the contact angle were carried out to assess the hydrophobic or hydrophilic character of the surface. For this purpose, five successive distilled water (DW) deposits and five ethylene glycol (E) deposits were carried out for the purpose of determining the polar component. The determination of the contact angle values was carried out using the Axio Vision app. The values recorded for each sample included the angles formed to the left and right of the droplet, as well as the angle obtained by the tangent method. Based on this data, the average contact angles and standard deviation were calculated (Table 2), providing a clear characterization of the wetting behavior of the analyzed surfaces.

Table 2

Quantitative analysis of contact angles on additive-manufactured dental guides with polar and non-polar liquids

Sample	Angle DW (º)	Deviation	Angle E (º)	Deviation
GD1	60	3	54	2.7
GD2	55	5.05	50	2.5
GD3	71	3.55	36	1.08
GD4	54	3.24	35	2.1
GD5	69	6.9	-	-

The values obtained when determining the contact angle using water as the test liquid varied between 54° and 71°. This highlights a spectrum from a moderately hydrophilic tendency in the case of samples GD2 (55°) and GD4 (54°) to a more hydrophobic behavior in the case of samples GD3 (71°) and GD5 (69°). These differences between the contact angle values are due to either the additive manufacturing process used (samples G2 and G3, obtained from the same material) or the type of filament used in the FDM process (samples GD4 and GD, obtained through the same technology). The results obtained indicate that the surfaces favor wetting with saliva and oral fluids and thus reduce bacterial adhesion and biofilm formation during clinical procedures. Furthermore, compatibility with the oral environment is ensured, and the interaction with hydrophilic surfaces reduces wear.

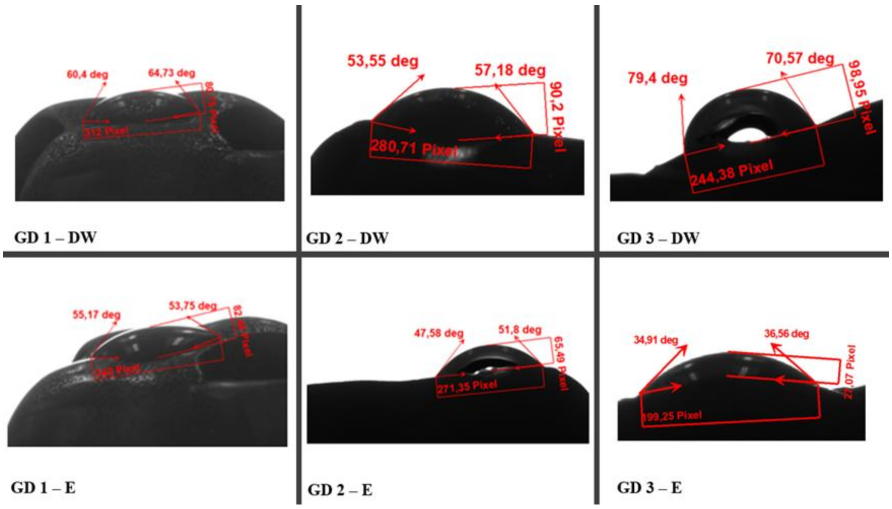


Fig. 3. Contact angle visualization of 3D printed dental guide surfaces with distilled water and ethylene glycol for GD1, GD2, and GD3 samples.

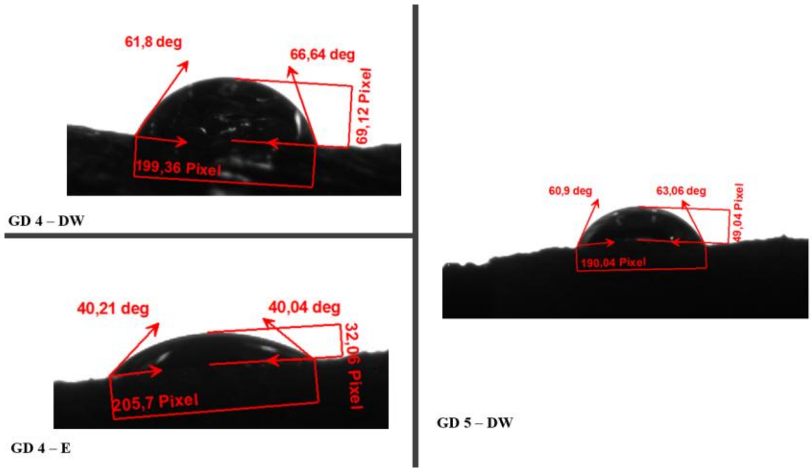


Fig. 4. Contact angle visualization of 3D printed dental guide surfaces with distilled water and ethylene glycol for GD4 and GD5 samples.

3.2. Evaluation of solid-liquid interactions

The values of the polar and dispersive components of each liquid were selected from reference sources in the scientific literature. Thus, for distilled water, a polar component of 51 mN/m and a dispersive component of 21.8 mN/m were considered, while for ethylene glycol the polar component is significantly lower, with a value of 2.3 mN/m, and the dispersive component is 48.5 mN/m.

The calculated surface free energy values are presented in Table 3.

Table 3

Surface free energy evaluation of 3D printed dental guides using distilled water and ethylene glycol as test liquids

Surface Free Energy, Distilled Water (mN/m)	
GD1	38.15
GD2	46.18
GD3	34.97
GD4	44.40
GD 5	34.28

From the results obtained, it is observed that the GD2 sample shown the highest surface free energy value (46.18 mN/m), followed by the GD4 sample (44.4 mN/m). This values suggest an increased affinity for the interaction with polar liquids and a more hydrophilic character compared to the other samples. Slightly lower values are observed in the case of samples GD3 (34.97 mN/m) and GD5 (34.28 mN/m), which suggests a less hydrophilic behavior in their case. For sample GD1, an intermediate value (38.15 mN/m) was obtained, indicating a moderately hydrophilic behavior. The results obtained are consistent with those obtained when determining the contact angle.

3.3. Determination of surface roughness

For the roughness evaluation, three determinations were made on the surface of each sample to ensure optimal comparison and reproducibility of the parameters. The obtained results indicate that the GD5 sample (FDM-PEEK 200 µm) showed the highest roughness parameters: Ra = 4.89 µm, Rt = 116.93 µm, and Rq = 9.57 µm. The GD3 sample (MSLA-polymer resin) showed low values for all parameters (Ra = 2.1 µm, Rt = 22.87 µm, Rq = 2.76 µm), suggesting a smooth surface. The GD1 sample made through the SLM technique using Ti6Al4V powder showed a moderate roughness (Ra = 3.99 µm, Rt = 39.96 µm).

In conclusion, the hydrophilic character, surface free energy values, and roughness values define the interaction behavior of each 3D-printed surgical guide with the biological environment. Of all the samples, those manufactured by the MSLA technique (GD3 sample) highlighted favorable characteristics for the dental guides used in implantology, showing optimal surface properties.

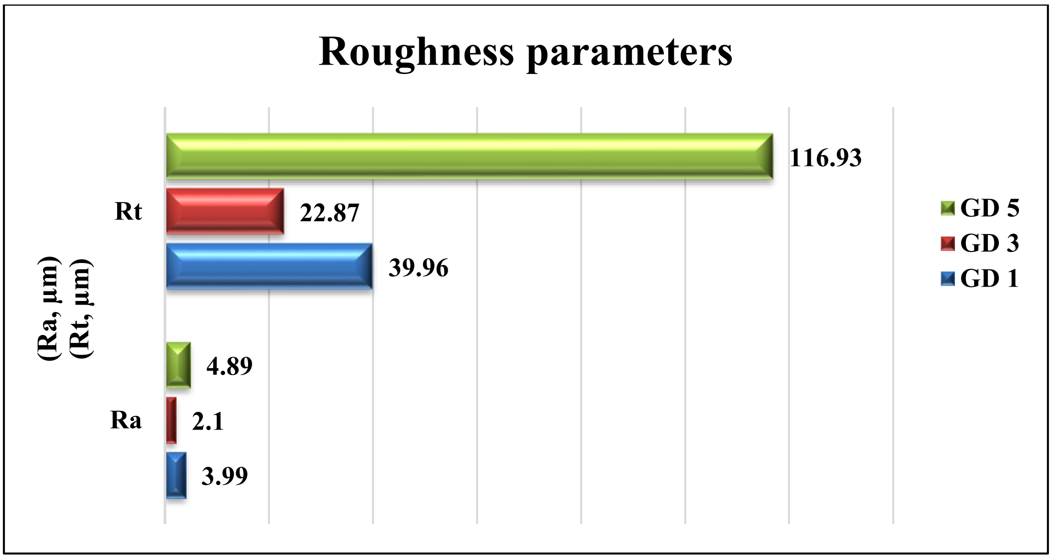


Fig. 5. Arithmetic average (Ra) and maximum height of the profile (Rt) values of selected 3D-printed dental guides.

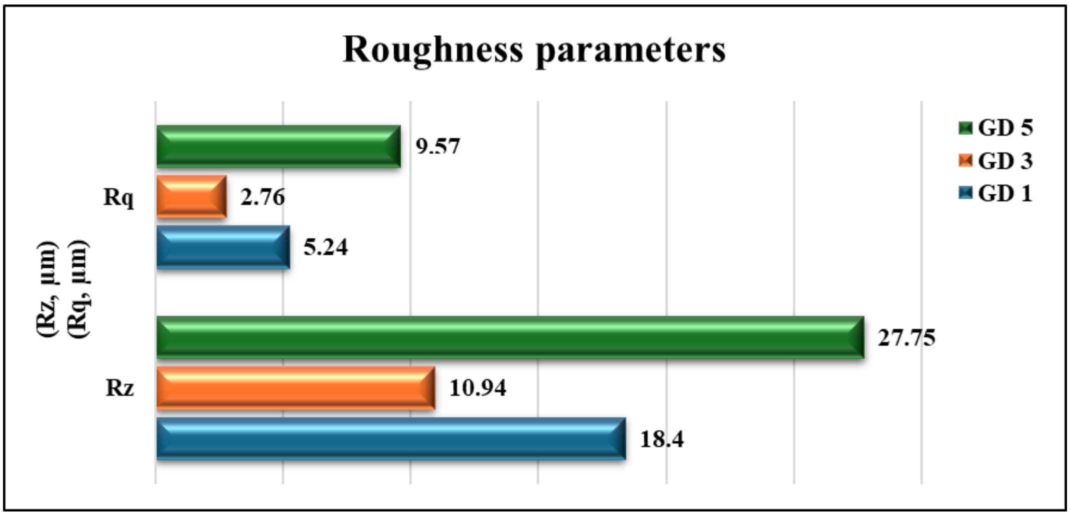
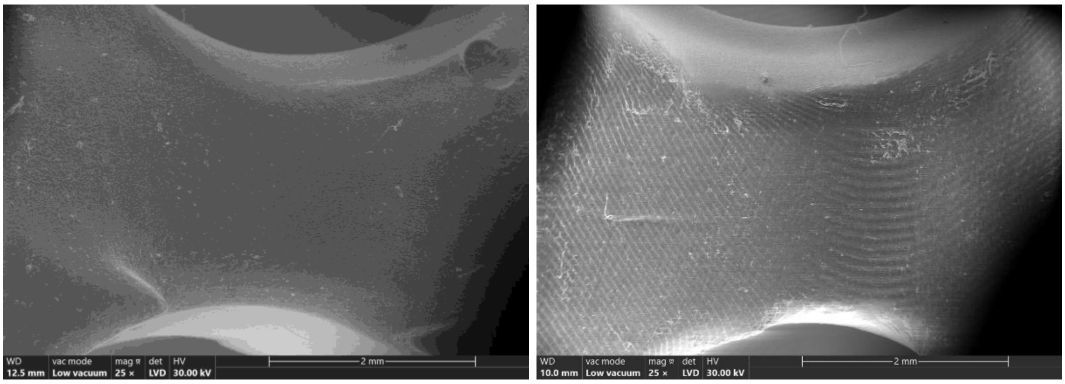


Fig. 6. Root mean square average (Rq) and average maximum height of the profile (Rz) values of selected 3D-printed dental guides.

3.4. Surface morphology

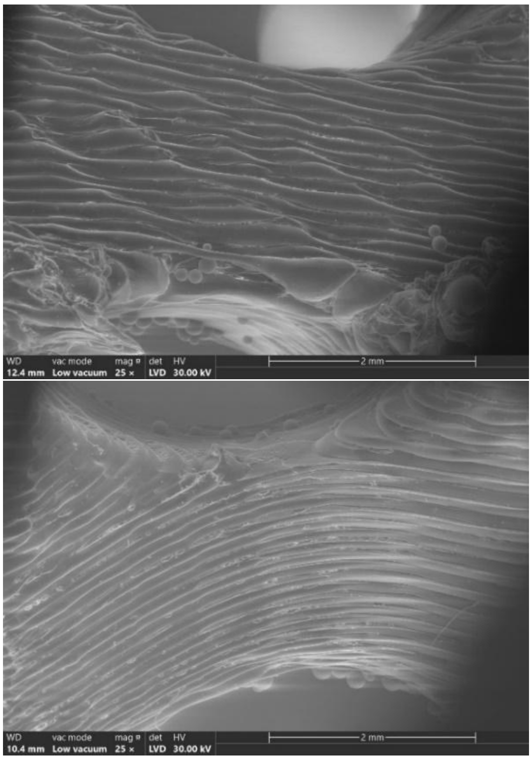
Surface morphology of the experimental samples was investigated by scanning electron microscopy, in order to reveal the influence of raw materials and processing techniques on this characteristic.

The GD1 sample has a compact surface, the particles are partially melted, agglomerated and spherical in shape, on the inner side the structure is compact with dense granules and areas with minor microcracks that have appeared because of the solidification process.



(a) (b)

Fig. 7. SEM images on the surface of the GD1 sample (a - external side, b – internal side)



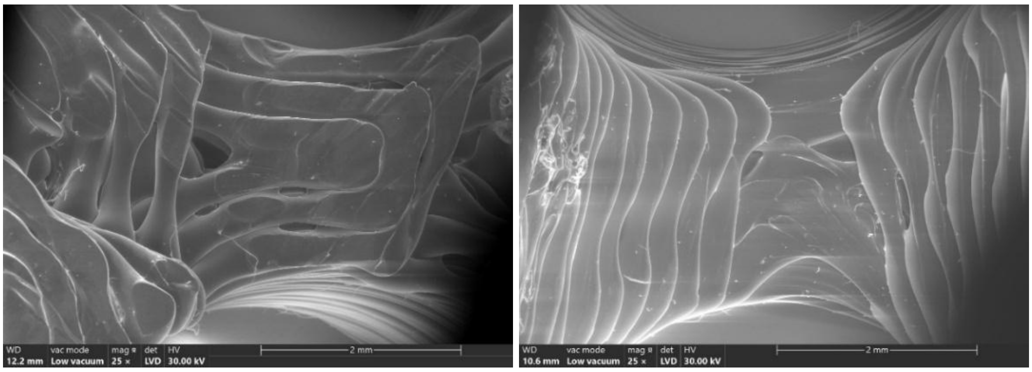
(a) (b)

Fig. 8. SEM images on the surface of the GD2 sample (a - external side, b – internal side)

On the opposite side, the GD2 sample reveals a layered texture with irregular parts, also observable the micropores and resin agglomerations that occurred during the photopolymerization process, which indicate incomplete solidification zones that can lead to destabilization of mechanical and surface properties.

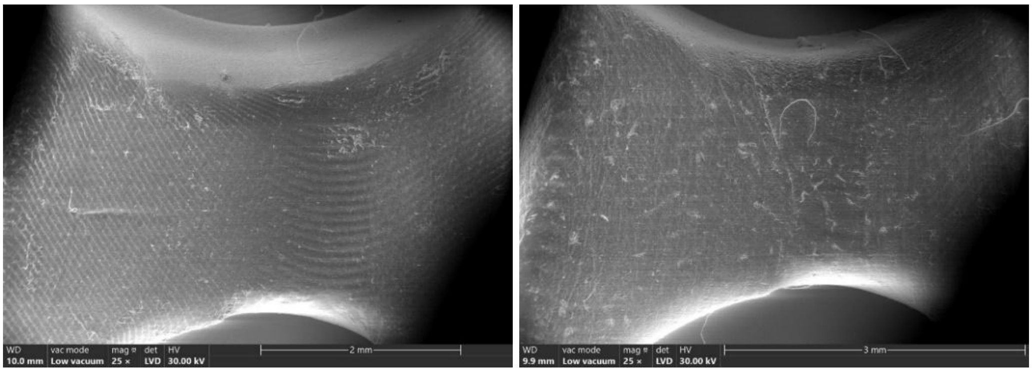
As far as the GD3 sample a smooth and more homogeneous topography is observed by comparison with the simple stereolithography technology (GD2), the layers are very well defined, thus indicating an improved adhesion and resolution of the layer by using masked stereolithography.

It can thus be observed by using SEM analysis, that additive manufacturing parameters combined with a particular type of material directly affect the microstructural integrity and surface characteristics of dental surgical guides.



(a) (b)

Fig. 9. SEM images on the surface of the GD3 sample (a - external side, b – internal side)

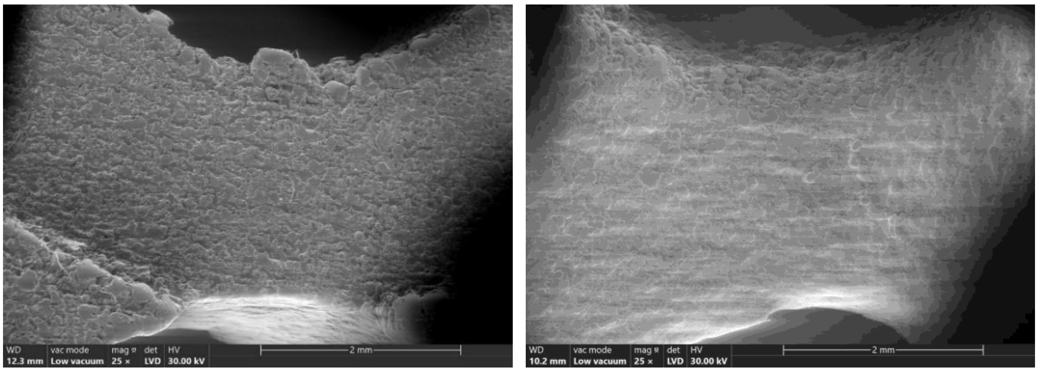


(a) (b)

Fig. 10. SEM images on the surface of the GD4 sample (a - external side, b – internal side)

The GD4 and GD5 samples show different patterns and morphologies, although the technology is the same, the composition of the material influences the structure. In the case of the GD4 sample, which was obtained by using FDM technology with PEEK material, a well-defined layered structure is observed, the deposition lines are parallel, smooth and the spaces between layers are restricted, indicating a strong bond between the extruded filaments. The surface is compact, with minor defects arising from the thermal extrusion process.

On the opposite side, the GD5 sample, also made by FDM technology, but by using a different filament of polymer, reveals a visible and pronounced surface texture, with deposited wavy shapes. Through SEM analysis, the two samples made with the same technologies but with different layer thickness present a layered, continuous, and orderly structure. However, the GD5 sample depicts an irregular surface with a higher porosity, characteristics that can decrease the mechanical behavior.



(a) (b)

Fig. 11. SEM images on the surface of the GD5 sample (a - external part, b - interior part)

4. Conclusions

The experimental measurements performed on five 3D-printed surgical guides made from different materials and using different 3D printing techniques confirm that surface properties are influenced more by processing technique than by the materials used. The dental guide manufactured by MSLA (GD3) achieved the most balanced combination of dimensional fidelity, uniform surface morphology, and moderate hydrophilicity.

The GD1 sample (SLM-Ti6Al4V) displayed a more irregular structure originating from partially fused particles and heterogeneous melting tracks. The experimental results obtained suggest that is necessary a surface post-processing to obtain proper surface properties before using in oral cavity for this type of samples.

The PEEK-based guides obtained through FDM exhibited a surface feature strongly dependent on layer thickness. The sample made from PEEK with a layer thickness of 200 μm has noticeably rougher textures than the sample made from PEEK with a layer thickness of 100 μm. Such features may be useful where mechanical fastening or microlocking is desired but could simultaneously elevate susceptibility to microbial adhesion without proper finishing or polishing.

The experimental results underline that additive manufacturing provides an efficient platform for manufacturing personalized surgical guides for dental implantation surgery, but the clinical performance of the final device depends on a rational pairing between raw material, including their shape, and 3D printing methods.

Among the samples experimentally evaluated, those obtained by the MSLA technique provide the most favourable surface properties, while samples obtained by the SLA and SLM techniques require additional surface modifications to have properties suitable for their use in the oral cavity.

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