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Study of Technological Chains for Rapid Prototyping of Orthodontic Dental Products

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The paper presents results from studying the possibilities of digital layering technologies (DLP SLA - Digital Light Projector Stereolithography) for construction of biomedical orthodontics devices (aligners). Experimental data on the mechanical and aesthetical properties (transparency) of the materials used has been studied in comparison with the conventional technologies for producing the aligners - Vacuum Forming (VF). The paper discuss the influence of the design of the devices (e.g. thickness) and technological parameters (e.g. stirring time) of the processes on the mechanical properties and orthodontics functionality of the materials as well as the quality and accuracy of the devices (models and functional prototypes for dental applications).

***Keywords:** Materials in dentistry, Orthodontics, Stereolithography.*

I. INTRODUCTION

The treatment of orthodontic deviations aims to influence the growth of the upper and lower jaw [1]. Depending on the situation, the growth of one or both jaws can be slowed down or stimulated. The force is produced by the patient's muscles and transmitted to the teeth and jaws. Functional orthodontic appliances are used to treat deep, open and/or distal bite.

Braces, aligners and sometimes oral surgery are used for the correction of irregularly aligned teeth [2], [3]. Over the course of the patient's treatment the dentists will swap the existing aligners for new ones designed to get the teeth in place for the next phase. The dentist must have relevant information about the mechanical properties of the aligners in order to plan all phases of the treatment. Some important properties of these devices are as follow:

(i) transparency and aesthetic appearence,
(ii) biocompatibility,
(iii) stability at body and food temperature,
(iv) stiffness and rigidity.

Of the all requirements listed the mechanical properties (stiffness/rigidity) are of primary importance. Also important is the transparency of the aliners used for treting children. The rest of the properties are largely researched and predetermined by the manufacturers.

The dynamic development of digital dentistry opens wide opportunities for more and more innovative approaches in the planning and implementation of treatment by applying CAD/CAM technologies in orthodontics practice [4]. More and more often in daily practice, digital technologies such as intraoral scanners, laboratory scanners and cone beam computed tomography. 3D systems facilitate the direct fabrication of orthodontic appliances from 3D models. Known printing technologies differ in the materials and methods used to create the respective objects [5] - [8].

The first attempt to produce a retainer directly from a digital model was made in 2014 by A. Nasef et al. They report the successful fabrication of a retainer from SVST, without a physical model, using an SLS 3D-printer. Although accuracy was not evaluated, this study pioneered the use of 3D printing in orthodontics. Due to the use of an SLS printer in the study, the printed retainer is white and opaque, which is unacceptable to the most of patients [9].

Today, there are over thirty different 3D additive technologies offered by forty different companies (for example, molten material deposition, selective laser sintering, etc.) [7] - [9]. Stereolithography (SLA) is the first material-additive rapid prototyping process of this kind. Complex form models are created by sequentially

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curing layers of photopolymer resin using laser beam or DLP (digital projector).

In this study we use DLP-SLA (Digital Light Projector Stereolithography technology) NextDent OrthoFlex (Vartex - Dental B.V., Soesterberg, The Netherlands) in which the model is built in a bath filled with liquid photopolymeric resin, on a vertically movable platform in a suspended position (top down approach) [10]. On the platform, supports are initially printed to ensure the stability of the physical model and especially its overhangs. DLP is controlled by the corresponding STL files performing layer by layer polymerization of the liquid material. Then the platform is immersed in the bath until the hardened layer is completely covered with liquid resin. The method finds application in dentistry in making of models, casting prototypes, surgical guides, splints, individual spoons, temporary restorations, gingival mask, prostheses, etc. It is possible to make occlusal splints and orthodontic appliances [11], [12]. The OrthoFlex is transparent class 2a biocompatible photopolymerizing material developed for the production of 3D printed occlusal splints and retainers. It has a strength of 67MPa, modulus of elasticity - 1721MPa and Charpy strength 15 kJ/mm2. This type of materials when used in less load bearing aplications contain acrylate resigns and photoinitiator (e.g. dimethoxy-phenolacetophenone). They are characterised by fast polymerization and relatively good geometrical accuracy and stability of the printed objects.

In this study the orthodontic devises produced with this ("digital") technology are compared with the same devices produced by "conventional" process chain covering the following stages: (i) generating a model either by scanning of the tooth profiles and production of the model by layering 3D technology or taking a replica of the patient's dental profile (in our study, the second approach was used); (ii) vacuum forming of the aligners using specialized polymer pholio made by PET-G (a copolymer that constitutes two repeating units polyethylene terephthalate and glycol which prevents the crystallization of PET upon heating and makes it clear, lesss brittle and more resistant to mechanical stress [13].

II. EXPERIMENTS

PROCESS CHAINS

In the digital technology study, an impression was initially scanned from a patient with a Comphort+ intraoral scanner into an STL file, which was transferred to a CAD/CAM system in order to modify the resulting shell shape in thickness. The files are then fed to the control CAM program for "slicing" and determining the current sections to build. In the study, 10 aligners with different thicknesses (0.15; 0.25; 0,5; 0,75; 1.0; 1.15; 1.25; 1.5; 1.75; 2.0 mm) were made (Fig.1). The build was carried out with the following parameters optimized and recommended by the 3D printer manufacturer:

Z-axis speed 23 mm/h;
5 min mixing before printing;
Drying 10 min;
Post-cure 30 min;
Printing inclination 80°-90°;
3 mm minimum base;
1.5 mm supports;
Wash for 3 min. in ethanol;
Dry for 2 min with a fan.

The "conventional" process chain includes generating a model by taking a replica of the patient's dental profile; vacuum molding of the aligners. The production of the ceramic model can be carried out in two ways: (i) scanning of the tooth profiles and production of the model by layer-by-layer 3D technology; (ii) taking a replica of the patient's dental profile. In our study, the second approach was used.

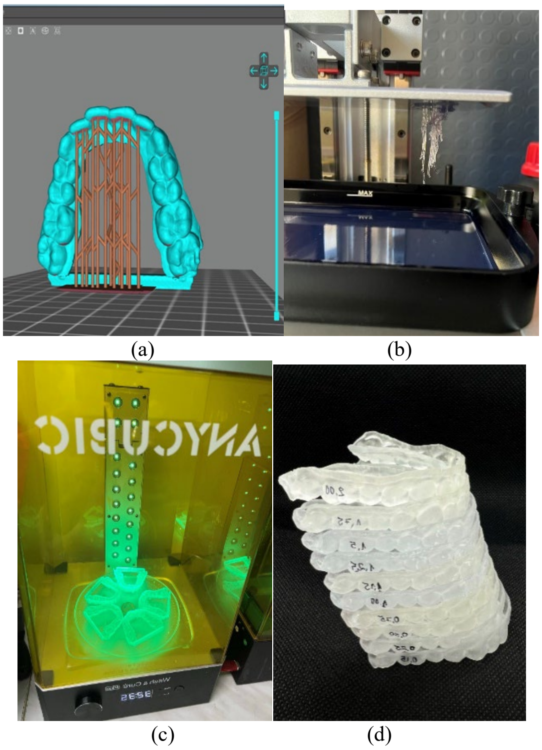

(a) (b)
(c) (d)

Fig.1 The CAD design of the aligners with the supporting structure (a), DLP-SLA 3D printer (b), post curing camera (c) and a set of produced aligners (d).

STUDY OF THE TRANSPARENCY

The transparency of orthodontic aligners in different thicknesses (in the range from 0.15mm to 2.00mm) was investigated since a set of several aligners of different thickness and progressive impact on the patient's occlusal characteristics are used during the course of treatment. Other factors such as the type of technology (3D printed or moulded), the post curing time and surface texture of the printed aligners have also been investigated.

The experiments were carried out according to the scheme of Fig.2 in which light is passed through the sample and the luminous flux per unit area (Lux) is measured after passing through them.

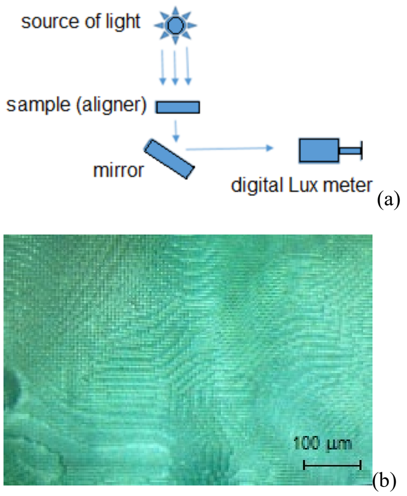


Fig. 2 Experimental set-up for transparency study (a); the texture of the printed aligner (b).

MECHANICAL BEHAVIOUR OF THE ALIGNERS

The aligners will apply a system of forces on the teeth to shift them to desired position. Since they exert forces thanks to their particular shape they are elastically deformed in the maximum range of couple of millimetres. Therefore it is important to know their behavior under tension and compression in the elastic region of behavior (e.g. 5 mm) - Fig.2. Load-displacement curves was obtained and the stiffness $K=\Delta F/\Delta l$ as a function of sample thickness d, mm was calculated. The deformation rate of 1 mm/min was applied and an INSTRON 3384 universal testing machine was used in the +/-0.05N force and +/-0.05mm displacement accuracy mode. The statistical error in determining the stiffness of the studied samples was within 12%.

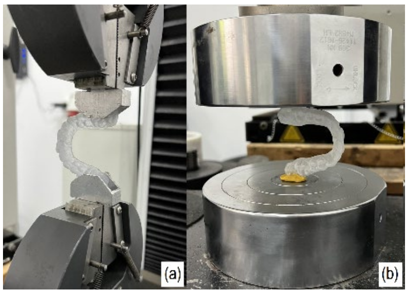


Fig. 3 Tensile (a) and compressive (b) testing of the aligners.

III. RESULTS

TRANSPARENCY

In gemnaral the dependence of the sample transparency on the thickness can be assumed to be linear and its change can be calculated by the empirical formula:

$$\%\Delta I = 2.5 + 5.5\ d,$$

whrere ΔI is the change (%) in luminous flux per unit area after the light pass troug the sample with thickness d, mm. ΔI range from 3% for small (0,15-0.5mm) ticknesses to 12% for thicknesses of 2mm. It can be concluded that within the studied range of thicknesses, the optical qualities of the 3D printed devices with d<0,5 mm do not change significantly and for greater thicknesses (Fig.4), this change although noticeable does not unacceptably disturb the aesthetic qualities of the product.

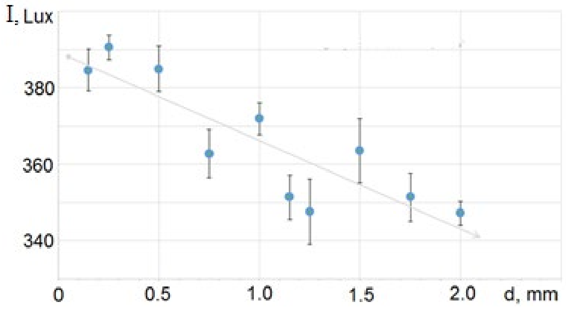


Fig.4 Transparency of aligners measured by illuminance (I, Lux) of the light passing through them as a function of their thickness (d).

The transparency of aligners made by conventional technology (Vacuum Formed) was slightly better than 3D printed (DLP SLA) - Fig.5. This difference is about 2-3% for smaller thicknesses (d < 1.0 mm) and reaches 5% for thicker samples. Still the aesthetical appearance is axeptable.

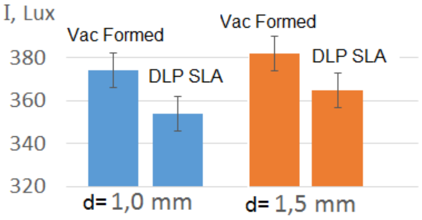


Fig.5 Comparison of the DLP SLA and Vacuum formed aligners.

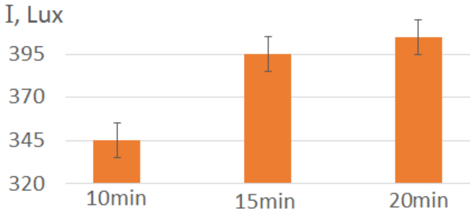
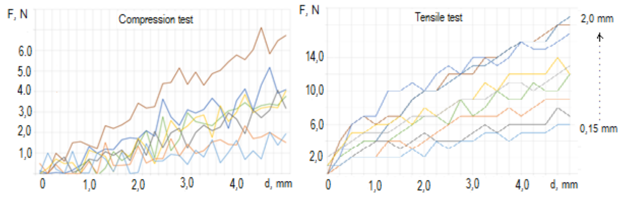


Fig.6 The influence of the resign mixing time on the transparency of the DLP SLA aligners.

Many technological factors affect the sample transparency. In the case of Vacuum formed aligners, they are well studied and come down to the influence of molding temperature and cooling rate on the degree of crystallinity of the structure. With the DLP SLA technology we have additional conditions affecting this property. For example, the roughness of the aligners resulting from the step effect during the construction of the layers leads to scattering of light and an increase in opacity (Fig.2,b). Even more important factor is the mixing and homogenization of the resin before the photo polymerization process. Fig.6 shows the effect of stirring time on the transparency of the DLP SLA aligners. A sample with a thickness of 1.0 mm was tested. It can be seen that if insufficient mixing time is applied (less than 15 min) the transparency drops by about 20%.

MECHANICAL PROPERTIES

Analyses of the strain curves shown in Fig.7 reveal up to a 70% increase in the forces required to realize a 5 mm reference elastic strain of the aligner when the shell thickness is changed from 0.15 to 2.0 mm. For compressive loads the force differences are in the range of 2-7N, and for tensile loads in the range of 6-19N.



(a) (b)

Fig.7 Compression (a) and tension (b) diagrams for aligners with thickness 0.15-2.0 mm.

The slope of the curves reveals the aligners stiffness (K=ΔF/Δl) changes within the range of 0.05-0.2 in compression and 0.3-0.8 in tension. I.e. the orthodontic structure shows about 4 times greater stiffness in tension than in compression. It should be noted that occlusal deformations (jaw closure and masticatory movements) occurring in aligners are expected to be mainly tensile making thickness variation an effective factor in determining the geometry of the orthodontic appliance set. The curves showing the $K_{comp} = \Delta F/\Delta h$ (Fig.8,a) and $K_{tens}=\Delta F/\Delta l$ (Fig.8,b) as a function of the aligner's thickness (d) change are not monotonous but rather show a three distinguished regions: I, II and III for “thin”, “medium” and "thick" shells due to the stress state change from more pronounced plane-stressed to bulk-stressed state. Table 1 summarizes the values of the stiffness coefficient for this three regions which could be utilized for the design of the aligner’s geometry.

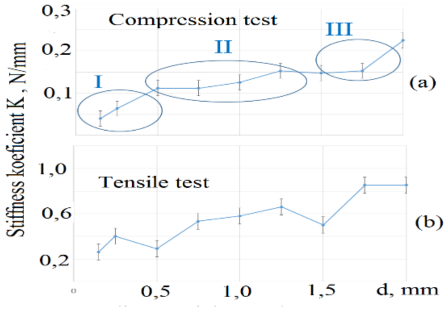


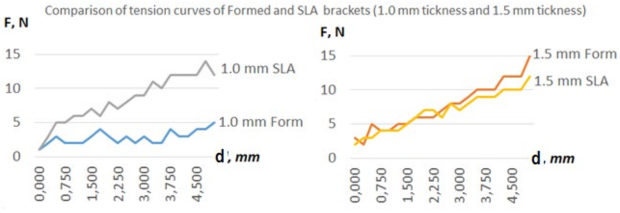
Fig.8 Stiffness in (a) - compression (b) tension as function of their thickness.

The stresses arising in the most loaded section (in the middle of the aligner, attached to the “dentes incisive”) can be roughly calculated assuming the simplification of pure compression/tension load at 5 mm strain and they amount to about 0.2 MPa and 0.5 MPa respectively (for aligners with d = 1.0 mm).

The comparison of the deformation diagrams of aligners manufactured by the Vacuum forming and DLP SLA technologies shows that at smaller thicknesses (d<1.0mm) the aligners manufactured by the “digital” technology have about twice the stiffness of those produced by “traditional” technology (Fig. 9,a). For thicker devices, the stiffness is practically the same (Fig.9, b).

Table 1 Stiffness coefficient (K) for aligners with different thickness (d)

d, mm	0,15-0,5	0,75-1,5	1,75-2,0
tension	0,3	0,6	0,8
comporession	0,05	0,1	0,2



(a) (b)

Fig.9 Deformation diagrams of aligners produced by moulding (traditional technology) and digital technology (SLA). Two thicknesses are compared: 1.0 (a) and 1.5 mm (b).

IV. CONCLUSIONS

1). The orthodontic devices produced by DLP SLA are not inferior to conventional ones in terms of both mechanical and optical (aesthetic) properties. This property change with the thickness of the device producing different forces on the teath. The effectiveness of the thickness change in the “digital” devices is higher than that of the conventional onse. More particularly they show an increase of up to 70% in the forces required to deform the aligner depending on its thickness. The presented diagrams for mechanical behavior of the aligners could be used for design purpuses.

2). The stiffness of the devices measured by the coefficient (K=ΔF/Δl) changes about 4 times when the thickness increases from 0.15 to 2 mm. This makes it possible to plan to use a set of aligners of different thickness to achieve progressive corrective results during the course of treatment.

3) The transparency of the aligners does not differ significantly of that of the Vacuum formed devices. Although this property of the DLP SLA devices could be improved by optimizing the technological parameters such as layer thickness and stirring time.

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