Research Article RW Materials https://www.rwpublisher.com/

Received: 29 March 2024 | Revised: 22 May 2024 | Accepted: 05 June 2024 | Published: 17 June 2024 | Open Access: Research Article

RW Materials 2024, 02, 39-46. https://doi.org/10.70498/rwm/20240006

journal homepage: https://www.rwpublisher.com/journal/rw-materials

Investigation of Mechanical Properties of PLA based 3D Printed Dental Crown

Nazrul Islam Khan*, Sanjeev Kumar, Rishabh Raj, Paritosh Singh, Shivam Jha

Affiliation:

Department of Mechanical Engineering, Netaji Subhas University of Technology, New Delhi, India-110078

Correspondence:

nazrul@nsut.ac.in

This research aims to comprehensively investigate the mechanical properties encompassing tensile strength, compressive strength, hardness, and saliva absorption of Polylactic acid (PLA)-based three-dimensional (3D) printed dental crowns. The study provides valuable insights into the performance characteristics of PLA-based dental crowns, with a particular focus on their ability to withstand mechanical forces and absorb saliva. PLA filament derived from PLA pellets and produced using the Fused Deposition Modeling (FDM) technique with a raster angle of 45º was employed to mechanical testing. The Creality Ender-3 S1 FDM 3D Printer is utilized for the manufacture of samples. Through meticulous comparison with the mechanical properties of natural enamel teeth, the study aims to assess the suitability of PLA-based 3D printed dental crowns as a substitute for traditional dental crown materials. A detailed analysis and comparison of the study leads to a significant contribution to understand PLA-based dental crowns and their potential in dental prosthetic applications. Ultimately, the outcomes of the study advocates for the adoption of PLA-based dental crowns as a viable and effective alternative in dental practice.

KEYWORDS: **Polylactic acid (PLA); Three-dimensional (3D) printing; Mechanical properties; 3D printed PLA crown.**

This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Tooth loss can have a huge impact on quality of life hence figuring out an optimal substitute becomes important, and a suitable replacement should have some desired properties which include tribological properties [1, 2]. Teeth for humans serve multiple purposes such as breaking food, helping in speech and shaping the face. Just like any other body part they are prone to diseases and fractures, hence requiring medical attention. In cases like cavities and fractures, teeth may need to be drilled out or may require replacement. In such cases, dental crowns can be used to substitute the damaged teeth. Materials used for making dental crowns should be safe for human use and reliable so they should have some appropriate biological and mechanical properties, different types of materials can be used to make dental crowns like metals, ceramics, and polymers [3]. Commonly Titanium and its alloys are used for dental crowns but other materials like zirconia, cobalt-chromium and alumina are also often used instead of Titanium though they are reliable, but they are not cheap and affordable for everyone and require weeks or even months to fully manufacture. Polymers on average don't cost as much as alloys therefore dental crowns made from polymers can be relatively more affordable and take less time to manufacture as additive manufacturing has developed to the point that a usable model can be printed within days if not hours [9-10]. PLA is one such affordable polymer [6-7]. 3D printing or additive manufacturing can be used to commercially manufacture dental crowns on large scale in reasonable time, there are various 3D printing techniques like Stereolithography (SLA), Fused Deposition Modeling (FDM), Digital Light Processing (DLP) but FDM stands out as an affordable [11-12] and scalable method to 3D print thermoplastics [8].

In view of the above context, 3D printed PLA samples were manufactured and analyzed for their mechanical properties so that they can be used for making suitable dental crowns very much needed for dental implant applications.

2. Experimental section

2.1. Materials

The filament used for this experiment was 3D Premium PLA white 3D Printer Filament of 1.75 mm diameter. Artificial saliva (Salivary) supplied by Torion Lifesciences was used to conduct the saliva absorption test. To print the samples, Creality Ender-3 S1 FDM 3D Printer was used. The printing parameters such as printing temperature of 190°C, printing speed of 150 mm/min and infill density of 100% were kept fixed during the 3D printing process.

2.2. Methodology and Characterization

The tests were performed by following American Society for Testing and Materials (ASTM) and International Organization for Standardization (ISO) standards to gain information about mechanical properties of PLA. After collecting data about mechanical properties of PLA it was compared with human enamels mechanical properties to conclude if PLA is usable to manufacture 3D printed dental crowns or not. To find the compression strength of the samples UTM Instron with 100 kN load cell was used. For tensile test, UTM Instron 5KN was used. For hardness test of the samples, Mitutoyo (HM-200) were used.

2.2.1 Tensile test

The tensile tests were performed to determine the tensile strength of 3-D printed PLA specimens as per ASTM D 638 standard as shown in **Fig. 1.** The tests were performed on four specimens to obtain an average value of tensile strength for PLA. The extension rate for the samples was 5 mm/min. In tensile strength assessments using dumbbell-shaped specimens, dimensions are crucially chosen to balance factors such as grip accommodation, specimen stability, and stress distribution. The length ensures secure grip placement, while the diameter influences load-bearing capacity.

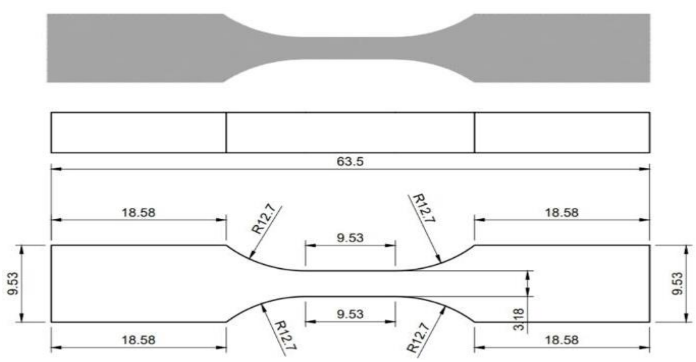

Fig. 1. Dimensions of a tensile test specimen.

2.2.2. Compression test

ASTM D 695 standard portrays a testing method for obtaining the compressive strength and compressive modulus of a polymer. For the compressive modulus estimations, four cylindrical samples were created by following ASTM D695, and were tested with a compression rate of 10 mm/min to gain an average compressive strength value of PLA. The dimensions of the test samples are shown in **Fig. 2.**

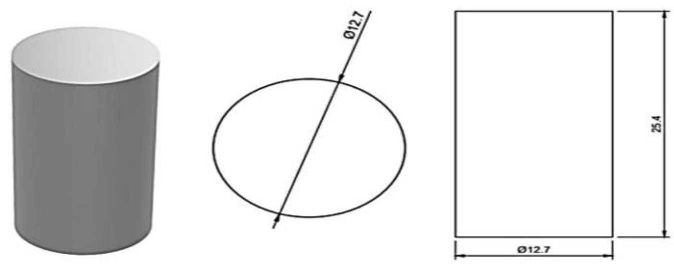

Fig. 2. Dimensions of a compression test specimen.

2.2.3. Hardness test

ASTM D785 standard was followed to perform hardness test for the PLA samples. Vickers hardness test was conducted on the PLA samples with Vickers hardness testing machine. ASTM D785 describes the test method for testing and determining the hardness of rigid plastics. The dimensions of the test specimen are shown in **Fig. 3.** Three test samples were tested to obtain an average hardness value. A square pyramidal shaped indenter was used to apply a set amount of force on the samples the indenter was pressed into the surface of the material with a specific force for a predetermined dwell time, ranging from a few seconds to tens of seconds. After the dwell time, the force was removed, and the size of the indentation was measured using an optical microscope.

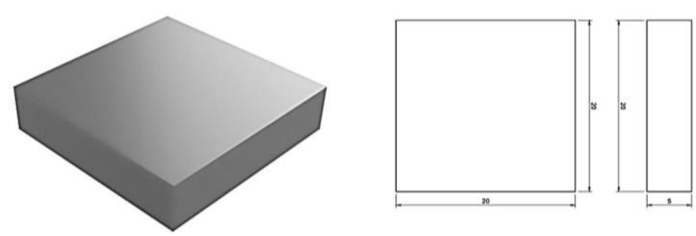

Fig. 3. Dimensions of a hardness test specimen.

2.2.4. Saliva absorption test

Saliva absorption test was conducted on PLA samples to study the effects of saliva on PLA over a long period of time. The test was conducted by following ISO 62 standard. The test specimens (three from each batch) were kept in artificial saliva for around 30 days and their weights were measured periodically to look for the trends and patterns. During the saliva absorption tests on cuboid-shaped specimens, dimensions were carefully chosen to optimize surface area, volume, and aspect ratio. These factors influence absorption rate and uniformity. Thickness is crucial, affecting penetration depth and test outcomes. Material composition and surface properties must resemble real-world conditions. Environmental factors like temperature and humidity were standardized. Overall, meticulously calibrated dimensions ensure reliable results, unaffected by external factors.

3. Results and Discussion

The mechanical properties such as tensile strength, hardness and compressive strength along with saliva absorption test were performed on the 3D printed samples.

3.1. Tensile properties of the samples

An exhaustive analysis of several key parameters was conducted to evaluate the tensile properties of the samples under examination. The tensile test data is shown in **Table 1** and the stress vs. strain plots are shown in **Fig. 4.** The mean value of tensile stress observed was 18.95±1.46 MPa. The observed tensile strain at maximum load remained consistent across the samples, fluctuating marginally between 0.087 mm/mm and 0.090 mm/mm. The average Young's modulus observed was 264.92±14.9 MPa. Strain, representing the change in length of the material, is typically plotted along the x-axis in stress-strain diagrams. This parameter quantifies the extent of deformation experienced by the material under applied stress, providing valuable insights into its mechanical behaviour and performance. The average tensile strain at maximum load of the samples was 0.090±0.001 mm/mm showing acceptable deformability of the samples. These findings provide valuable insights into the stiffness and elastic behaviour of the tested specimens within the specified strain range, contributing to a comprehensive understanding of their mechanical properties under tensile loading conditions. **Fig. 5** shows the broken tensile test samples.

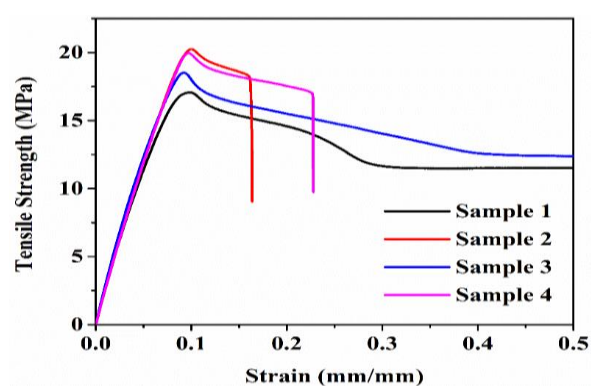

Fig. 4. Stress vs. strain plots of tensile test samples.

Table 1. Tensile properties of PLA samples.

Samples	Max. Load (N)	Extension at Max. Load (mm)	Tensile Stress at Max. Load (MPa)	Tensile Strain at Max. Load (mm/mm)	Modulus (MPa)
Sample 1	542.64	0.93	17.06	0.089	260.54
Sample 2	643.58	0.95	20.24	0.090	255.37
Sample 3	588.86	0.88	18.52	0.087	287.11
Sample 4	634.59	0.93	19.96	0.088	256.68
Mean	602.42	0.92	18.95	0.089	264.92
SD	46.50	0.03	1.46	0.0015	14.95
Max.	643.58	0.95	20.24	0.090	287.11
Min.	542.64	0.88	17.06	0.087	255.37

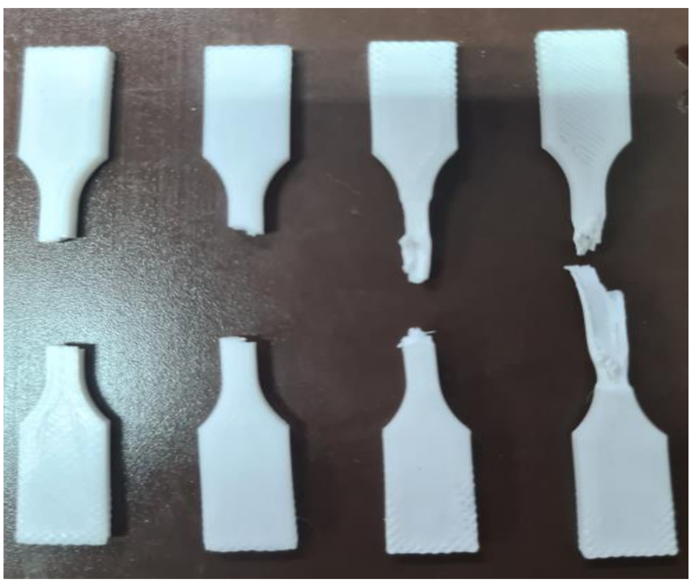

Fig. 5. Post-tensile test deformed specimens.

3.2 Compression properties of the samples

The compression test was conducted on cylindrical specimens with a height and diameter of 12.7mm. The test results are listed in **Table 2** and the typical compression stress vs. strain plots are shown in **Fig. 6.** The test results revealed a range of compressive strengths among the samples. Sample 1 exhibited the highest compressive strength at 53.72 MPa, followed closely by Sample 2 at 48.54 MPa, while Samples 3 and 4 displayed significantly lower strengths at 27.66 MPa and 26.93 MPa, respectively. The yield strength (Offset 0.2%) ranged from 21.96 MPa to 29.01 MPa across the samples, while Sample 1 is showing the highest yield strength. The maximum load endured by the samples varied, with Sample 1 withstanding the highest load of 6805.38 N. The modulus of elasticity (automatic) ranged between 984.81 MPa and 1203.37 MPa, with Sample 1 exhibiting the highest modulus. Additionally, the compressive strain (extension) at the maximum load ranged from 69.96% to 70.00%, showcasing consistent behavior among the samples. The mean compressive strength across all samples was calculated to be 39.22 MPa, with a standard deviation of 13.93 MPa, indicating moderate variability within the dataset. These findings provide valuable insights into the compressive properties of the tested specimens, facilitating a comprehensive understanding of their mechanical behaviour under compressive loading conditions. The compression samples after deformation and failure are shown in **Fig. 7.** Comparing the mechanical properties of 3D printed polylactic acid (PLA) dental crowns with those of natural enamel provides insights into the feasibility of replacement. The provided data showcases PLA's compressive strength ranging from 26.93 MPa to 53.72 MPa, with a mean of 39.22 MPa, and a yield strength varying between 21.96 MPa and 29.96 MPa. In contrast, natural enamel exhibits compressive strengths typically ranging from 100 MPa to 500 MPa, showcasing a substantial disparity in hardness and resilience. Considering these differences, the feasibility of replacing natural enamel crowns with 3D printed PLA alternatives is nuanced.

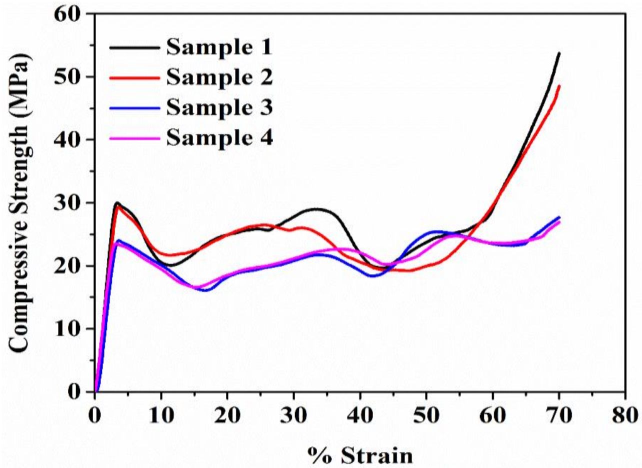

Fig. 6. Compression of stress vs. strain plots of test samples.

While PLA offers advantages such as customization and ease of fabrication, its mechanical properties may not match the performance of natural enamel in the demanding oral environment. Enamel's unique properties, including its ability to withstand chewing forces and resist abrasion, are crucial for long-term durability and functionality. Moreover, the biocompatibility and long-term stability of PLA in the oral cavity require thorough investigation to ensure compatibility with surrounding tissues and resistance to degradation over time.

Fig. 7. Post-compression test showing deformation.

While advancements in additive manufacturing and biomaterials continue to improve PLA's performance, replicating the intricate properties of natural enamel remains a significant challenge. In conclusion, while PLA dental crowns may offer advantages in certain aspects, the decision to replace natural enamel crowns should be made cautiously, considering a comprehensive evaluation of both mechanical performance and clinical outcomes. Close collaboration between materials scientists, dentists, and patients is essential to ensure optimal treatment outcomes and patient satisfaction.

Table 2. Compression properties of the PLA samples.

Samples	Compressive Strength (MPa)	Yield Strength (Offset 0.2%) (MPa)	Maximum Load (N)	Modulus (Automatic) (MPa)	Compressive (Extension) at Maximum Comp. load (%)
Sample 1	53.72	29.01	6805.38	1203.36	70.00
Sample 2	48.54	27.80	6149.38	1182.92	70.00
Sample 3	27.66	22.17	3504.33	1000.18	69.96
Sample 4	26.93	21.96	3411.60	984.80	70.00
Mean	39.22	25.24	4967.67	1092.82	69.99
SD	13.92	3.69	1764.11	116.31	0.01
Min.	26.93	21.96	3411.60	984.80	69.96
Max.	53.72	29.01	6805.38	1203.36	70.00
Range	26.79	7.04	3393.78	218.55	0.03

3.3. Hardness properties of the samples

Hardness test values tell us about PLA's resistance to deformation, scratching, or indentation when subjected to external indentation forces. Hardness is significant in setting of dental crowns as it can give a thought regarding a material's protection from extremely durable distortion. In dental covers hardness should be basically equivalent to hardness of human polish like a substitute for human teeth. **Table 3** presents Vickers's Hardness (HV) values for three different samples at varying levels of applied force. At a force of 0.3, Sample 1 and Sample 2 both displayed a force of 17.1 HV, while Sample 3 exhibited a slightly higher force of 17.9 HV. As the force increased to 0.5, Sample 1 showed the highest force at 18.6 HV, followed by Sample 3 at 18.2 HV, with Sample 2 registering a force of 16.7 HV. At the highest force level of 1 unit, Sample 1 and Sample 3 displayed forces of 17.9 HV and 16.1 HV, respectively, while Sample 2 maintained a force of 16.7 HV. These measurements provide insights into the comparative responses of the samples under varying force conditions. The data reveals that the hardness of PLA samples ranges between 16.7 HV and 18.6 HV across different force levels, while natural enamel typically exhibits much higher hardness due to its dense crystalline structure. Natural enamel, with a Vickers hardness ranging from 300 HV to 400 HV, far exceeds the hardness values of PLA. This stark contrast highlights the superior resistance of natural enamel to wear and abrasion, crucial factors in the demanding oral environment. The indentation on the PLA samples is shown in **Fig. 8.**

Table 3. Vickers hardness number of PLA samples for different force values are given below.

Force	Sample 1 (HV)	Sample 2 (HV)	Sample 3 (HV)
0.3 Kg	17.1	17.1	17.9
0.5 Kg	18.6	16.7	18.2
1 Kg	17.9	16.7	16.1

Considering the mechanical properties, including hardness, alongside compressive and yield strength, reveals significant differences between PLA and natural enamel. PLA may offer advantages in terms of ease of fabrication and customization, but its mechanical properties do not fully match the resilience and durability of natural enamel.

3.4. Saliva absorption analysis

After keeping the samples in saliva for around 30 days and measuring the weights variation due to absorption periodically, the following data was gathered to calculate percentage weight gain. The percentage increment in weight due to absorption of artificial saliva and the final samples after weight gain are shown in **Fig. 9(a) and (b)** respectively.

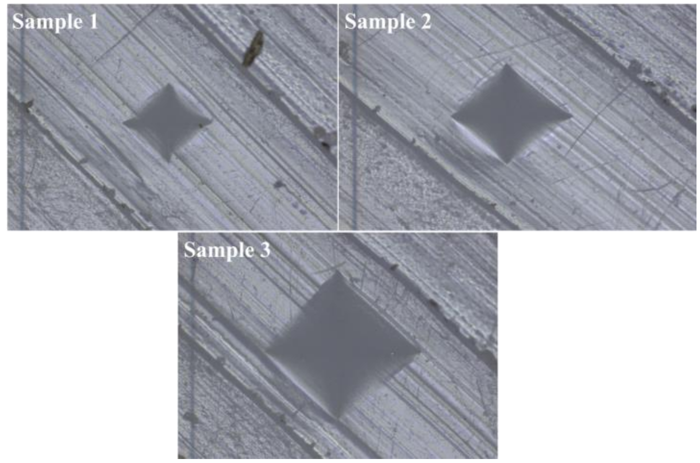

Fig. 8. Indentation on 3D printed test samples.

It can be observed that after 14 days, all the samples achieved saturation and thereafter very minimal weight gain has been attained. These observations highlight the effects of saliva exposure on the weight of different samples over time. The weight variations observed in samples exposed to saliva over approximately 30 days indicate a potential for absorption of saliva by the materials. All samples (three from each batch) experienced slight weight increases over the 30-day period, indicating some degree of saliva absorption. However, the magnitude of weight change varied among the samples. While this suggests potential interactions between the samples and saliva, further analysis is needed to understand the implications for their performance as dental crowns.

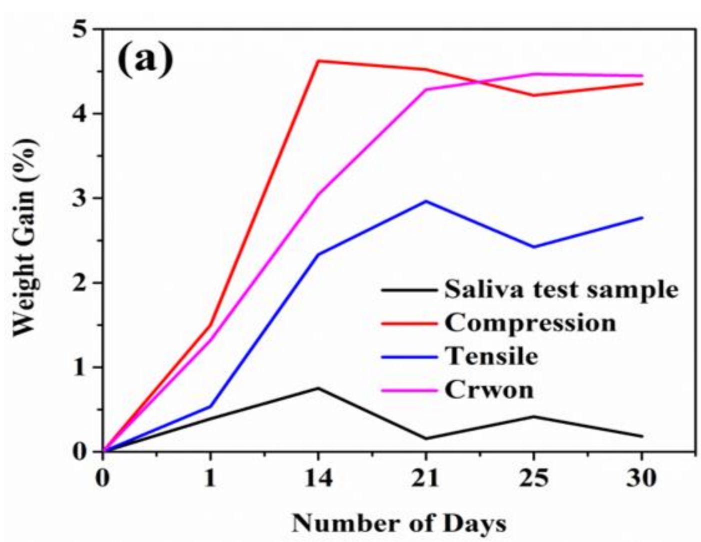

Fig 9(a) Variation of % weight gain after saliva absorption for 30 days, (b) digital image of samples after 30 days of saliva absorption.

4. Conclusions

In conclusion, comparing natural enamel tooth and 3D printed polylactic acid (PLA) dental crowns reveals significant differences in mechanical properties and dental applicability. Enamel's exceptional load-bearing capacity, minimal tensile strain, high tensile stress (39.9-52.5 MPa), compressive strength (48.2-62.0 MPa), flexural strength (52.5-65.9 MPa), and hardness ensure its effectiveness in protecting tooth structure and maintaining long-term functionality. In contrast, 3D printed PLA dental crowns offer versatility and ease of manufacturing but exhibit lower compressive and yield strength, as well as tensile stress at maximum load, compared to enamel. These limitations highlight the challenges PLA faces in demanding oral conditions. Despite this, PLA's manufacturing flexibility suggests potential for improvement through further research and development. Enhancing PLA formulations, printing methods, and post-processing techniques could improve its mechanical properties, making it a viable option for dental crowns. Although currently not as durable as enamel, future advancements in 3D printed PLA technology might achieve durability and functionality comparable to enamel. Moreover, saliva-soaked 3D printed specimens show better mechanical properties than their as-printed counterparts, while extruded PLA samples perform even better. Additionally, PLA-based dental implants produced via 3D printing can be cost-effective than traditional metallic and ceramic implants.

Acknowledgments

The authors thank the Advanced Material Research Lab, Department of Mechanical Engineering (West), Netaji Subhas University of Technology for providing necessary infrastructure to carry out the experimental research work.

Disclosure statement

The authors declare no relevant financial or non-financial interests.

Data availability

Raw data of the research article is available with the authors and will be provided as per a request from the journal.

Ethical approval

Not applicable.

References

[1] Saintrain, M. V. D. L., & de Souza, E. H. A. (2012). Impact of tooth loss on the quality of life. *Gerodontology*, *29*(2), e632-e636. https://doi.org/10.1111/j.1741-2358.2011.00535.x

[2] Zheng, Y., Bashandeh, K., Shakil, A., Jha, S., & Polycarpou, A. A. (2022). Review of dental tribology: Current status and challenges. *Tribology International*, *166*, 107354. https://doi.org/10.1016/j.triboint.2021.107354

[3] Jiang, X., Yao, Y., Tang, W., Han, D., Zhang, L., Zhao, K., ... & Meng, Y. (2020). Design of dental implants at materials level: An overview. *Journal of Biomedical Materials Research Part A*, *108*(8), 1634-1661. https://doi.org/10.1002/jbm.a.36931

[4] Gubbi, P., & Wojtisek, T. (2018). The role of titanium in implant dentistry. In *Titanium in medical and dental applications* (pp. 505-529). Woodhead Publishing. https://doi.org/10.1016/B978-0-12-812456-7.00023-8

[5] Narayana, P. S. V. V. S., & Srihari, P. S. V. V. (2019). Biofilm resistant surfaces and coatings on implants: A review. *Materials Today: Proceedings*, *18*, 4847-4853. https://doi.org/10.1016/j.matpr.2019.07.475

[6] Nampoothiri, K. M., Nair, N. R., & John, R. P. (2010). An overview of the recent developments in polylactide (PLA) research. *Bioresource technology*, *101*(22), 8493-8501. https://doi.org/10.1016/j.biortech.2010.05.092

[7] Puls, N., Carluccio, D., Batstone, M. D., & Novak, J. I. (2021). The rise of additive manufacturing for ocular and orbital prostheses: a systematic literature review. *Annals of 3D Printed Medicine*, *4*, 100036. https://doi.org/10.1016/j.stlm.2021.100036

[8] Popescu, D., Zapciu, A., Amza, C., Baciu, F., & Marinescu, R. (2018). FDM process parameters influence over the mechanical properties of polymer specimens: A review. *Polymer Testing*, *69*, 157-166. https://doi.org/10.1016/j.polymertesting.2018.05.020

[9] Honigmann, P., Sharma, N., Okolo, B., Popp, U., Msallem, B., & Thieringer, F. M. (2018). Patient-specific surgical implants made of 3D printed PEEK: material, technology, and scope of surgical application. *BioMed research international*, *2018*. https://doi.org/10.1155/2018/4520636

[10] Gubbi, P., & Wojtisek, T. (2018). The role of titanium in implant dentistry. In *Titanium in medical and dental applications* (pp. 505-529). Woodhead Publishing. https://doi.org/10.1016/B978-0-12-812456-7.00023-8

[11] Jiang, X., Yao, Y., Tang, W., Han, D., Zhang, L., Zhao, K., ... & Meng, Y. (2020). Design of dental implants at materials level: An overview. *Journal of Biomedical Materials Research Part A*, *108*(8), 1634-1661. https://doi.org/10.1002/jbm.a.36931

[12] Narayana, S. V. V. S., & Srihari, S. V. V. P. (2019). A review on surface modifications and coatings on implants to prevent biofilm. *Regen. Eng. Transl. Med*, *6*, 330-346.