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Development of a DLP 3D printer for orthodontic applications

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Abstract

Recent advances in Additive Manufacturing (AM) technologies have allowed a widespread diffusion of their use in different fields. 3D printing is becoming commonplace for biomedical applications requiring the custom fabrication of prostheses and appliances fitting patient-specific anatomies. In this work, the feasibility of a vat photopolymerization technology, based on Digital Light Processing (DLP), has been investigated for the manufacturing of polymeric orthodontic appliances. A custom DLP 3D printer has been developed by exploiting an off-the-shelf digital projector, with the aim at studying the influence of printing parameters on the surface roughness. The feasibility of using Dental LT Clear resin, a biocompatible photopolymer specifically designed for SLA technology, has been finally verified.

Keywords: custom DLP 3D printer; additive manufacturing; orthodontic appliances.

1. Introduction

Additive Manufacturing (AM) is emerging as a novel and powerful set of technologies, which are based on a process of joining materials, usually layer upon layer, through different techniques (e.g. material extrusion, material jetting, powder bed fusion, vat photopolymerization, etc.) [1].

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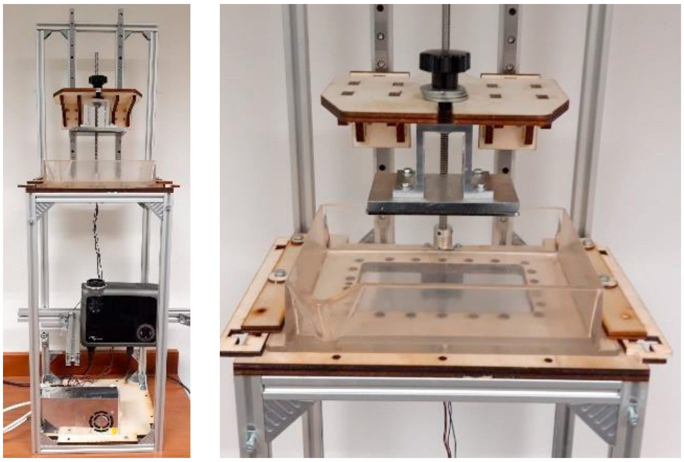
One of the main advantages of AM relies on its capability to deal with the complexity of real 3D structures. Parts are directly manufactured from a digital three-dimensional model by adding material, opposed to subtractive manufacturing methodologies, such as CNC milling [1]. Nowadays, AM is increasingly used for medical and orthodontic applications [2-4]. While impractical for a large-scale production of simple parts, AM can be particularly suitable for all those applications where a high level of individual customization is required. In the orthodontic field, for example, removable oral appliances are often proposed as an alternative to metal brackets for the correction of malocclusion problems. In this context, AM can be considered an appropriate approach to rapidly and economically fabricate appliances designed by considering the patient-specific dental anatomy, thus reducing patient discomfort and enhancing treatment effectiveness [4, 5]. Despite the undeniable advancement of AM technologies in the last decade, there are still many challenges that should be faced, which mainly regard materials (in terms of availability, biocompatibility, mechanical properties, aging and colorless transparency), resolution, tolerances and surface roughness. Among AM technologies, vat photopolymerization is one of the most promising and in part already used in orthodontics. It is a process in which a liquid photopolymer in a vat (i.e, a resin tank) is selectively cured by light-activated polymerization. This technology is characterized by a high level of dimensional accuracy and a good finishing quality [6]. Stereolithography (SLA) and Digital Light Processing (DLP) can be grouped into vat photopolymerization-based AM approaches. In SLA-based approaches, light exposure is carried out by scanning a concentrated ultraviolet laser beam on the surface of the photopolymer. The time required to produce a single layer (slice) of the whole 3D model depends on the scanning speed of the laser beam and on the slicing area that must be polymerized. DLP-based approaches also rely on the photopolymerization process, with the significant difference that each single layer is polymerized all-at-once by projecting a single digital image (mask) [7]. This results in shorter printing time with respect to SLA-based approaches, which are characterized by point-by-point polymerization.

In this work, the development of a custom DLP 3D printer, assembled with a commercial DLP projector, is presented. Characteristics and potentialities provided by vat photopolymerization and DLP technology have been experienced in the direct manufacturing of patient-specific appliances for orthodontic treatments. In particular, the feasibility of using a resin specifically designed for SLA technology has been verified. In the following, section 2 introduces the hardware set-up and the calibration procedure, section 3 describes the characterization of the developed 3D printer in terms of surface roughness. Results are also compared to the performance of a commercial SLA printer (formlabs Form 2 3D Printer). In section 4 a case study of an orthodontic application is discussed. Conclusions, critical observations and possible future perspectives are finally drawn in section 5.

2. Custom DLP 3D printer

A custom DLP 3D printer has been developed by using an off-the-shelf DLP projector (OPTOMA EX330e), equipped with a 1024 × 768 micromirror array, a 3D printing mechanism and a set of custom-made mounts (Fig. 1). The 3D printer has been developed by vertically placing the projector with respect to the resin tank, thus avoiding the use of mirrors, which are commonly adopted to reflect patterns from the projector [7]. This choice allows to decrease the overall width of the 3D printer providing, at the same time, a high flexibility in the definition of the printing area. The proposed technical solution, indeed, gives the possibility to scale the active illuminated area by moving the projector with respect to the resin tank without handling the mutual position between projector, mirror and vat. The scaling of the printing area allows to match specific needs since projected pixel sizes can be reduced when small models (e.g., clear aligners) must be fabricated, thus increasing resulting quality. Moreover, the adopted solution makes the structure frame simpler from a mechanical point of view and allows a reduction of the number of components.

Although commercial DLP projectors are not specifically designed to be used as light sources in DLP stereolithography, since characterized by limitations in the uniformity of their light spectrum [8], their use can significantly reduce the prototype cost, simplifying at the same time the system design. The 3D printing mechanism is composed of an aluminum platform, a trapezoidal leadscrew, a flanged leadscrew nut, a stepper motor and two vertical linear guides. The machine is controlled by an Arduino Mega board, with a Ramps 1.4 Shield, a single Pololu Stepper Motor Driver (Stepstick A4988), which supplies power to the NEMA 17 stepper motor, and a single mechanical end-stop at the bottom of the Z axis. The electronical package is supplied by a 12V/20A power supply wired with Ramps, and with Arduino Mega connected to the PC through USB cable. The printing process follows the bottom-up architecture. The image masks are projected on the bottom of the build platform through the resin tank. The build platform moves upward pulling the object out of the resin and allowing the uncured resin to fill the space under the platform created by the polymerized resin. The slice thickness (i.e, layer height) is controlled by the distance between the tank floor and the build platform. The main advantage of bottom-up approach is that it requires only a restricted amount of resin in the tank. On the other hand, the polymerized layer is directly placed on the bottom of the resin tank, which must then be unresponsive to the curing wavelength. The resin tank used is "T-1000 VAT" supplied by G3D. The tank is made of a polydimethylsiloxane (PDMS) floor and a fluorinated ethylene propylene (FEP) protective layer on top to get a good anti-sticking effect and durability.



(a) (b)

Fig. 1. (a) Layout of the assembled DLP 3D printer, (b) detail of the build platform and polymerization vat.

The printer resolution is strictly related to the hardware setup. The vertical translation of the printing platform is obtained by a flanged nut assembled with a trapezoidal leadscrew, having 2 mm pitch and l = 8 mm lead (four starts), and two vertical linear guide rails. A NEMA 17 stepper motor, having a step angle θ = 1.8°, has been used to drive the leadscrew. The theoretical vertical resolution, r_z, can then be obtained as $r_z = l\theta / 360°$. A minimum translation value of 0.02 mm is obtained if the half-step mode is used. The horizontal resolution, r_{xy}, is strictly related to the projector resolution and the size of the projected area. A rectangular projected area of about 110 × 80 mm has been defined for a horizontal resolution r_{xy} = 120 mm/1024 pixels ≈ 0.11 mm/pixel. The zoom wheel of the projector lens can be used to further adjust the size of the projected area, thus modifying r_{xy}.

Before the beginning of the printing process, the build platform is lowered on the bottom of the resin tank in order to make their surfaces parallel, thus guaranteeing a first layer with a uniform thickness. In this phase, the projector settings as focus, keystone distortion, brightness and contrast are tuned with the aim at producing a sharp image on the build platform. The dimensional accuracy is achieved by overlapping a projected calibration grid with a known template.

3. Surface roughness measurements

3.1. Materials and methods

Dental LT Clear Resin has been used to verify the feasibility of the assembled 3D printer in the manufacturing of dental appliances. This material is a biocompatible and transparent photopolymer, formulated by formlabs for the SLA technology, and specifically designed for the manufacturing of dental splints and retainers by the Form 2 machine. The aim of the present work is to assess if this resin can be also used for the DLP technology and compare the results of these two technologies characterizing the surface roughness of the printed parts. This feature is of utmost importance for orthodontic appliances and was selected to test the effectiveness of the 3D printer. In particular, a low level of roughness reduces the invasiveness associated to the appliance's fitting on the dental anatomy.

Roughness measurements were carried out on prismatic specimens with a size of 20 × 15 × 12 mm^3 (XYZ) printed by using two different building orientations in accordance to ISO/ASTM 52921:2016 [1]: parallel to the X, Y, and Z axes (Fig. 2-a) and re-oriented by rotating the part by 45° around the geometric center along the Z axis (Fig. 2-b)). The specimens were printed one at a time in order to maintain the same location and light distribution, which are aspects that might slightly affect the surface roughness. For each sample, measurements along and perpendicular to the build direction were carried out. Measurements perpendicular to the build direction were aimed at investigating the *absolute* roughness of the DLP 3D printer, that is the roughness which is only due to the way the material is processed (i.e., each single layer is polymerized all-at-once by projecting a single digital image). On the other hand, measurements along the build direction were addressed to investigate the roughness due to the layer growing. Finally, a specimen with the same size was printed using the above-mentioned Form 2 (SLA technology) for comparison purposes. Roughness measurements were performed through the Hommel Etamic T8000 measurement system (Fig. 3), considering a travel length of 1.5 mm and a measurement speed of 0.15 mm/s.

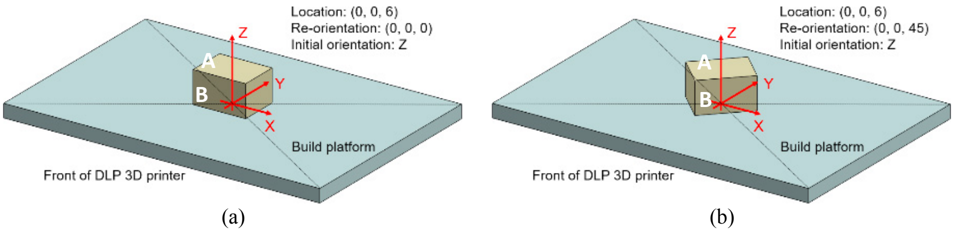


Fig. 2. Build directions for the printed specimens: (a) prismatic specimen parallel to the X, Y, and Z axes, (b) prismatic specimen re-oriented by 45° along Z axis.

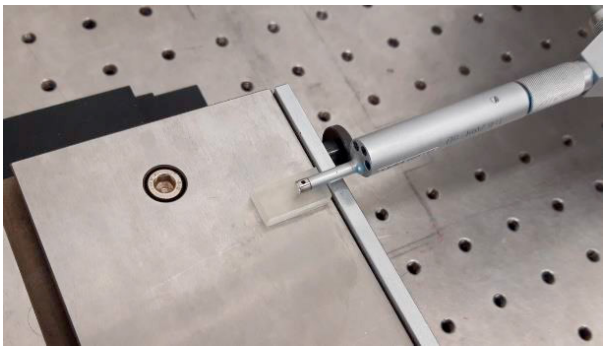


Fig. 3. Roughness measurements by Hommel Etamic T8000 system.

Creation Workshop V1.0.0.75, a free software for slicing and control of the 3D printing process, was used. DLP curing settings for the Dental LT Clear Resin were unknown since the resin was designed for the SLA technology. For this reason, an empiric procedure was adopted to investigate and select the process parameters required to configure a proper slicing profile in accordance to the specific resin. In particular, different exposure times were experimented (9 s, 12 s, 15 s, 18 s, 21 s, etc.) to print a cube-shaped specimen. The curing process demonstrated to not guarantee a complete polymerization of the resin, as well as the adhesion of the part to the build platform, for exposure time values below 15 s. An exposure time value of 18 s showed good results in terms of printing accuracy and was used to fabricate samples for roughness measurements. Fig. 4 reports all the settings of the slicing profile adopted. However, it is worth noting that this slicing profile is only applicable for the specific DLP printer developed in this work. The use of a different DLP projector, for example, or a variation in the distance between the projector lens and the resin vat, which has been fixed at 250 mm for the experimental tests discussed in this paper, would affect the curing settings since light distribution, irradiance and energy density would change [2, 3].

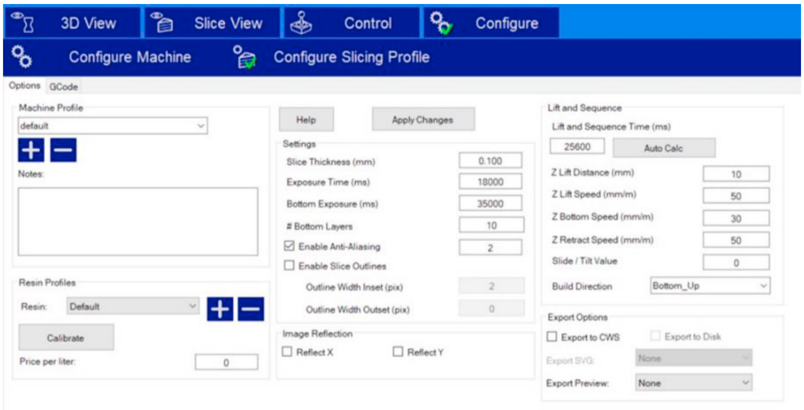


Fig. 4. Slicing profile adopted to print Dental LT Clear resin.

3.2. Results

The surface roughness measurements were carried out on the top surface (surface A, area of 20 × 15 mm^2) and on the side of the sample (surface B, area of 20 × 12 mm^2), as represented in Fig. 2-a and 2-b. The results of the measurements are shown in Table 1. In the following, A_x, A_y and B_x, B_z indicate measurements along x, y and z directions on the top and side surfaces, respectively.

Table 1: Roughness measurements performed on DLP and SLA samples with re-orientation (0, 0, 0) and (0, 0, 45).

	Re-orientation (0, 0, 0)	Re-orientation (0, 0, 45)	Re-orientation (0, 0, 0)	Re-orientation (0, 0, 45)
	DLP Ra	**DLP Ra**	**SLA Ra**	**SLA Ra**
A_x	0.67 µm	0.67 µm	0.72 µm	1.0 µm
A_y	0.47 µm	0.68 µm	1.27 µm	1.46 µm
B_x	1.79 µm	2.46 µm	1.90 µm	2.73 µm
B_z	0.95 µm	0.88 µm	0.55 µm	0.90 µm

The results obtained for the top surface (A_x and A_y) of the DLP samples evidence lower roughness values with respect to the SLA samples. This outcome could be due to the different nature of the two technologies. DLP technology polymerizes each single layer all-at-once by projecting a single mask, while SLA technology polymerizes each layer by scanning a concentrated ultraviolet laser beam on its surface. Scanning path, scanning speed and laser spot are aspects which affect the value of roughness. However, Form 2 is supported by PreForm slicing software, which does not allow to customize and control these settings. The influence of the scanning-based approach of SLA is confirmed by comparing the results of the samples with different re-orientations. In the case of DLP samples, the re-orientation (0, 0, 45) does not produce significant changes. On the other hand, in the case of SLA samples, different values of roughness were found by comparing re-orientation (0, 0, 0) and re-orientation (0, 0, 45). The main difference between these two approaches is related to the scanning path used by the laser to build up each single layer. For the side-surface of the samples (B_x and B_z), the roughness values are quite similar, generally higher than those measured for A_x and A_y. Re-orientation (0, 0, 45) also affects the roughness of the side-surface of DLP samples. The higher roughness values associated to this re-orientation status can be explained by the pixilation effect described by Monzon et al. [4]. A schematic description of the pixilation effect is provided in Fig. 5. In conclusion, it is worth noting that the roughness of the samples manufactured with the developed DLP printer is very close and, in some cases, better than that obtained for the samples printed with Form 2. This result might be further improved by upgrading some components of the 3D printer, produced in wood for the prototype shown in Fig. 1, using stiffer materials (e. g., an aluminum). This would guarantee a higher control on z axis during lifting and retraction movements. This aspect could be beneficial for geometrical accuracy and surface roughness.

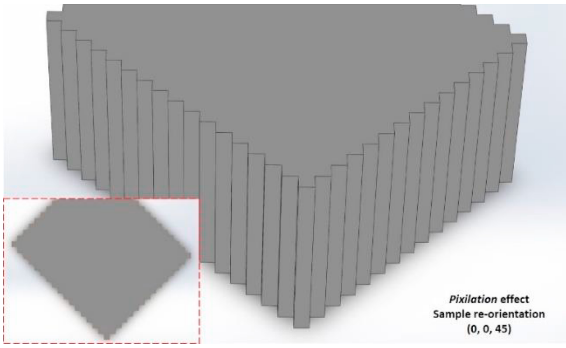


Fig. 5. Schematic representation of pixilation effect of the DLP samples with re-orientation (0, 0, 45).

4. Fabrication of an orthodontic appliance by DLP printing

The developed DLP 3D printer has been finally experienced in the fabrication of a challenging orthodontic appliance, such as a clear aligner. In the orthodontic field, transparent plastic aligners are often proposed as an alternative to metal brackets for the correction of malocclusion problems and are particularly appreciated by many patients for their low impact on facial aesthetics. This treatment is based on the use of a set of thin transparent plastic templates (aligners), which are sequentially placed (every 2 weeks) on the patient's dentition. Each individual template is designed by CAD tools and produced to fit the optimal intermediate position of the teeth over the course of the therapy. The aligner is conventionally manufactured by a vacuum thermoforming process of a thermoplastic polymer disk (thickness between 0.75 and 1 mm) carried out on a 3D model (mold) reproducing the patient's dental anatomy. Typically, these models are fabricated by using additive manufacturing [5]. This manufacturing process is quite reliable in terms of geometrical accuracy, transparency and availability of a wide range of biocompatible polymers. Nevertheless, one significant issue is related to the thickness variation due to the thermoforming process. Thickness values vary accordingly to the mold geometry and this variation is heterogenous and difficult to predict and/or control (for some areas the thickness increases and for some other areas it decreases) [6, 7]. Consequently, the force delivery properties of thermoplastic aligners and, thus, the orthodontic treatment effectiveness, can be affected [8, 9]. For this reason, a reliable and well-characterized 3D printing process would be of outmost importance in the orthodontic field. The direct fabrication by additive manufacturing of these appliances would allow a re-design of the geometry, based on the possibility to pointwise handle the appliance's thickness. Such an approach would enable the tuning of the magnitude of the force locally produced by the appliance, optimizing the treatment and reducing the patient discomfort [10, 11]. These considerations highlight the potentialities connected to the direct and additive manufacturing of the appliances. The focus of the present section is to evidence the possibility to print orthodontic appliances by using the developed DLP 3D printer, experimenting the biocompatible Dental LT Clear resin. Moreover, details about the configuration of the slicing profile and the procedure used for part orientation and support generation are provided.

Two appliances, having two different thickness values (0.5 mm and 1 mm), were printed by adopting the layout shown in Fig. 6. They were rotated by 20° with respect to their vertical orientation to facilitate the resin leakage from the solidifying geometry. The slicing profile was set as described in section 3.1 (Fig. 4). The vertical orientation of the part was aimed at minimizing the number of required supports, thus simplifying the post-processing procedures, which can affect the transparency of the appliance. Fig. 7-a shows the polymerization of a single layer by projector lighting. The printed block (shown in Fig. 7-b and composed of base plate, supports and appliances) was removed and washed with Form Wash machine equipped with a magnetically coupled impeller for 15 minutes in isopropyl alcohol (IPA). After the washing process, the supports were mechanically removed, and the appliances washed for additional 5 minutes to clean the part from any residuals generated by supports' removal.

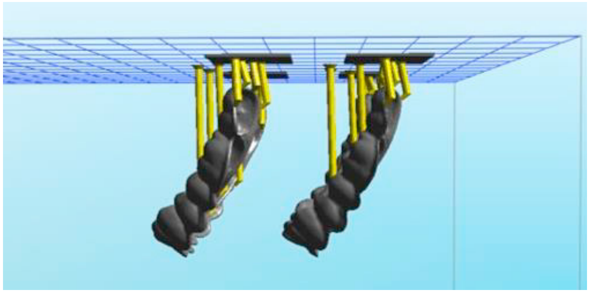


Fig. 6. Printing layout used to manufacture dental aligners.

The results are shown in Figs. 8-a and 8-b. Both the appliances present a reasonable level of definition in terms of geometry, thickness accuracy and degree of transparency. However, it is worth noting that the thicker appliance presents a significant discrepancy, with respect to the digital model, in correspondence of the internal part of the incisors (dotted red line in Fig. 8-b). In this region, the resin has been partially trapped and solidified, thus creating a swelling region, which would preclude the appliance fitting on the dental anatomy. This inaccuracy is less pronounced with the 0.5 mm thick appliance. Fig. 9-a shows a detail of the aligner printed with Dental LT Clear resin, where it is possible to see the slicing of the geometry and its accuracy, Fig. 9-b instead provides a detail of the printing defect presented in Fig. 8-b. This printing issue can be ascribed to the high viscosity value of Dental LT Clear resin, which does not allow a prompt resin leakage once the build platform is lifted after the curing of each single slice. In order to validate the influence of this aspect, the same appliance geometries, with the same printing layout, have been also fabricated by using the UV DLP Firm resin, supplied by Photocentric as a photopolymer specifically designed resin for DLP technology. This resin is characterized by a significantly lower viscosity at room temperature. The appliances printed with this resin show a higher level of accuracy and finer details (Fig. 8 -c, -d), evidencing how the viscosity influences the printing process. This finding suggests that the implementation of a heating system on the resin vat, to decrease the viscosity value, would improve also the results achievable by using Dental LT Clear resin. In addition, the slicing profile could be further optimized by increasing the "*z-lift distance*" parameter and decreasing the "*z-lift speed*" parameter. A longer time interval would then been introduced between the curing of two subsequent slices, increasing the accuracy of the printed part to the detriment of the printing time.

(a) (b)

Fig. 7. (a) Phase of the 3D printing process of the orthodontic appliance showing the polymerization of a single layer by direct light projection, (b) fabricated appliances attached to the build platform.

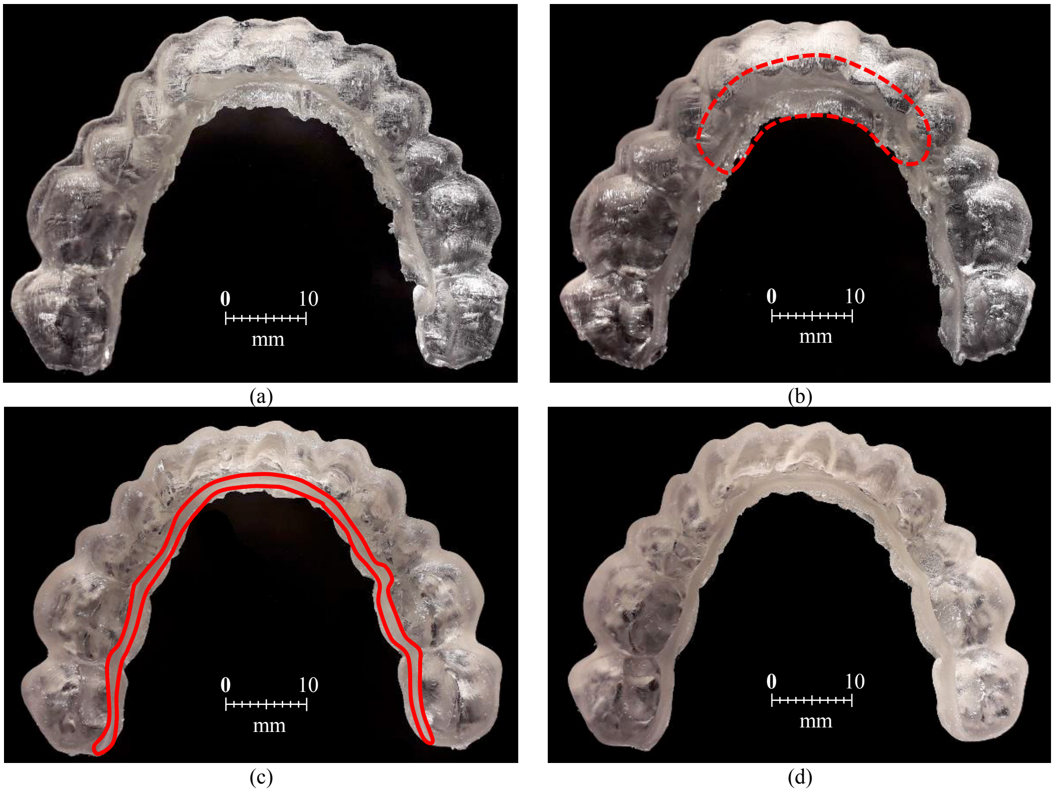


Fig. 8. (a) Dental LT Clear resin 0.5 mm thickness, (b) Dental LT Clear resin 1 mm thickness, (c) UV DLP Firm resin 0.5 mm thickness, (d) UV DLP Firm resin 1 mm thickness. In (b) the dotted line highlights the defect of the aligner thick 1 mm, where the resin has been partially trapped and solidified, compromising in part the accuracy of the geometry. In (c) the red line shows the high accuracy of the aligner's thickness.

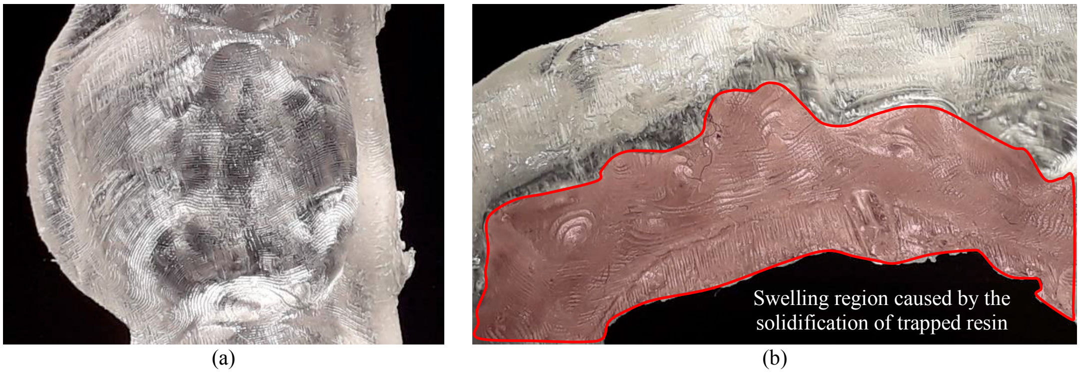


Fig. 9. (a) Detail of the slicing effect of the 0.5 mm thick aligner printed with Dental LT Clear resin, (b) detail of the defect of the 1 mm thick aligner shown in Fig 8-b printed with Dental LT Clear resin.

5. Discussion and conclusions

Considering the growing interest on additive manufacturing for orthodontic applications, this work proposes the development of a custom DLP 3D printer, designed for the direct manufacturing of orthodontic appliances. The presented solution is based on a DLP 3D printer assembled with an off-the-shelf digital projector, which is characterized by a higher flexibility with respect to existing commercial solutions. Distance between projector and resin tank, indeed, can be easily changed in order to scale the printing area, increasing or reducing the printing resolution in accordance to the specific requirements. Moreover, the use of a wide range of materials can be experimented as demonstrated by using Dental LT Clear resin, a photopolymer designed for ultraviolet laser beam polymerization. Results obtained in the fabrication of an orthodontic appliance evidence the potentialities of this technology in terms of feasibility and reliability. However, further studies and enhancements are essential before considering this approach a real alternative to molding or thermoforming processes in the manufacturing of orthodontic appliances. In this work, settings for the resin curing process were empirically found, but the characterization of the projector light spectrum and the use of photosensitive resins with detailed curing specifications would be of utmost importance to provide an appropriate material curing. These improvements would be beneficial to get a higher control on material processing in order to have a lower surface roughness, good optical properties and dimensional accuracy, which are necessary requirements for the manufacturing of orthodontic appliances.

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