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3D-Printed Zirconia Restorations

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Review Article

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ABSTRACT

Zirconia, also known as zirconium dioxide, or ZrO_2, is a preferred ceramic material in dentistry because of its superior durability, chemical resistance, and compatibility with biological processes. The increasing demand for monolithic zirconia, which has traditionally been used as a substructure material in bilayer restorations, has led to advancements in manufacturing techniques. Although subtractive manufacturing (milling) is still the main technique for producing zirconia restorations, additive manufacturing (3D printing) has also emerged as an innovative technique with remarkable benefits such as improved material efficiency, complex design possibilities and reduced material waste. Resolution restrictions, interlayer bonding concerns, and porosity continue to be difficulties, nevertheless, and demanding post-processing techniques like sintering and debinding are necessary to provide the greatest mechanical and aesthetic properties. According to recent research, 3D-printed zirconia offers marginal fit and adaptation that are clinically acceptable and mechanically comparable to those produced with subtractive manufacturing. Nonetheless, factors such as layer alignment, sintering settings, and margin design significantly influence the accuracy and durability of the final restoration. More long-term study is required to establish standardized techniques and evaluate the therapeutic usefulness of additively produced zirconia, as its clinical applicability has not been sufficiently explored despite the encouraging results. This review examines the latest developments, advantages and disadvantages of additive manufacturing for zirconia restorations, emphasizing its potential to advance digital dentistry.

Keywords: Additive manufacturing, dental materials, 3D-printed zirconia

3D Baskı Zirkonya Restorasyonlar

Derleme

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ÖZ

Zirkonya, zirkonyum dioksit (ZrO_2) olarak da bilinen, üstün dayanıklılığı, kimyasal direnci ve biyouyumluluğu nedeniyle diş hekimliğinde sık tercih edilen bir seramik malzemedir. Geleneksel olarak iki katmanlı restorasyonlarda altyapı malzemesi olarak kullanılan zirkonyaya olan talebin artması, üretim tekniklerinde ilerlemelere yol açmıştır. Zirkonya restorasyonlarının üretiminde halen en yaygın yöntem eksiltmeli üretim (frezeleme) olsa da eklemeli üretim (3D baskı), malzeme verimliliğinin artması, kompleks tasarımların üretilebilmesi ve daha az malzeme israfı gibi önemli avantajlarıyla yenilikçi bir teknik olarak ortaya çıkmıştır. Bununla birlikte, çözünürlük sınırlamaları, katmanlar arası bağlanma sorunları ve porozite gibi zorluklar devam etmekte olup, en iyi mekanik ve estetik özellikleri sağlamak için sinterleme ve bağ çözücü (debinding) işlemleri gibi işlem süreçleri gerekmektedir. Son araştırmalarda eklemeli üretilen zirkonya, kenar uyumu ve iç uyum açısından klinik olarak kabul edilebilir olup, mekanik özellikleri frezeleme ile üretilen zirkonyalarla karşılaştırılabilir düzeydedir. Bununla birlikte, katman hizalaması, sinterleme ve marjin tasarımı gibi faktörler, final restorasyonun doğruluğunu ve dayanıklılığını önemli ölçüde etkilemektedir. Eklemeli üretilen zirkonyanın klinik uygulanabilirliği umut verici sonuçlara rağmen standartlaştırılmış tekniklerin belirlenmesi ve terapötik etkinliğinin değerlendirilmesi için daha fazla uzun vadeli çalışmaya ihtiyaç vardır. Bu derleme, zirkonya restorasyonları için eklemeli üretimdeki en son gelişmeleri, avantajları ve dezavantajları inceleyerek dijital diş hekimliğinin ilerlemesine katkı sağlamayı amaçlamaktadır.

Anahtar Kelimeler: Eklemeli üretim, dental materyaller, 3D-baskılı zirkonya

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Introduction

In dentistry, Zirconia, referred to as zirconium dioxide or ZrO_2, is a ceramic material with high strength, resistance to chemical breakdown, thermal stability, and biocompatibility.[1,2] It is widely used in dental procedures, including implants, crowns, and bridges. Zirconia has historically been utilized as a substructure material because of its opacity. However, the use of zirconia in monolithic forms has grown due to common problems such as delamination, chipping of porcelain, and fractures in the bilayer system.[1,2]

There are two primary techniques used in the production of zirconia restorations: the first is subtractive manufacturing, also known as milling, and the second is additive manufacturing, commonly referred to as 3D printing, which has become increasingly popular in dentistry in recent years. A

pre-sintered solid zirconia disc is molded using milling machines and then re-sintered to obtain the final restorative form in the subtractive manufacturing technique, which is the most widely used technique for fabricating zirconia restorations. Although numerous studies have demonstrated that subtractive manufacturing can produce clinically acceptable restorations, this technique is not without its limitations.[3,4] The primary limitation of the subtractive technique is that the diameter of the milling tool limits the accuracy of the milling process..[5,6] Furthermore, because a significant quantity of material is removed in order to achieve the ultimate restoration, the subtractive manufacturing approach frequently results in significant material waste.[5,7] The use of 3D printers in the industrial field began in 1986 when Charles Hull introduced and patented stereolithography (SLA).[8] The additive manufacturing technique allows for the creation of dental restorations with complex geometries that are challenging to produce using conventional techniques, all while reducing production time.[5,6] This review will focus on zirconia (ZrO_2) production, particularly in the context of additive manufacturing technology, which represents an emerging field of practice in dentistry.

Some benefits of additive manufacturing technology include the accurate creation of complex shapes, greater design liberty, and the ability to support various designs. They also offer greater material efficiency compared to conventional techniques.[3] Hesse et al.[2] and Revilla-León et al.[9] reported that one of the disadvantage of additive manufacturing is that the degree of production accuracy changes based on the technology employed. In particular, challenges with resolution, surface finish, and interlayer adhesion may arise when post-processing techniques such as micro-scale 3D printing and sintering are necessary.[9,10] Additional frequent difficulties faced in additive manufacturing include dimensional inaccuracies, extended printing durations, inconsistent post-processing techniques across printing methods, interlayer contraction, dimensional variations caused by printing settings, and differences in the surface and physical characteristics of the final product.[11-13]

Xing et al.[14] indicated that zirconia ceramics created through 3D printing displayed mechanical properties that were comparable to those made using subtractive techniques, showing similar results in fracture toughness and hardness. In research by Miura et al.[3], zirconia samples made with varying layer orientations were examined, showing that blocks with perpendicular layer orientations had greater flexural strength than those with angled orientations. Nevertheless, the modulus of elasticity, chemical composition, and fracture toughness remained unaffected. Similarly, Lyu et al.[15] found that although orientation influenced manufacturing accuracy, monolithic crowns created at various angles were clinically satisfactory in terms of precision. Li et al.[16] noted that 3D-printed zirconia demonstrated enhanced marginal fit and displayed accuracy comparable to that achieved via subtractive manufacturing techniques. Additionally, they noted that 3D printing might be more effective for producing intricate designs.

Additive Manufacturing Technologies for Zirconia

Additive manufacturing is a type of computer-aided manufacturing (CAM) technology that constructs items layer by layer according to a digital design. In contrast to conventional manufacturing techniques, additive manufacturing adds material gradually, allowing for the creation of complex and accurate structures. The American Society for Testing and Materials (ASTM) committee classifies additive manufacturing (AM) technologies into seven categories: stereolithography (SLA), material jetting (MJ), material extrusion or fused deposition modeling (FDM), binder jetting, powder bed fusion, sheet lamination, and direct energy deposition.[17] While multiple 3D-printing techniques are used in dentistry, the specific techniques for zirconia restorations are still limited. These mainly consist of stereolithography (SLA), digital light processing (DLP), and direct inkjet printing (DIP).[18,19] Direct manufacturing techniques like powder bed fusion and direct energy deposition are rarely used for zirconia due to its low thermal conductivity and high melting temperature.[20]

Indirect techniques such as SLA, MJ, material extrusion, DLP, and binder jetting are preferred as they can enhance consolidation and reduce the risk of cracking. Conversely, direct techniques heighten the risk of thermal shock because they involve melting substances with a focused energy source and rapidly cooling them in uncontrolled thermal environments. Conversely, indirect techniques involve protocols for gradual heating that reduce thermal shock.[21,22]

Indirect techniques such as SLA, MJ, material extrusion, DLP, and binder jetting are favored as they enhance consolidation and reduce the risk of cracking. Direct procedures increase the risk of thermal shock since they use concentrated energy to melt materials and quickly cool them in uncontrolled thermal environments. In contrast, indirect techniques use procedures for slow heating procedures that reduce thermal shock. Crucial elements influencing the precision, resolution, and both mechanical and aesthetic properties of components involve the raw materials and binders utilized, printing settings (e.g., layer thickness, printing speed and direction, characteristics of the nozzle or light source), along with post-printing processes like debinding and sintering. The debinding procedure consists of eliminating organic substances by heating them to temperatures between 80 and 120°C.[23]

In dentistry, SLA and DLP printing technologies function through comparable mechanisms but use varying light techniques. In the DLP process, polymerization takes place over a large surface area, while SLA performs polymerization point by point. Consequently, DLP enables quicker manufacturing.[1,23-25] However, voxel pixelation problems can occur due to DLP's rapid production process on complicated surfaces. On the other hand, SLA provides greater manufacturing precision and is more successful at creating complicated surfaces.[1,20,23,25,26]

Compared to subtractive techniques, 3D printing is more cost-effective and facilitates the production of complex structures. However, additive manufacturing is more susceptible to environmental conditions and typically requires additional post-processing steps.[27,28] In subtractive manufacturing, finishing processes such as polishing, finishing, and heat treatment have minimal impact on the physical properties.[29] In contrast, post-print cleaning methods and curing processes in additive manufacturing have a more significant effect on the mechanical properties of the final product.[29-31] Liebermann et al.[29] reported in their study with 3D-printed from 3 mol%-yttria-stabilized zirconia that

ultrasonic activation as a finishing process in additively manufactured zirconia was not only ineffective but also caused structural damage. The final stage in the manufacturing of zirconia restorations produced with SLA/DLP generally consists of two steps, debinding and sintering.[32] An essential point to be considered in zirconia ceramics obtained by additive manufacturing is the debinding process, which means the removal of the organic matrix to be applied to the obtained ceramic green bodies. Inappropriate heating rates, holding temperature and time in the debinding process cause damage such as cracks and blister formation in the green body.[33] Although there are various approaches for the debinding process applied to SLA/DLP-formed parts, there is no universal procedure.[27] Sintering is the final stage where the pores between the particles are eliminated to assemble fully dense components and a well-controlled microstructure, creating a high-performance zirconium. The density and strength of sintered zirconium is directly dependent on the sintering temperature and temperature grade. The heating process must be done very carefully and slowly so that the whole surface of the green part can absorb and distribute the energy homogeneously. Rapid heating can lead to the formation of internal stresses, which can lead to internal cracks that can cause fracture of the green body.[32,33] The sintering of zirconium samples below 1400 °C can lead to poor mechanical properties, while sintering above 1600 °C can increase porosity.[27]

Marginal Fit

The type of margin design used in additively manufactured crowns significantly influences the accuracy of marginal fit.[1] Li et al.[34] reported that rounded shoulder and chamfer margin designs exhibited superior marginal fit in additive manufacturing. Many studies have indicated that a marginal accuracy deviation of up to 120 µm is considered clinically acceptable.[35,36] Lee et al.[35] compared subtractive manufacturing with SLA and DLP techniques and found that while subtractive manufacturing demonstrated higher accuracy, additive manufacturing also remained within acceptable limits. Similarly, Kim et al.[25] compared subtractive manufacturing and SLA in terms of flexural strength and fracture toughness, finding no significant differences. However, when Vickers hardness values were assessed, the reported value was below the standard 1200 HV[37,38] despite being within clinically acceptable ranges.

The direct inkjet technique has been widely used to produce 3D structures.[39,40] In this technique, printers dispense photopolymer from small multi-nozzles to fabricate 3D objects. Camargo et al.[41] reported that crowns produced using the inkjet technique demonstrated accuracy and adaptation similar to those made using milling techniques. The research also indicated that the least accuracy in both additively and subtractively produced crowns was found in the occlusal region.

Porosity

A key component influencing a material's mechanical qualities is its porosity; better mechanical strength is correlated with reduced porosity. Zandinejad et al.[42] reported that increased porosity in additively manufactured zirconia leads to a reduction in flexural strength. In addition, the flexural strength of zirconia produced with a 3D printer with 0% porosity was found to be higher than that of subtractive manufacturing. Similarly, Buj-Corral et al.[43] suggested that reducing layer thickness and production speed is necessary to minimize the porosity of zirconia produced with 3D printers.[21]

Aesthetic

In dentistry, aesthetic factors are crucial, and according to certain research, additive manufacturing problems, such as gaps, cracks, and issues with interlayer bonding, contribute to the formation of pores. The presence of these pores not only increases the likelihood of restoration failure but also adversely affects the aesthetic properties of the final product, such as a decrease in translucency.[23,44,45] The overall visual result is improved when perfect interlayer bonding and integration are achieved.[23] Regarding perfect integration and to reduce interlayer gaps, proper sintering is necessary. [46,47]

There is a lack of clinical studies on additively produced zirconia. Kao et al.[48] conducted a short-term clinical study on zirconia crowns produced with 3D printing, evaluating marginal discoloration, marginal fit, anatomical conformity, surface texture, and color matching. They reported a high success rate. Additionally, no wear on opposing teeth or periodontal adverse effects were observed.

Conclusions

Additive manufacturing has greatly progressed the production of zirconia restorations, providing benefits such as reduced waste, increased design options, and enhanced material efficiency. Outcomes from techniques such as SLA and DLP have been favorable, despite challenges like porosity, dimensional inaccuracies, and the need for precise post-processing. Although initial research suggests that mechanical and cosmetic outcomes are similar to subtractive techniques, further investigation is necessary to assess long-term treatment effectiveness and develop standard protocols. Additive manufacturing could significantly enhance dental procedures and zirconia restorations.

Conflicts of Interest Statement

The authors of the present study declare no conflicts of interest.

References

1. Toksoy D, Önöral Ö. Influence of glazing and aging on the marginal, axial, axio-occlusal, and occlusal fit of 3-unit monolithic zirconia restorations fabricated using additive and subtractive techniques. J Prosthet Dent 2024;131:658.e1-658.e9.
2. Hesse H, Özcan M. A review on current additive manufacturing technologies and materials used for fabrication of metal-ceramic fixed dental prosthesis. J Adhes Sci Technol 2021;35:2529-2546.
3. Miura S, Shinya A, Ishida Y, Fujisawa M. Mechanical and surface properties of additive manufactured zirconia under the different building directions. J Prosthodont Res 2023;31;67(3):410-417.
4. Li R, Xu T, Wang Y, Sun Y. Accuracy of zirconia crowns manufactured by stereolithography with an occlusal full-supporting structure: An in vitro study. J Prosthet Dent 2023;130:902-907.
5. Kyung KY, Park JM, Heo SJ, Koak JY, Kim SK, Ahn JS, Yi Y. Comparative analysis of flexural strength of 3D printed and milled 4Y-TZP and 3Y-TZP zirconia. J Prosthet Dent 2024;131:529. e521-529. e529
6. Lerner H, Nagy K, Pranno N, Zarone F, Admakin O, Mangano F. Trueness and precision of 3D-printed versus milled monolithic zirconia crowns: An in vitro study. J Dent 2021;113:103792

7. Giugliano TS, Zhang Y, Janal MN, Lim CH, Smith RM, Choi M. In vitro comparison of physical characteristics of milled versus printed zirconia discs. J Prosthodont 2023.
8. Tian Y, Chen C, Xu X, Wang J, Hou X, Li K, Lu X, Shi H, Lee ES, Jiang HB. A review of 3D printing in dentistry: Technologies, affecting factors, and applications. Scanning 2021;17:9950131.
9. Revilla-León M, Meyers MJ, Zandinejad A, Özcan M. A review on chemical composition, mechanical properties, and manufacturing work flow of additively manufactured current polymers for interim dental restorations. J Esthet Restor Dent 2019;31:51-57
10. Rues S, Zehender N, Zenthöfer A, Bömicke W, Herpel C, Ilani A, Erber R, Roser C, Lux CJ, Rammelsberg P, Schwindling FS. Fit of anterior restorations made of 3D-printed and milled zirconia: An in-vitro study. J Dent 2023;130:104415
11. Branco A, Silva R, Santos T, Jorge H, Rodrigues AR, Fernandes R, Bandarra S, Barahona I, Matos APA, Lorenz K, Polido M, Colaço R, Serro AP, Figueiredo-Pina CG. Suitability of 3D printed pieces of nanocrystalline zirconia for dental applications. Dent Mater 2020;36:442-455.
12. Sa MW, Nguyen BNB, Moriarty RA, Kamalitdinov T, Fisher JP, Kim JY. Fabrication and evaluation of 3D printed BCP scaffolds reinforced with ZrO2 for bone tissue applications. Biotechnol Bioeng 2018;115:989-999.
13. Hsu HJ, Lee SY, Jiang CP, Lin R. A comparison of the marginal fit and mechanical properties of a zirconia dental crown using CAM and 3DSP. Rapid Prototyp J 2019;25:1187-1197.
14. Xing H, Zou B, Li S, Fu X. Study on surface quality, precision and mechanical properties of 3D printed ZrO2 ceramic components by laser scanning stereolithography. Ceram Int 2017;43:16340-16347.
15. Lyu J, Yang X, Li Y, Tan J, Liu X. Dimensional accuracy and clinical adaptation of monolithic zirconia crowns fabricated with the nanoparticle jetting technique. J Prosthet Dent 2024;132(5):985.e1-985.e7.
16. Li R, Chen H, Wang Y, Zhou Y, Shen Z, Sun Y. Three-dimensional trueness and margin quality of monolithic zirconia restorations fabricated by additive 3D gel deposition. J Prosthodont Res 2020;64:478-484.
17. Revilla-Leon M, Meyers MJ, Zandinejad A, Özcan M. A review on chemical composition, mechanical properties, and manufacturing work flow of additively manufactured current polymers for interim dental restorations. J Esthet Restor Dent 2019;31:51-57
18. Zhu H, Zhou Y, Jiang J, Wang Y, He F. Accuracy and margin quality of advanced 3D-printed monolithic zirconia crowns. J Prosthet Dent 2025;133(5):1284-1292
19. Dewan H. Clinical Effectiveness of 3D-Milled and 3D-Printed Zirconia Prosthesis-A Systematic Review and Meta-Analysis. Biomimetics (Basel) 2023;8.
20. Khanlar LN, Salazar Rios A, Tahmaseb A, Zandinejad A. Additive manufacturing of zirconia ceramic and its application in clinical dentistry: A review. Dent J 2021;9:104.
21. Abualsaud R, Alalawi H. Fit, precision, and trueness of 3D-printed zirconia crowns compared to milled counterparts. Dent J 2022;10:215.
22. Chavez LA, Ibave P, Wilburn B, Alexander IV D, Stewart C, Wicker R, Lin Y. The influence of printing parameters, post-processing, and testing conditions on the properties of binder jetting additive manufactured functional ceramics. Ceramics 2020;3:65-77.
23. Branco AC, Colaço R, Figueiredo-Pina CG, Serro AP. Recent advances on 3D-printed zirconia-based dental materials: a review. Materials 2023;16:1860.
24. Lüchtenborg J, Willems E, Zhang F, Wesemann C, Weiss F, Nold J, Sun J, Sandra F, Bai J, Reveron H, Chevalier J, Spies BC. Accuracy of additively manufactured zirconia four-unit fixed dental prostheses fabricated by stereolithography, digital light processing and material jetting compared with subtractive manufacturing. Dent Mater 2022;38:1459-1469.
25. Kim MS, Hong MH, Min BK, Kim YK, Shin HJ, Kwon TY. Microstructure, flexural strength, and fracture toughness comparison between CAD/CAM milled and 3D-printed zirconia ceramics. Appl Sci 2022;12:9088.
26. Komissarenko DA, Sokolov PS, Evstigneeva AD, Slyusar IV, Nartov AS, Volkov PA, Lyskov NV, Evdokimov V, Putlayev V, Dosovitsky AE. DLP 3D printing of scandia-stabilized zirconia ceramics. J Eur Ceram Soc 2021;41:684-690.
27. Sokola P, Ptáček P, Bafti A, Panžić I, Mandić V, Blahut J, Kalina M. Comprehensive Study of Stereolithography and Digital Light Processing Printing of Zirconia Photosensitive Suspensions. Ceramics 2024;7:1616-1638.
28. Galante R, Figueiredo-Pina CG, Serro AP. Additive manufacturing of ceramics for dental applications: A review. Dent Mater 2019;35:825-846.
29. Liebermann A, Schultheis A, Faber F, Rammelsberg P, Rues S, Schwindling FS. Impact of post printing cleaning methods on geometry, transmission, roughness parameters, and flexural strength of 3D-printed zirconia. Dent Mater 2023;39:625-633.
30. Hwangbo NK, Nam NE, Choi JH, Kim JE. Effects of the washing time and washing solution on the biocompatibility and mechanical properties of 3D printed dental resin materials. Polymers 2021;13:4410.
31. Piedra-Cascón W, Krishnamurthy VR, Att W, Revilla-León M. 3D printing parameters, supporting structures, slicing, and post-processing procedures of vat-polymerization additive manufacturing technologies: A narrative review. J Dent 2021;109:103630.
32. Zhang X, Wu X, Shi J. Additive manufacturing of zirconia ceramics. A state-of-the-art review. J Mater Res Technol 2020;9:9029-9048.
33. Sun J, Binner J, Bai J. 3D printing of zirconia via digital light processing. optimization of slurry and debinding process. J Eur Ceram Soc 2020;40:5837-5844.
34. Li R, Chen H, Wang Y, Sun Y. Performance of stereolithography and milling in fabricating monolithic zirconia crowns with different finish line designs. J Mech Behav Biomed Mater 2021;115:104255.
35. Lee HB, Noh M-J, Bae EJ, Lee WS, Kim JH. Accuracy of zirconia crown manufactured using stereolithography and digital light processing. J Dent 2024;141:104834.
36. Schriwer C, Skjold A, Gjerdet NR, Øilo M. Monolithic zirconia dental crowns. Internal fit, margin quality, fracture mode and load at fracture. Dent Mater 2017;33:1012-1020.
37. Candido LM, Fais LMG, Reis JMdSN, Pinelli LAP. Surface roughness and hardness of yttria stabilized zirconia (Y-TZP) after 10 years of simulated brushing. Revista de Odontologia da UNESP 2014;43:379-383.
38. Roy M, Whiteside L, Katerberg B, Steiger JA. Phase transformation, roughness, and microhardness of artificially aged yttria-and magnesia-stabilized zirconia femoral heads. J Biomed Mater Res A 2007;83:1096-1102.
39. Yarahmadi M, Roa J, Zhang J, Cabezas L, Ortiz-Membrado L, Llanes L, Fargas G. Micromechanical properties of Yttria-doped zirconia ceramics manufactured by direct ink writing. J Eur Ceram Soc 2023;43:2884-2893.
40. Liu K, Sun H, Tan Y, Shi Y, Liu J, Zhang S, Huang S. Additive manufacturing of traditional ceramic powder via selective laser sintering with cold isostatic pressing. Int J Adv Manuf Technol 2017;90:945-952.
41. Camargo B, Willems E, Jacobs W, Van-Landuyt K, Peumans M, Zhang F, Vleugels J, Van-Meerbeek B. 3D printing and milling accuracy influence full-contour zirconia crown adaptation. Dent Mater 2022;38:1963-1976.
42. Zandinejad A, Das O, Barmak AB, Kuttolamadom M , Revilla-León M. The flexural strength and flexural modulus of stereolithography additively manufactured zirconia with different porosities. J Prosthodont 2022;31:434-440.
43. Buj-Corral I, Vidal D, Tejo-Otero A, Padilla JA, Xuriguera E, Fenollosa-Artés F. Characterization of 3D printed yttria-stabilized zirconia parts for use in prostheses. Nanomaterials 2021;11:2942.

44. Revilla-León M, Al-Haj Husain N, Barmak AB, Pérez-López J, Raigrodski AJ, Özcan M. Chemical composition and flexural strength discrepancies between milled and lithography-based additively manufactured zirconia. J Prosthodont 2022;31:778-783.
45. Silva NR, Witek L, Coelho PG, Thompson VP, Rekow ED, Smay J. Additive CAD/CAM process for dental prostheses. J Prosthodont 2011;20:93-96.
46. Kim JH, Maeng WY, Koh YH, Kim HE. Digital light processing of zirconia prostheses with high strength and translucency for dental applications. Ceram Int 2020;46:28211-28218
47. Li X, Zhong H, Zhang J, Duan Y, Li J, Jiang D. Fabrication of zirconia all-ceramic crown via DLP-based stereolithography. Int J Appl Ceram Technol 2020;17:844-853.
48. Kao CT, Liu SH, Kao CY, Huang TH. Clinical evaluation of 3D-printed zirconia crowns fabricated by selective laser melting (SLM) for posterior teeth restorations: Short-term pilot study. J Dent Sci 2023;18:715-721.