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Ultimate flexural strength and Young's modulus analysis of denture base resins for masked stereolithography 3D printing technology

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ABSTRACT

Purpose: of the study is to investigate the ultimate flexural strength and Young's modulus of some materials, which can be used for complete denture fabrication by Masked stereolithography 3D printing technology.

Design/methodology/approach: Three groups of five specimens each were fabricated. Two of the groups are 3D printed by Masked SLA 3D printer of two commonly used denture base resins. The third group is set to be a control as the specimens were fabricated of a heat-curing acrylic resin. A three-point flexural test tested the objects, and the data collected was used to determine ultimate flexural strength and Young's modulus calculation. All the results are compared to the ISO Standard 20795-1.

Findings: The data shows that the mean ultimate flexural strength of the 3D printed specimens is 87 MPa - 89 MPa. Their results are very similar to those for the heat-curing acrylic resin, which means the ultimate flexural strength is 93 MPa. The mean Young's modulus obtained for the first group of 3D printed specimens is 2263.21 MPa and 2377.44 MPa for the second one. As for the control group, 2396.06 MPa is achieved. When ISO Standard 20795-1 is inspected, all the data obtained covers the minimum requirements.

Research limitations/implications: The limitations of the study concern to some additional factors that should be observed for more detailed evaluation. For example, the level of the final polymerization of light-curing resins for 3D printing, their ability to washstand to different defect and denture-bearing area characteristics (the notch for the labial and buccal frenulum, chambers for torus release, etc.), the ability of the materials to withstand to cyclic load, etc.

Practical implications: 3D printing is faster and cheaper than conventional methods for complete denture fabrication. The knowledge about the mechanical properties of the different materials for 3D printing is very valuable for properly selecting a material and approach for complete denture fabrication.

Originality/value: Nowadays, 3D printing is essential in dentistry. For this reason, observation and knowledge of the raw materials properties is very important for the proper choice of a material and/or technology for each clinical case.

Keywords: 3D printing, Masked SLA, Complete denture, Denture base resin, Prosthetic dentistry

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BIOMEDICAL AND DENTAL MATERIALS AND ENGINEERING

1. Introduction

Additive manufacturing is a process that has been known since the 1980s. Because of the current stage of technological development in the 1980s, the process lacked progress during the next decades. Just after 2000, because of the rapid development of information technologies, additive manufacturing became more popular in the industry [1-3]. At this stage, the subtractive manufacturing methods (as a part of CAD/CAM technology) were still much more popular than the additive ones. Just at the end of the first decade of the current century and the green technologies development, the issue of the wasted material in the manufacturing process started to be discussed. As a result of this new direction of industrial progress, additive manufacturing has become increasingly popular. It is a process that generates less waste than computer-aided milling and allows for the fabrication of complex structures. The characteristics of additive manufacturing are huge advantages to the conventional approach, and even subtractive computer aided manufacturing [4-9].

The industry, healthcare and dentistry have made great progress with CAD/CAM technologies integration and development, especially during the COVID pandemic [10]. Nowadays, additive manufacturing is well-known in dentistry as it is a part of the manufacturing process in almost every dental technician's laboratory and dental practice [11-18]. At the same time, CNC milling machines are still the gold standard for fast, accurate, and predictable results. The major disadvantages of the additive process are as follows: it is very susceptible to environmental conditions and specific to each process internal factors. 3D printer manufacturers, in most cases, successfully overcome the effect of the surrounding factors by controlling the internal environment in the working space. At the same time, the process can be affected by technical imperfections or just a result of wearing out the hardware. The obstacles can limit the achievement of a repeatable result, which can be a reason for variations in the characteristics of the final products made at different times [19-22]. At the same time, the investigation of the mechanical or physical properties of 3D printed products is always actual due to lack of enough data, frequent modification or just replacement of the raw materials. There is also a lack of scientific data about the characteristics of the final products (dentures – as far as dentistry is concerned) after their fabrication and use after a period.

Vat polymerisation additive technologies have become well-known in dentistry due to their widespread use. They have many applications in dental practice as they allow the fabrication of temporary or permanent crowns, surgical guides, splints, models, patterns for the casting process, and even removable dentures. Denture fabrication is a complicated and time-consuming process, which should be done precisely [23]. At the same time, the requirements for dental material are many and very specific. They should allow a final product fabrication with good enough mechanical properties; it should also be aesthetic, biocompatible, maintain its mechanical and physical properties after years of use, and it should not be allergenic or cause any irritation [24-26]. As a result of the increasing popularity of vat polymerization 3D printing technologies, the amount of newly offered or modified materials started to increase very fast. At the same time, each additive process in this group is very specific.

For this reason, the mechanical properties of the final product are a function of the raw material and additive process characteristics, surrounding conditions and specific internal factors for each manufacturing process [27-29]. This could be a reason for the fabrication of dentures with various properties, which could be a serious problem in the treatment of edentulous patients with 3D-printed complete dentures [30-36]. This and the increasing popularity of masked stereolithography determine the main purpose of the current study, which is to investigate the ultimate flexural strength and Young's modulus of some materials, which can be used for complete denture fabrication by masked stereolithography 3D printing technology.

2. Materials and methods

For the study, all specimens and testing methods are selected to correspond to the ISO standard 20795-1. Three groups of five specimens each are fabricated. All of them have the shape of a plate with the following dimensions: length – 70 mm, width – 10 mm and height of 3.3 mm (Fig. 1).

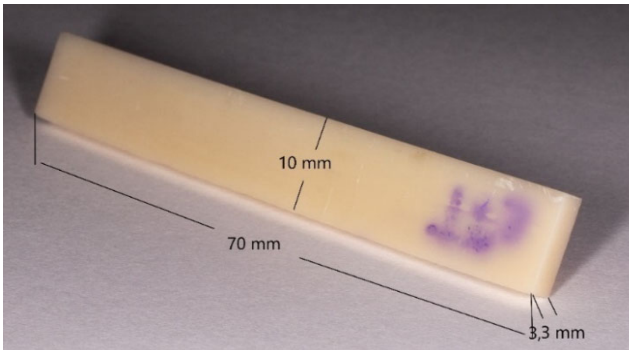

Fig. 1. A specimen with desired dimensions made of NextDent C&B MFH polymer

The first group of objects were 3D printed (by Masked SLA 3D printer) of NextDent Denture 3D+ polymer, and the second one was manufactured by the same printer as NextDent C&B MFH polymer. The third group was meant to be a control group and was made of heat-curing acrylic resin (Villacryl H Plus, Zhermack) by the conventional lost wax technique (Fig. 2).

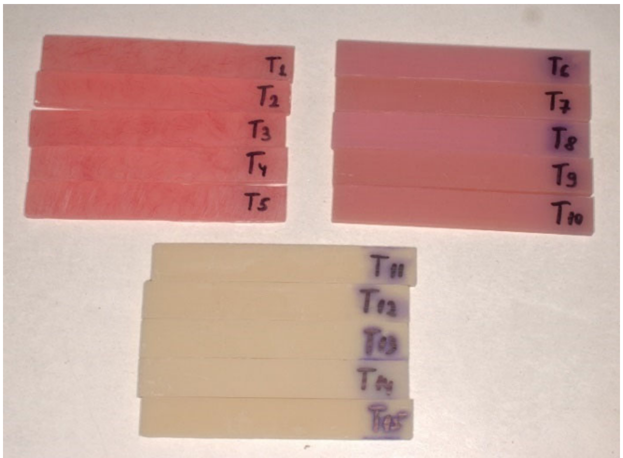

Fig. 2. Three groups of specimens: T1-T5 made of heat-curing acrylic resin, T6-T10 made of NextDent Denture 3D+ polymer and T11-T15 made of NextDent C&B MFH polymer

NextDent Denture 3D+ is a polymer based on methyl methacrylate, which is indicated for denture base fabrication. NextDent C&B MFH is a polymer based on similar substances indicated for temporary crowns and bridges. It can be used for denture teeth. Both materials are indicated for DLP and MSLA.

The 3D-printed objects were rinsed with 99% isopropyl alcohol for 5 min. Afterward, they were light-cured in a special unit for 30 minutes at 60°C. The post-curing unit can generate light with wavelengths from 315-550 nm with 108W UVA and 108W UVB output power. After the final polymerization, the supporting structures of the 3D printed objects were removed, and a dimension check was made by a digital calliper with accuracy up to 0,01mm.

To prepare the control group, a set of five specimens with 20% bigger sizes than the previous two groups was created by generic CAD software. Afterwards they were 3D printed by a Masked SLA machine, and immediately after the post-processing procedure, they were flasked and replaced with heat-curing acrylic resin. The acrylic specimens were trimmed and polished with sandpaper until they reached the appropriate dimensions. During this process, a water cooling system was used to prevent extreme temperatures from rising. Finally, a digital calliper check was made to verify the desired dimensions of the fabricated specimens.

Immediately after their fabrication, all the specimens (from the three groups) were stored in a water container at room temperature. Before the testing, all the specimens were measured at three points, one on each end and one in the middle. They were fabricated and prepared so that the three measured dimensions for each object deviate no more than ± 0.02 mm.

A special gauge for the load testing machine was fabricated for the study. It was made of two parallel cylindrical supports with a diameter of 3.2 mm long enough to ensure at least 10.5 mm space for the specimen. The space between the supports was set to 50 mm and was verified by a calliper.

Once the testing machine was prepared and the gauge was installed and set to a proper position, the specimens were pulled out of the container and dried with a napkin. Then, they were aligned over the flexural test rig so that the loading cylinder was at the centre of the test object. The testing machine was programmed to provide a constant displacement rate of 5 mm/min, and the ultimate flexural testing procedure was initiated (Fig. 3). The force of the loading plunger was increased from zero until the specimen broke. All testing data was saved and used for further calculation and analysis.

Fig. 3 A specimen made of NextDent Denture 3D+ polymer, situated between the branches of the testing machine

The maximum load at break was used for the ultimate flexural strength calculation by formula 1.

$$\sigma = \frac{3Fl}{2wh^2}, \text{MPa} \quad (1)$$

where:

F – is the maximum load applied to the specimen before it breaks down in N.

l – is the distance between the supports, in mm.

w – is the width of the specimen measured immediately before testing in mm.

h – is the height of the specimen measured just before the testing in mm.

The Young's modulus was calculated by formula 2.

$$E = \frac{F_1 l^3}{4wh^3 d}, \text{MPa} \quad (2)$$

where:

F_1 – is the load at a point in the straight-line portion of the load /deformation curve in N.

l – is the distance between the supports, in mm.

w – is the width of the specimen measured immediately before testing in mm.

h – is the height of the specimen measured just before the testing in mm.

d – is the deformation corresponding to the load F_1, in mm.

3. Results

The load/deformation curve of the specimens made of heat-curing acrylic resin shows that the load and deformation increase proportionally to 38.99 N (Fig. 4). The deformation increases with higher rates until a load of 150 N is reached. Then, the object became destroyed.

The load/deformation curve of specimens made of NextDent C&B MFH shows that load and deformation increase proportionally to 38.13 N. When specific load levels and deformation are reached, the load starts to decrease as the deformation increases.

The load/deformation curve of specimens made of NextDent Denture 3D+ shows that the load and deformation increase proportionally until 36.05 N. After that, the deformation rises at a higher rate than the load until the specimen is destroyed.

The chart (Fig. 5) shows the results collected for the ultimate flexural strength. The highest strength value obtained is 103.02 MPa, corresponding to the heat-curing acrylic resin. Such a result is followed by NextDent Denture 3D+ - by 95.9 MPa and NextDent C&B MFH – by 95.46 MPa. All the observed specimens have ultimate flexural strength, which is higher than 65 MPa. NextDent Denture 3D+ polymer also shows the lowest UFS result of 74.5 MPa, followed by NextDent MFH C&B polymer – 82.69 MPa and the control group – 84.58 MPa.

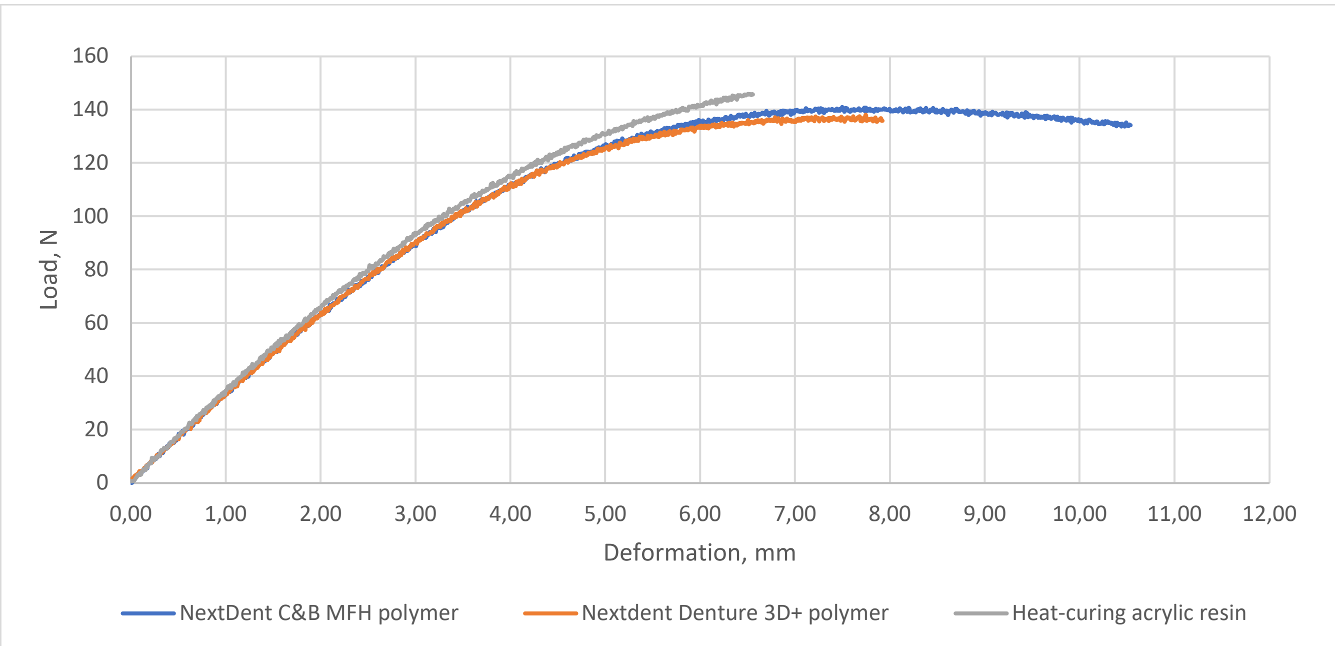

Fig. 4. The load/deformation curves of each group of tested specimens

The highest mean ultimate flexural strength is achieved for heat-curing acrylic resin – 93.38 MPa. It is followed by the NextDent C&B MFH specimens group, with a mean ultimate flexural strength of 89.39 MPa and NextDent Denture 3D+ specimens with 86.57 MPa.

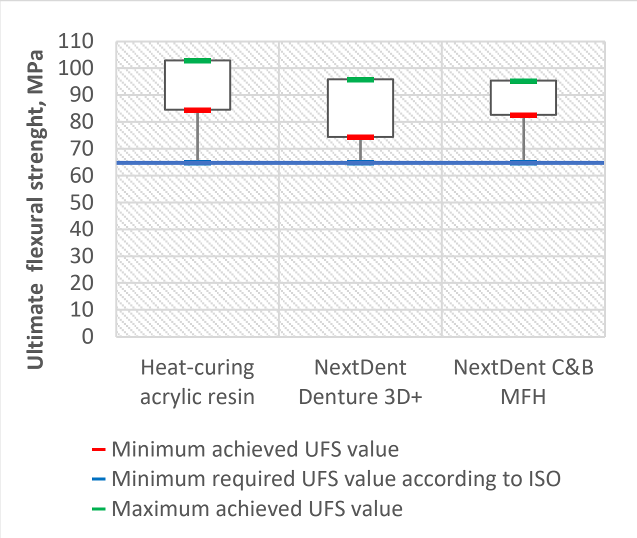

Fig. 5. The chart presents the variation of the ultimate flexural strength (UFS) of the observed groups of objects

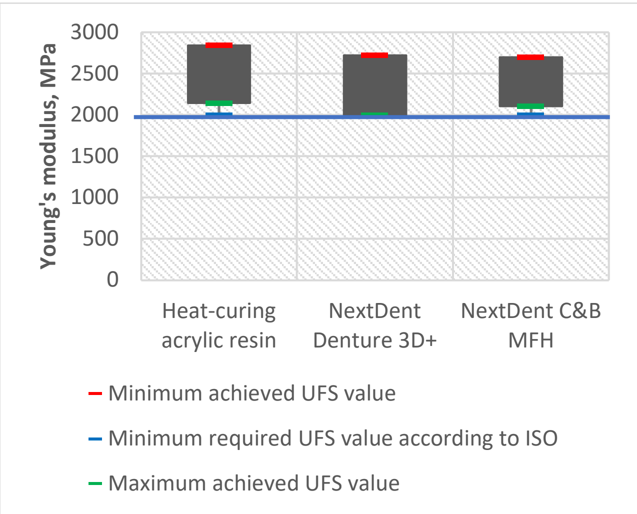

Fig. 6 The chart presents the variation of the Young's modulus for each group

The highest Young's modulus value is achieved by the heat-curing resin – 2842.77 MPa, followed by the NextDent Denture 3D+ with 2717.91 MPa and the NextDent C&B MFH with 2694.11MPa (Fig. 6). Just one of the five NextDent Denture 3D+ specimens observed has Young's modulus which is 2000 MPa. All the observed objects generally show higher Young's modulus than 2000 MPa.

The highest mean value for Young's modulus is achieved by the heat-curing acrylic resin – 2396.06 MPa, followed by NextDent C&B MFH resin with 2377.44 MPa and NextDent Denture 3D+ with 2263.21 MPa.

4. Discussion

When the area of the proportional limit of the load/deformation curve is observed, it is noticeable that the curve of the heat-curing acrylic resin is slightly steeper than the rest of the specimens. It means that the heat-curing acrylic resin should have a slightly lower elastic deformation rate as the load increases. It is important to be noted that the observed resins for 3D printing show almost identical curves when the area to the proportional limit is inspected. For such a reason, they are compared only to heat-curing acrylic resin and not between them. In addition, the specimens have a 3.3 mm thickness, which is thicker than most areas of acrylic dentures. This factor does not affect the results achieved for Young's modulus because it is an indicator of the relative material stiffness and is unaffected by the specimen's thickness.

Complete dentures should be stiff and firm during function. Otherwise any elastic deformation of the base will move the artificial dental arch away from the neutral zone reducing the stability of the denture. When the stability has been lost, the denture loses its retention and support. Such results in an increased risk of fracture. That is why the materials for complete dentures should be stiff but not brittle. They should be able to resist relative elastic deformation because of the denture-bearing area-specific resilience. At the same time, the denture should not be too thick, as it may cause functional or excessive perceptional discomfort. It is the reason why the higher Young's modulus of the materials is essential for successful complete denture fabrication. According to the ISO Standard 20795-1, all the observed materials are suitable for this purpose as their mean Young's modulus is higher than 2000 MPa [37]. It defines them as reliable materials for complete denture fabrication.

According to the ultimate flexural strength data achieved, it is apparent that all the observed materials are suitable for complete denture fabrication, including NextDent MFH C&B polymer. The heat-curing acrylic resin shows slightly better results than the 3D-printed materials when the mean values for the ultimate flexural strength are observed. Some other scientific works completely or partially support these results [38-40]. Such a characteristics allows the complete denture of all observed materials to withstand the masticatory forces successfully.

Several studies observe the masticatory forces of completely edentulous patients with complete dentures. They denote that the forces depend on many factors such as gender, how long the patient was completely edentulous, the materials of which the denture is fabricated, the adaptation of the patient, etc. [41] For such a reason, each study presents variable results [42-45]. Some of them exceed the ultimate flexural strength observed in the current study. Not every occlusal force, which is higher than the ultimate flexural strength of the material, could cause the destruction of the denture. The occlusal forces are partially distributed straight forward to the alveolar ridge, causing compression to the denture base material. At the same time, they are partially transferred in the oblique or horizontal direction, causing flexural deformation of the denture's base. Some more factors should be discussed: the condylar guidance angle of the patient, the size of the denture bearing area, the form and the height of the alveolar ridges, and the morphology of the artificial teeth, as they affect the stability of the complete denture and the value of horizontal and vertical vector of the occlusal forces. Such factors can withstand or generate horizontal vectors of the occlusal forces. It is the reason that the results achieved in vivo are not comparable to those achieved in vitro.

In order to make a more detailed assessment of the properties of the material for additive manufacturing of denture base, some additional factors should be observed. For example, the level of the final polymerization of light curing resins for 3D printing, their ability to washstand to different defect and denture bearing area characteristics (the notch for the labial and buccal frenulum, chambers for torus release etc.), the ability of the materials to withstand to cyclic load, etc. All of them affect the ability of the complete denture to be firm and to withstand the occlusal forces. Such a fact can also affect the selection of materials and technology for complete denture fabrication.

5. Conclusions

Nowadays, additive manufacturing is developing very fast as it is an essential part of almost every industry, including healthcare and dentistry. For such a reason, investigating the mechanical properties of each material for 3D printing is very important for practice. The current study examines two types of resins for 3D printing. It reveals that the observed resins have very similar mechanical properties. The ultimate flexural strength and Young's modulus of NextDent C&B MFH are sufficient to allow its use in the fabrication of denture bases.

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Additional information

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