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Dimensional accuracy and surface roughness of polymeric dental bridges produced by different 3D printing processes

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ABSTRACT

Purpose: To compare the dimensions accuracy and surface roughness of polymeric dental bridges produced by different 3D printers.

Design/methodology/approach: Four-part dental bridges were manufactured by three printing systems working on the basis of digital light projection (DLP) stereolithography (SLA), laser-assisted SLA and fused deposition modeling (FDM). The materials used from SLA printers are liquid methacrylate photopolymer resins, while FDM printer use thin wire plastic polylactic acid. The accuracy of the external dimensions of dental bridges was evaluated and the surface roughness was measured.

Findings: It was found that compared to the base model, the dimensions of the SLA printed bridges are bigger with 1.25%-6.21%, while the corresponding dimensions of the samples, made by FDM are smaller by 1.07%-4.71%, regardless the position of the object towards the substrate. The samples, produced by FDM, are characterized with the highest roughness. The average roughness deviation (Ra) values for DLP SLA and lase-assisted SLA are 2.40 µm and 2.97 µm, respectively.

Research limitations/implications: For production of high quality polymeric dental constructions next research should be targeted to investigation of the polymerization degree, stresses and deformations.

Practical implications: Our study shows that 3D printers, based on laser-assisted and DLP SLA, can be successfully used for manufacturing of polymeric dental bridges – temporary restorations or cast patterns, while FDM system is more suitable for training models. The results will help the dentists to make right choice of the most suitable 3D printer.

Originality/value: One of the largest fixed partial dentures – four-part bridges, produced by three different commercial 3D printing systems, were investigated by comparative analysis. The paper will attract readers' interest in the field of biomedical materials and application of new technologies in dentistry.

Keywords: Materials, Biomaterials, 3D printing, Dimensional accuracy, Surface roughness

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BIOMEDICAL AND DENTAL MATERIALS AND ENGINEERING

1. Introduction

In recent years, the application of additive technology (AT) in dental medicine is rapidly growing [1-9]. This is mainly due to the continuous development of new and better printing technologies as well as materials which enlarges the applications of AT for the production of various structures in almost all areas of dental medicine – surgery, oral implantology, orthodontics, prosthetic dentistry. In dental medicine, the most frequently used AT are: stereolithography (SLA), fused deposition modeling (FDM), selective electron beam melting (SEBM), selective laser sintering (SLS), selective laser melting (SLM) and ink-jet printing (IJP) [1,3,10]. Using SLA, FDM and IJP processes various dental constructions can be produced from non-metallic materials – individual impression trays; replicas of plaster models and study models for prosthetic dentistry [11-14] and orthodontics [15,16]; bases for prosthesis and even complete dentures [17]; surgical guides for dental implants [18,19]; provisional crowns and bridges [20-22]; cast patterns for press-ceramics and metal casting [23,24].

For the successful application of these constructions in dentistry, the accuracy and surface quality are important factors. In 3D printing processes they depend on the optical properties of the polymers used, the thickness of the building layer and the orientation in respect to the building direction [25-27]. Ide Y. et al. [28] investigated the influence of the inclination of the object and the building direction in Polyjet and FDM printing. They used samples with shape of triangular prism and different angles, varying from 5^o-60^o. It was established that the 3D printed samples with acute angles characterize with low precision as well as the surface roughness is different in each printing direction. Hence, in manufacturing a precise medical models with sharp angles, the type of AT and the printing direction should be taken into account. The group of Minev E. [29,30] developed *Grid* method for investigation and analysis the distribution of the uncertainties in the process of rapid prototyping. It was found, that the linear and angular deviations in respect to the nominal dimensions and their distribution are geometric characteristics. As a result new sample for studying the geometrical accuracy was developed, which overcomes the disadvantages of a pyramidal sample. In order to investigate the objects with volume, close to the natural teeth, Dikova et al. [31] used cubic samples with 5 mm sizes. The cubes were manufactured with 3D printer, working on the principle of digital light projection (DLP) SLA. They were printed in two positions towards the basis – horizontally and tilted at 45^o. It was established that the dimensions of the printed samples are larger than those of the virtual model and the surface roughness of the horizontal cubes is less than that of the inclined ones, as the roughness depends on the thickness of the building layer.

As the AT use different manufacturing processes, it is essential to know the possibilities these technologies offer for production of various types of dental constructions. While most of the published studies have address the possible replacement of the conventional plaster casts with 3D printed ones [11,12,15], there were very few studies on the precision of the printed fixed partial dentures (FPD) – bridges and crowns. In that group of dental constructions the 3D printing of polymer-based materials is mainly used for production of temporary FPD or cast patterns. Digholkar S et al. [20] investigated the mechanical properties of provisional crowns and bridges, fabricated by rapid prototyping and compared them with the CAD-CAM milled and conventionally manufactured. Mai HN et al. [21] established that CAD-CAM systems ensure higher fitting accuracy of polymeric interim crowns compared to the compression molding, as the polymer-jet 3D printing significantly increases the crowns accuracy. The precision of resin dental crowns is influenced by the number of samples produced by micro stereolithography with the most accurate details when 3 pieces are printed on a single platform [32]. The group of Dikova et al. [22] manufactured temporary four-part bridges and cast patterns from different polymers by DLP SLA. Their results showed that the dimensions of the both groups of samples, printed with the layer thickness, recommended by the producer, are larger than the base model and the surface roughness is higher as well.

The peculiarities of the technological processes in 3D printing of FPD from polymer-based materials define their higher geometrical and fitting accuracy but also higher surface roughness comparing to the conventional technology. As the crowns sizes are smaller than the bridges, it is expected the deformations of the latter to be larger and different for various AT. In manufacturing of temporary crowns and bridges this can affect the clinical success, while in production of cast patterns this can influence the next fabricating process. As dental bridges have more complicate shape and larger sizes than the crowns and taking into account that they are subjected to higher loads during the masticatory process, consequently, more attention should be paid to the properties of the bridge constructions. Presently, there is no sufficient information about the geometrical and surface properties of 3D printed bridges most probably due to both the multiple variants of bridges design and the wide variety of 3D printing processes. Our hypothesis is that not all technological processes of the 3D printing systems, currently available on the market, can ensure the necessary precision and surface quality of polymeric bridge constructions. Therefore, the aim of this study is to compare the dimensional accuracy and surface roughness of dental bridges produced by three different commercial 3D printers, working on the principles of laser assisted and DLP stereolithography and fused deposition modelling.

2. Experimental methods

2.1. Materials and samples manufacturing

The samples are four-part dental bridges, based on the same virtual 3D model. It was generated with *KaVo Surface* software using data of conventionally cast Co-Cr master bridge after scanning with *KaVo Everest-Scan Pro* scanner. Three different 3D printers are used for producing the samples: *RapidShape D30* (*http://www.rapidshape.de/*) using the Digital Light Projection Stereolithography (DLP) technology, *Form 1+* (*https://formlabs.com/*) using Laser-based Stereolithography (SLA) technology and *Leapfrog Creatr Dual Extruder* (*https://www.lpfrg.com/*) using Fused Deposition Modeling (FDM) technology. Table 1 summarizes the technical specifications of the printers and the polymers used for production of the samples.

Table 1.
Data for 3D printers and properties of the materials

3D printer					
Rapid Shape D30		Form 1+, Formlabs		Leapfrog Creatr Dual Extruder	
Technology					
Digital light projection (DLP) Stereolithography (SLA)		Stereolithography (SLA)		Fused Deposition Modeling (FDM)	
Resolution: LED technology, HD 1080 x 1920px		Laser Spot diameter	155 µm	Extruder size diameter	0.35 mm
Accuracy	+/- 29 µm	Laser Specifications	405 nm violet laser, 120 mW	Positioning precision	XY: 16.9 µm, Z: 0.5 µm
Material					
Methacrylate Photopolymer Resin, shade A3,5; NextDent C+B		Methacrylate Photopolymer Resin, White colour		Polylactic Acid (PLA)	
Flexural Modulus	2.3-2.5 GPa	Flexural Modulus	0.97 GPa	-	-
Hardness Shore	D 80 – 90	-	-	-	-

Table 2.
Technological parameters for 3D printing of dental Bridges

3D printer → Parameter ↓	Rapid Shape D30	Form 1+, Formlabs	Leapfrog Creatr Dual Extruder	
			Horizontal position	Vertical position
Number of printed objects	5	3	3	3
Layer thickness	50 µm	50 µm	50 µm	50 µm
Printed layers	305	266	220	196
Print time	68 min	57 min	58 min	50 min
Post cured	30 min	No	-	
Support structure	Yes	Yes, automatic generated	Yes, automatic generated	
Extrusion temperature	-	-	210 °C	
Bed temperature	-	-	25 °C	
Printing Speed (mm/s)	-	-	45	

Plastic polymers are supplied by the manufacturers of 3D printers and are designed for the respective machine type. The materials used from the SLA based printers are photo-reactive liquid resins (Methacrylate Photopolymer Resins), while FDM printers used thin wire plastic (PLA – Polylactic Acid) with a diameter of 1.75 mm. All samples are produced with the same layer thickness of 50 μm (Table 2) of polymers with similar optical properties – colour, colour density and transparency (Fig. 1, Fig. 2 and Fig. 3) in order to achieve better comparability.

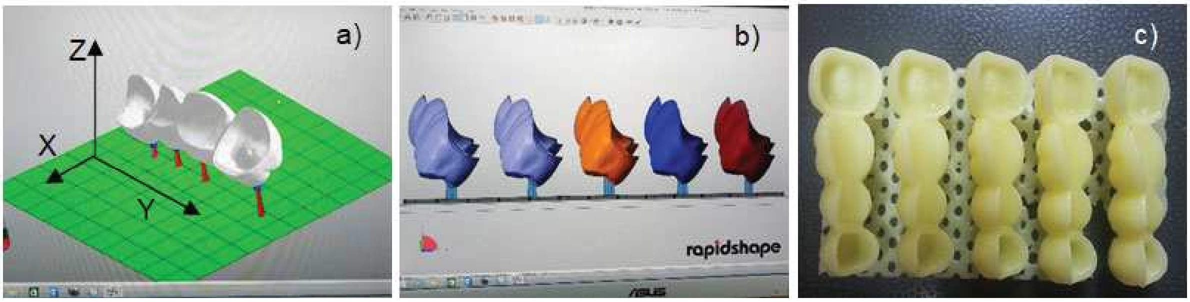


Fig. 1. Manufacturing of dental bridges by 3D printer "Rapid Shape D30": design of 3D virtual models – a) and b) and as-printed bridges – c)

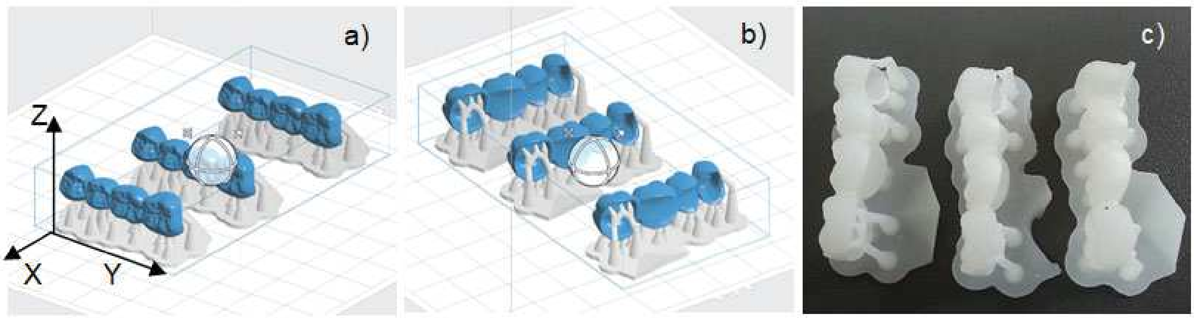


Fig. 2. Manufacturing of dental bridges by 3D printer "Form 1+": design of 3D virtual models – a) and b) and as-printed bridges – c)

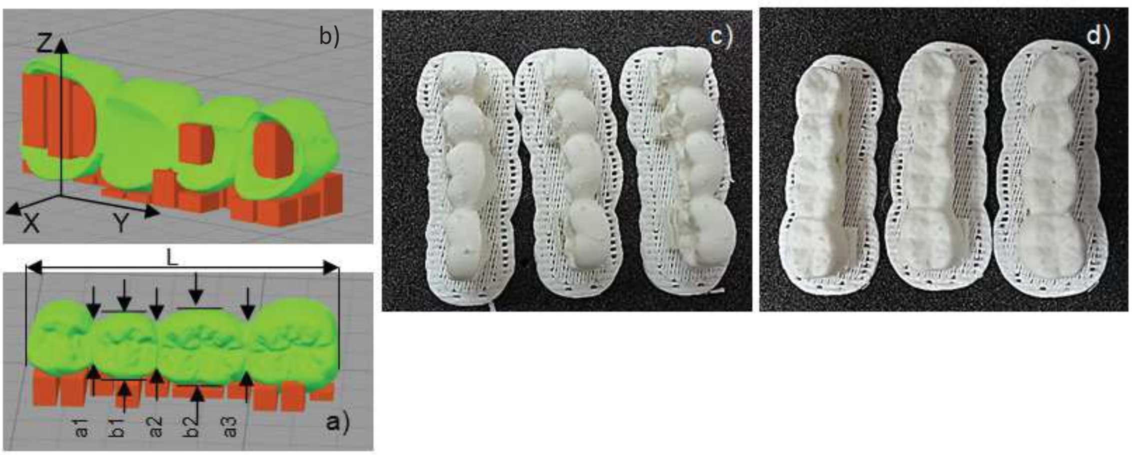


Fig. 3. Manufacturing of dental bridges by 3D printer "Leapfrog Creatr Dual Extruder": design of 3D virtual models – a) and b) and as-printed bridges in horizontal – c) and vertical – d) positions

The 3D printing technologies have specific features in the printing process, because of that the samples were differently positioned in respect to the base of the given 3D printing device: tilted – *RapidShape D30* (Fig. 1), horizontally against the base – *Form 1+* (Fig. 2), horizontally (H) and vertically (V) against the base – *Leapfrog Creatr Dual Extruder* (Fig. 3). The specific feature of the 3D printing process is the need to have a base, over which starts the building process. The support structures provide stability and proper orientation of the object in the process of printing. The type of the substrate, the number, form and positioning of the support structure, depend on the size and form of the objects, their position against the substrate, type of the printing process and material (Fig. 1, Fig. 2 and Fig. 3). The support structures can be generated manually as with *RapidShape D30* or automatically as with *Form 1+* и *Leapfrog Creatr Dual Extruder*.

Technological parameters for printed dental bridges with the different 3D printers are shown in Table 2.

2.2. Dimensional accuracy measurements

The accuracy of the external dimensions of the dental bridges is evaluated by measuring the values of the connections between bridge-bodies and bridge-retainers – *a1*, *a2* and *a3,* the width of the bridge bodies – *b1* and *b2* and the length of the bridge – *L* (Fig. 3a). Five measurement per every parameter are performed for the three dental bridges, by using caliper (0.02 mm accuracy) and micrometer (0.01 mm accuracy). The mean values and the standard deviations (SD) of the dimensions were calculated.

2.3. Surface roughness measurements

The surface roughness was studied by a profile meter (*Taylor Hobson Surtronik 3)*. The average roughness deviation (*Ra)* of the vestibular surface of the second bridge premolar was measured, since it contains the longest straight section. For each 3D printing technology, the roughness in 10 points of the 3 bridges was investigated, and the mean value *Ra,* standard deviation – SD and standard error – SE were calculated. Optical microscopy (*Olympos SZ51)* was used for observing the surface morphology.

3. Results

3.1. Dimensional accuracy

The mean values of the dental bridges dimensions, produced with the three 3D printers, are shown in Figure 4. Most of the dimensions of the structures, printed using the stereolithography method, are larger compared to those of the base bridge-model with a value of 1.25%-6.21% (Fig. 5). The largest increase in the dimensions of the bridges is produced by the DLP SLA. In case of FDM samples, almost all dimensions are smaller than the basic bridge-model with a value ranging between 0.10% and 4.71%, regardless of the position of the construction relative to the base. Only the length *L* is smaller with 0.10%-0.67% compared to the base model for all samples.

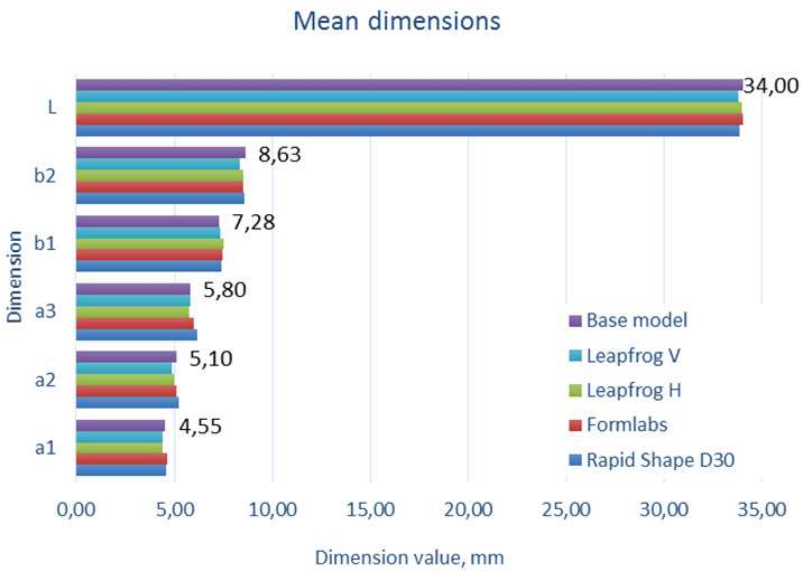
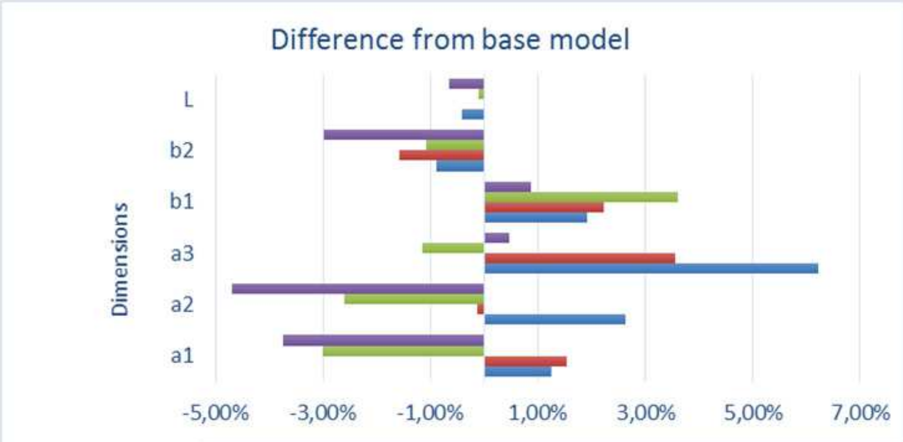


Fig. 4. Dimensions of polymeric dental bridges, produced by different 3D printers, and referenced values of the base model



	a1	a2	a3	b1	b2	L
Leapfrog V	-3,74%	-4,71%	0,46%	0,87%	-3,00%	-0,67%
Leapfrog H	-3,00%	-2,61%	-1,15%	3,59%	-1,07%	-0,10%
Formlabs	1,54%	-0,13%	3,56%	2,22%	-1,58%	0,00%
Rapid Shape D30	1,25%	2,61%	6,21%	1,91%	-0,89%	-0,41%

Fig. 5. Difference of the dimensions of 3D printed dental bridges with that of the base model

The standard deviations of the dimensions of bridges, made using the stereolithography method, are negligible – up to 0.08 mm (Fig. 6), regardless of the size and the position of the object. Standard deviations in FDM printed samples are greater: 0.026-0.401, influenced by the position of the object. The largest deviations have the *a1, a2* and *a3* dimensions of the bridges printed horizontally to the base (0.188, 0.238 and 0.401 respectively).

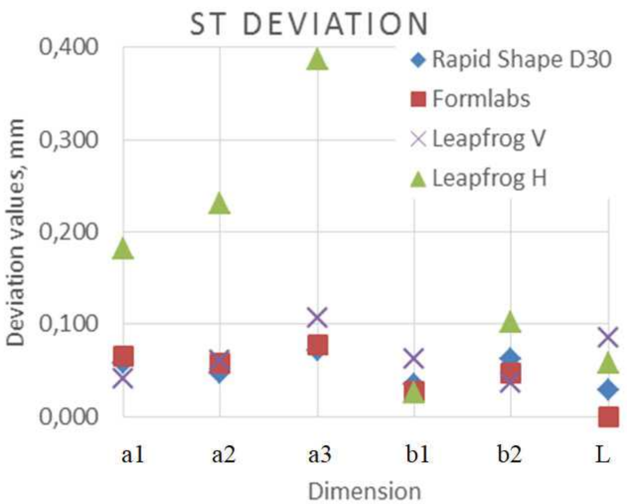


Fig. 6. Dimensions' deviations of polymeric dental bridges, produced by different 3D printers

When examining the geometrical characteristics of the dental bridges, it was found that the largest deviations were detected in the dimensions located alongside the building direction – Z axis or inclined toward it – palne XZ. For samples made using the stereolithography method, these dimensions are larger than the dimensions of the master bridge, and for the FDM, they are smaller. The length *L* of dental bridges characterizes with higher accuracy in the all three technologies. It is located ialong Y direction, which is not related to the direction of building.

3.2. Surface roughness

The average values of the mean surface roughness deviation (*Ra*) for both 3D printing technologies are 2.40 µm and 2.97 µm respectively for DLP SLA and laser SLA (Fig. 7). The same trend is maintained for the statistical deviation and the standard error of *Ra* values. They are smaller for the DLP SLA samples (SD = 0.67 and SE= 0.12) compared to these produced by laser SLA (SD =1.21 and SE=0.22). It was not possible to measure the average arithmetic deviation of the roughness (*Ra*) of samples made by the FDM process due to the low rigidity of the PLA plastic. Their roughness was assessed by examining surface morphology with an optical microscope.

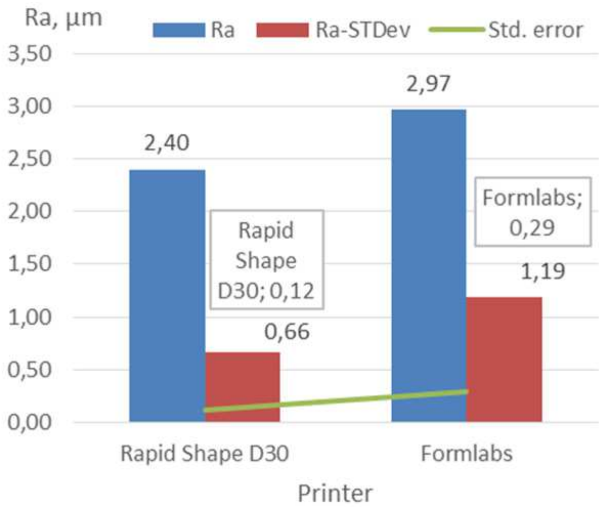


Fig. 7. Average arithmetic deviation Ra of the surface roughness of polymeric bridges, manufactured by DLP and laser SLA (Rapid Shape D30 and Formlabs respectively)

Figure 8 shows the surface of plastic dental bridges produced using different 3D printing technologies – DLP SLA, laser SLA and FDM. Regardless the types of the technological process, the individual layers of the bridge construction of the samples are clearly visible on the surface. They are least expressed in bridges made by laser SLA, and most strongly in FDM-specimens, due to the features of each technology. An optical microscope study showed that FDM samples were characterized by the highest roughness. In addition, some hardened polymer residues were seen at the sample surface, most probably formed at the end of the molding of the respective layer, which led to increase the roughness and reduce the quality.

4. Discussion

The specifics of the 3D printing processes, the properties of the polymers used and the position of the samples in relation to the base and the direction of building affect the geometrical characteristics and the roughness of the surfaces.

In the stereolithography process, the separate layer is formed by photopolymerization of a liquid monomer. In the process of DLP SLA the layer of a certain shape and thickness is irradiated by the LED source of the *RapidShape D30* printer. Depending on the optical properties of the material, the light refracts at a certain angle and is scattered. This results in irradiation of a larger area than the boundaries of the shape of the layer [25] and, respectively increase the dimensions of the workpiece.

In laser assisted SLA, the surface of the monomer is scanned with a laser beam, which at *Form 1+* printer has a 155 µm diameter. The entire layer area is obtained after overlapping photo-polymerized strips of a certain width. Due to the overlapping of the individual strips, a more complete polymerization is obtained over the entire thickness of the layer and a smaller amount of residual monomer remains. As a result, a detail with more accurate dimensions and smaller deformations is obtained. Due to the energy distribution in the cross section of the laser beam under Gaussian law, the light penetrates to different depths in the liquid monomer. The deeper penetration occurs alongside the axis of the laser beam and it decreases towards the periphery. This phenomenon leads to the formation of a polymerized strip with deep curvature and less scattering of light. Further this helps to obtain more accurate detail's sizes, but on the other hand, it causes a slightly higher roughness than the DLP SLA. Due to the rounding of the polymerized strips, the individual layers of the surface are less noticeable at a certain location of the surface of the workpiece relative to the direction of construction.

The FDM process is characterized by extruding a thermoplastic filament through a heated nozzle. According to the recommended manufacturer's data, the print speed of the *Leapfrog Creatr Dual Extruder* is 45 mm/s, the temperature of the extruded material is 210°C and the bed temperature is 25°C (Tab. 2). Therefore, in the process of building a given layer of the object, the molten plastic is cooled to room temperature at a relatively high speed, which is accompanied by a shrinkage of the material and reduces the dimensions [15]. The features of the process and material characteristics (plastic PLA) suggests the presence of increased roughness and numerous defects on the surface of the parts.

Considering the capabilities of 3D printing equipment and software used, dimensional variations in the different directions can be compensated during the process of deisgning the virtual 3D model. It is necessary to take into account not only the type of the technological process and the material used but also the purpose of the printed object. It should be noted that when making patterns for casting dental constructions, larger sizes can compensate the shrinking of the dental alloy. But when manufacturing provisional bridges and crowns, the accuracy is essential.

The surface quality of the constructions, produced by 3D printing, can be increased by additional processing – mechanical and/or chemical. The choice of the type of final processing depends on the purpose of the construction. The mechanical treatment includes grinding and polishing, which are most commonly used in fabrication of temporary bridges and crowns. While the chemical processing, done with solvents to dissolve surface roughness or varnishes to fill them, is used to produce casting patterns for metal details.

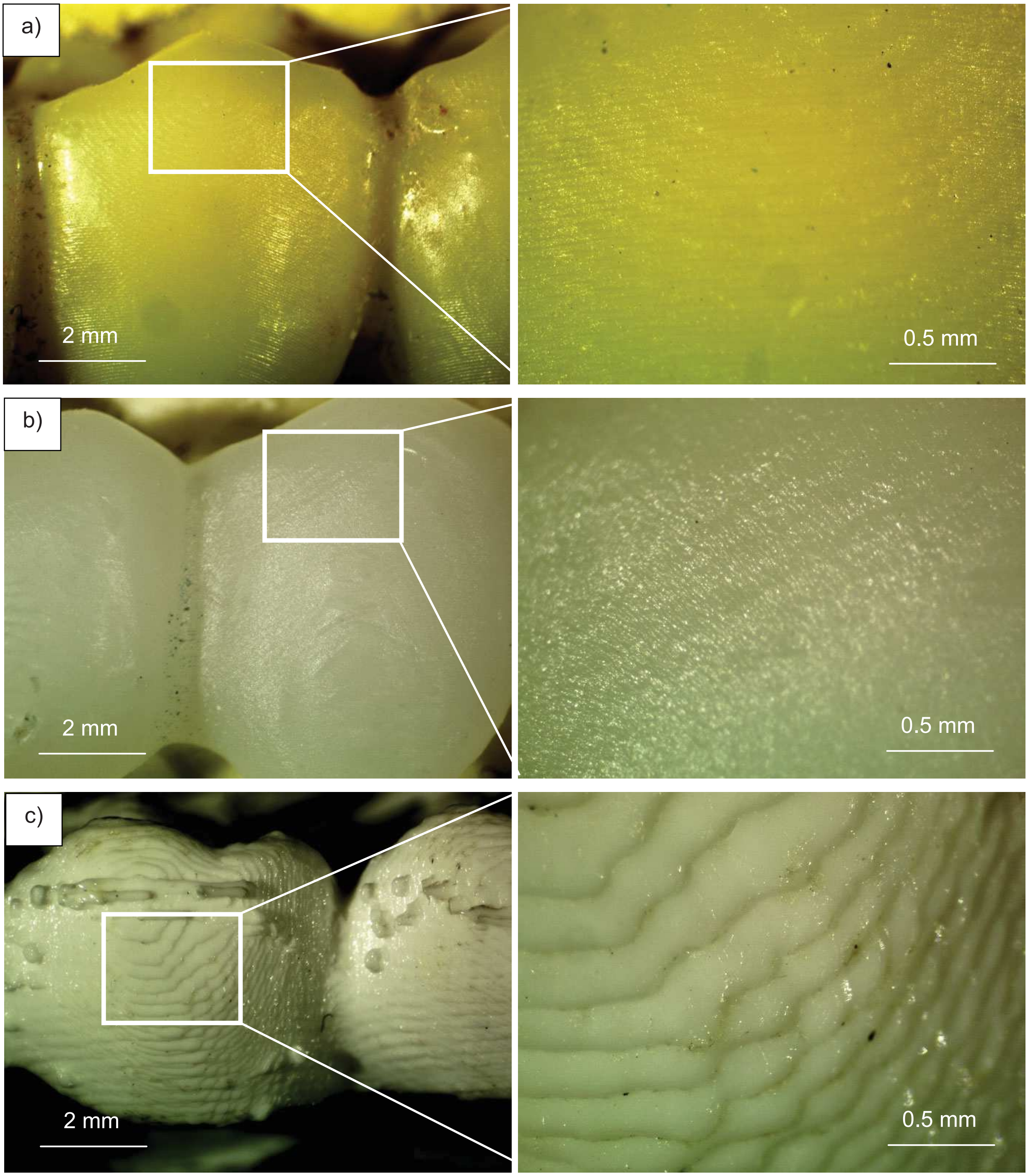


Fig. 8. Surface morphology of polymeric bridges, manufactured by different 3D printing processes: DLP stereolithography – a), laser assisted stereolithography – b) and fused deposition modeling – c)

When selecting a 3D printer for a particular application in dentistry, consideration should be given not only to the features of the process and the accuracy, but also to the type of material used. In order to make provisional bridges and crowns, it is necessary to use a plastic with a high biotolerance; for cast patterns – plastic with minimal expansion in heating and burning without residue; for individual impression trays and dental models – plastic with higher mechanical properties, high dimensional accuracy and minimal deformation; for training models materials with lower hardness and strength and greater roughness are acceptable.

Our results proved the hypothesis that not the all technological processes of the currently available 3D printing systems can ensure the necessary precision and surface quality of the polymeric dental bridges. From the 3D printers used, only the *RapidShape D30,* working on the principle of DLP SLA, is designed specifically for use in dentistry and is packed with a full range of materials. The research has shown that it can make bridge constructions with the necessary high precision. Size errors, detected in preliminary experiments, can be compensated during the desig of the virtual model, and the required smoothness is achieved by additional final processing. If suitable polymers are utilised, *Form 1+* printer, based on laser assisted SLA technology, also can be used with the same success for manufacturing of dental bridges. Due to the high roughness of the details produced the FDM-based *Leapfrog Creatr Dual Extruder* printer is suitable only for fabricating models for training.

5. Conclusions

A comparative study of the dimensional accuracy and surface roughness of four-part dental bridges, made by stereolithography and FDM, has been conducted. It has been found that not all 3D printers ensure the necessary quality of the polymeric bridge constructions. The specifics of the processes of 3D printing, the properties of the polymers used and the position of the samples relative to the substrate and the direction of the building, influence the geometric characteristics and surface roughness.

The dimensions of the constructions, printed with the method of stereolithography, are bigger than those of the master bridge, while the dimensions of samples made by FDM process are smaller than the basic model, regardless the position of the object towards the substrate. The deviations in the sizes are different in all three directions. The largest deviations are in the sizes, which are arranged parallel (axis Z) or obliquely (plane X-Z) to the direction of building, while the more precise dimensions are obtained in the axis Y, which is not related to the direction of building. The samples, produced by FDM, are characterized with the highest roughness. The average *Ra* values for DLP SLA and laser assisted SLA are 2.40 μm and 2.97 μm respectively.

The present research showed that 3D printers, based on laser assisted and DLP SLA, can be successfully used for manufacturing of polymeric dental bridges, while FDM system is more suitable for training models. The deviations in the sizes of the constructions, produced by 3D printing, can be compensated during the process of building a virtual model, while the surface quality can be improved by additional mechanical or chemical treatments.

In order to obtain bridge constructions with high dimensional accuracy and high surface quality with 3D printing, it is necessary to carry out preliminary tests to assess the characteristics and capabilities of each new technological process and apparatus. This type of study would help to obtain optimal production modes.

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