Laboratory efficiency of additive manufacturing for removable denture frameworks: A literature-based review

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The purpose of this literature review was to verify the laboratory efficiency of additive manufacturing (AM) systems for removable partial denture (RPD) frameworks. All available relevant articles in English published from 1990 to 2020 were found by searching online databases and by hand research. A total of 17 articles dealt with the surface roughness, fitness accuracy, and retentive forces of AM frameworks. The surface roughness of AM was inferior to that of casting and milling. Whether conventional cast or AM RPD frameworks had superior fitness accuracy could not be clarified. As compared with casting and AM, milling enabled the fabrication of RPD clasps with comparable or better fitness accuracy. Over time, AM clasps had retentive force values of superior consistency as compared with those of conventional cast clasps. Clasps fabricated by repeated laser sintering and high-speed milling could obtain smoother surfaces and more suitable retention than those of AM clasps.

**Keywords:** Additive manufacturing, Rapid prototyping, Metal framework, CAD/CAM

**INTRODUCTION**

In recent years, digital dentistry based on computer-aided design and computer-aided manufacturing (CAD/CAM) has become increasingly popular, and the workflow for the fabrication of crowns and fixed partial dentures has changed dramatically. Most current CAM systems are based on the subtractive technique, using a cutting tool to mechanically mill the material and achieve the desired geometry following computer-guided instructions. Metal and zirconia blocks have mostly been used in the milling process for fabricating prosthetic frameworks. However, the following disadvantages of the milling process have been identified: (1) it is hard to cut complicated shapes and/or undercut areas, (2) large quantities of cutting chips are not reused, (3) cutting accuracy deteriorates after cutting tools wear down, and (4) long processing times are required. Thus, milling would not be a suitable method for making removable partial denture (RPD) frameworks at this moment.

Additive manufacturing (AM), also known as 3D printing, is the process of building the material layer by layer directly from 3D digital data. Recent literature reflects the increased application of various AM techniques in several dental disciplines, namely, the fabrication of dental models, surgical guides for implant placement, and occlusal devices. The evolution of AM has fueled significant advances in restorative dentistry. These technologies are now available to improve clinical outcomes.

In 2009, seven AM categories were determined by the American Society for Testing and Materials (ASTM): stereolithography, material jetting, material extrusion, binder jetting, powder bed fusion (PBF), sheet lamination, and direct energy deposition. PBF technologies are the most common used for 3D metal printing in dentistry. Three types of PBF technologies, such as selective laser sintering (SLS), selective laser melting (SLM), and electron beam melting (EBM), have been introduced. With SLS technology, laser energy is used to heat and consolidate metal powder layer upon layer. Typically, the resulting parts are only sintered, but they demonstrate mechanical properties adequate for many applications. Achieving the melting point during the AM process is a critical step that differentiates the PBF technologies; only SLM and EBM technologies fully melt the metal powder. The main differences between these technologies are the energy source (fiber lasers, Nd: YAG lasers, or electron beam), energy power, chamber conditions (argon, nitrogen, or helium), temperature reached, layer thickness, and grain size.

SLS, SLM, and EBM are capable of producing high-quality metal restorations and prosthetic appliance frameworks. SLS and SLM technologies accomplish sintering and melting by the application of a laser beam. The material used is in the form of a powder, and a laser sinters and melts the powders.

In the SLS process, layers are built sequentially by fusing powder particles using a CO2 laser beam that traces a path on a powder bed based on the desired CAD design. In each layer, the laser elevates the temperature to the melting point, which fuses the powder particles. The process is repeated until the object is completed. SLM, on the other hand, is based on melting the powder rather than sintering it. Direct metal laser sintering (DMLS) technology produces metal parts using an ytterbium laser with high accuracy and better mechanical strength. Ytterbium fiber lasers have high power, mainly for metal cutting, and it is capable of maintaining a stably sized laser beam. In this technology, the metal is added layer by layer, and a laser beam is used to fuse powder at a definite point. Several materials can be used with SLS, such as ceramics, polymers, and metals, whereas DMLS is used to sinter metal particles.

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AM offers various advantages over the milling techniques. The additive technology allows the manufacture of an object regardless of its dimensional complexity and quantity. As compared to the milling process for dental prosthetic frameworks, AM has many advantages: (1) cutting chips are not produced; (2) shapes with free curves, undercuts, and hollow structures can be fabricated; (3) accuracy is not diminished by worn cutting tools; (4) many frameworks can be simultaneously prepared; (5) the process is totally automatic; and (6) the cost is relatively low.

Based on the above-mentioned benefits, AM would be an efficient method for manufacturing complex RPD frameworks. Nevertheless, more research is needed in this domain. The purpose of this literature-based review was to verify the laboratory efficiency of AM systems for the manufacturing of RPD frameworks.

METHODS

This review attempted to include all available literature on the CAM system of milling and AM techniques for fabricating RPD frameworks. The literature was gathered, the quality of the articles assessed, the available data extracted, and conclusions drawn from the descriptions of the studies. The assessment of all available relevant articles in English published from 1990 to 2020 was made by searching online databases and also manually searching publications at the Tsurumi University Library. The online search was performed from the electronic bibliographic database MEDLINE/PubMed using keywords, such as "removable denture", "metal framework", "CADCAM", "Computer-Aided Design", "additive manufacturing", "rapid prototyping", "laser sintering" and "laser melting". Figure 1 shows the flow chart of the article search for this review. A total of 820 articles were gathered from Web journals and the previous library. The relevant studies for the initial selection were chosen based on the article titles and abstracts. The exclusion criteria were as follows: (1) AM in fixed prosthodontics, (2) acrylic complete dentures, (3) implant superstructures, (4) AM techniques, and (5) properties of AM metals.

RESULTS

Finally, 17 articles were determined to be relevant to the application of AM/3D printing in the field of prosthodontics, including 12 in vitro studies and 5 clinical studies. The main parameters and the results of the 17 articles are shown in Table 1.

In vitro investigation

1) Fitness accuracy

The accuracy of AM frameworks with complete palatal coverage was objectively compared to conventional casting one. In this study, two AM techniques (SLM and EBM), computer-aided design/cast (CAD/cast), and conventional casting as a control were examined. Furthermore, both the SLM and EBM groups were tested pre- and post-finishing, for a total of six test groups. There was a significant difference in accuracy among the six frameworks; especially, both the prefinished and finished EBM had significantly less accuracy. The CAD cast and SLM indicated significantly higher accuracy than did the conventional technique. Therefore, digital workflows using AM techniques can be recommended for uncomplicated framework designs as the palatal plate.

On the complicated RPD frameworks, the fitting accuracy of conventional and AM RPD frameworks for maxillary Kennedy class III was compared. Measurement points were selected on the major connectors, rests, guiding plates, and approaching arm. Distinct discrepancies were revealed in the major connectors of all groups. As compared with AM frameworks, conventional cast frameworks fabricated using dental stone or printed resin patterns revealed significantly better fitting accuracy, particularly, in the major connectors and guide plates. The biggest gap (330±200 µm) was observed in the anterior strap of the major connector with the adaptation of the rests or reciprocation plates. Ye et al. reported that the 72.5% of RPD frameworks fabricated from the lost-wax
| Article                        | Year | Type of study | Evaluation points                        | Major findings                                                                 |
|-------------------------------|------|---------------|------------------------------------------|-------------------------------------------------------------------------------|
| Forrester et al.              | 2019 | in vitro      | Fitness accuracy of frameworks           | The computer-aided design/cast and SLM indicated significantly higher accuracy than did the conventional cast technique. |
| Soltanzadeh et al.            | 2019 | in vitro      | Fitness accuracy of frameworks and clasp | As compared with AM frameworks and retentive clasp, conventional cast frameworks and clasp revealed significantly better fitting accuracy. |
| Ye et al.                     | 2017 | in vitro      | Fitness accuracy of frameworks           | The conventional cast technique demonstrated better fitting accuracy than did the AM technique. |
| Tasaka et al.                 | 2019 | in vitro      | Fitness accuracy of frameworks and clasp | Overall discrepancies of the SLS framework and clasps were smaller compared to the AM-Cast. |
| Chen et al.                   | 2015 | in vitro      | Fitness accuracy of frameworks           | The automatic design optimization and additive fabrication procedure for RPD were able to deliver a more evenly distributed contact pressure and reduce the peak pressure. |
| Keltjens et al.               | 1997 | in vitro      | Fitness accuracy of clasp                | Regarding AM clasps, approximately 60% of RPDs had misfits between clasps and abutment teeth. |
| Arnold et al.                 | 2018 | in vitro      | Fitness accuracy of clasp                | As compared with lost-wax casting technique, rapid prototyping techniques showed distinct fitting irregularities over smaller vertical distances. |
| Torii et al.                  | 2018 | in vitro      | Surface roughness, fitness accuracy, and retentive forces of clasp | Digital relief on the acute corner sifting rest and clasp body lowered the gap distance on the rest region. |
| Koike et al.                  | 2011 | in vitro      | Surface roughness                       | EBM structures had a significantly rougher finish, slightly less strength, and slightly greater hardness as compared to SLM structures. |
| Takahashi et al.              | 2020 | in vitro      | Contamination, internal porosity, surface roughness, fitness accuracy, and retentive forces of clasp | Cast titanium clasps had significantly greater porosities than did AM titanium clasps. |
| Nakata et al.                 | 2017 | in vitro      | Surface roughness, fitness accuracy, and retentive forces of clasp | Co-Cr clasps fabricated by repeated laser sintering and high-speed milling could provide smoother surfaces and more suitable retention than those clasps fabricated by AM. |
| Schweiger et al.              | 2020 | in vitro      | Contamination and internal porosity and retentive forces of clasp | DMLS clasps displayed a smaller volume and a more homogeneous distribution of internal porosities as compared to the cast specimens. The mean initial retentive force values were 13.6 N (cast) and 15.7 N (DMLS). |
| Williams et al.               | 2006 | clinical study | Fitness accuracy of frameworks           | Co-Cr RPD framework exhibited good fit. |
| Bibb et al.                   | 2006 | clinical study | Fitness accuracy of frameworks           | Co-Cr RPD framework exhibited good fit. |
| Gao et al.                    | 2009 | clinical study | Fitness accuracy of frameworks           | Ti base framework was subjectively judged as acceptable. |
| Tregerman et al.              | 2019 | clinical study | Fitness accuracy of frameworks           | The completely digital fabrication (intraoral digital scan and SLM) had significantly better fitness than did the traditional analog one (physical impression and cast). |
| Almuffeh et al.               | 2018 | clinical study | Fitness accuracy of frameworks           | Laser-sintered RPDs might lead to better patient satisfaction than conventional cast RPDs. |
technique had a gap <50 µm, meaning that the occlusal rest contacted the tooth. Of the AM group, this value corresponded to 42.5%. The average thickness of AM RPD frameworks was greater than that of investment cast frameworks. These studies suggested that the conventional technique demonstrated better fitting accuracy than did the AM technique\textsuperscript{15,16}.

Similarly, Tasaka \textit{et al.}\textsuperscript{17} reported on the accuracy of RPD frameworks fabricated by 3D-printed pattern casting (AM-Cast) and those fabricated by SLS. Statistically significant differences were observed at the proximal plates, minor connectors, lingual bars, and joining areas of the teeth supported. The fabrication accuracies of AM-Cast and SLS RPD frameworks differed depending on the specific structural component. However, overall discrepancies of the SLS framework were smaller compared to the AM-Cast framework, except the lingual bar. As Chen \textit{et al.}\textsuperscript{18} proposed, superior accuracy and reproducibility of the AM fabrication were suggested. Overall, which method of fabricating RPD frameworks —conventional casting or AM— has superior accuracy cannot be determined. However, both methods revealed clinically acceptable adaptations.

Regarding AM clasps, Soltanzadeh \textit{et al.}\textsuperscript{19} reported the approaching arm for the retentive clasp showed a high amount of misfit (gap), which was similar to the study by Keltjens \textit{et al.}\textsuperscript{19}, which reported that approximately 60% of RPDs had misfits between clasps and abutment teeth. In the present study, 95% of specimens had gaps greater than 311 µm. The fit of RPD clasps fabricated by means of four different CAD/CAM systems —indirect rapid prototyping (wax inject printing combined with the lost-wax casting technique [LWT]), direct rapid prototyping (SLM), indirect milling (wax milling with LWT), and direct milling (resin milling [polyetheretherketone])— were evaluated\textsuperscript{20} and compared those fittings with that of conventional LWT. The fitting accuracy of the clasps in both the horizontal and vertical dimensions were measured by light microscopy. Most of RPDs exhibited smaller vertical measuring distances. As compared to other methods, the worst fit was found for clasps fabricated using indirect and direct rapid prototyping, which were unstable on the master model, making them unsuitable for clinical use. As compared with LWT, milling techniques enabled the fabrication of RPDs that fit comparably or better. However, RPDs fabricated with rapid prototyping techniques showed distinct fitting irregularities over smaller vertical distances. Tasaka \textit{et al.}\textsuperscript{17} reported that the accuracy of three typical clasps (Akers clasp, ring clasp, and RPI clasp) and rests fabricated by 3D printed pattern casting and those fabricated by SLS. Overall discrepancies of clasps and rests were smaller for SLS as compared to AM-cast. To decrease the gap distances at the clasp arm and rest, digital relief on the acute corner sitting rest and clasp body should be performed\textsuperscript{21}.

2) Surface roughness
EBM had significantly less accuracy than did the other materials\textsuperscript{14}. This result would be caused by the surface roughness resulting from using EBM techniques. Surface roughness values ranged from 22 to 63.5 µm, with CAD casting being the smoothest, and EBM prefinished the roughest\textsuperscript{14}. Koike \textit{et al.}\textsuperscript{22} compared SLM and EBM techniques for producing titanium structures. Both techniques produced favorable results for the manufacture of dental prostheses, with EBM structures having a significantly rougher finish, slightly less strength, and slightly greater hardness as compared to SLM structures. The surface finish with AM techniques was an area of concern due to the deposition process of powdered metal alloys, resulting in a rough surface\textsuperscript{22}. Takahashi \textit{et al.}\textsuperscript{23} examined the surface roughness of AM and cast clasps with three titanium alloys (commercial pure titanium [grade 2], Ti-6Al-4V, and Ti-6Al-7Nb). AM titanium clasps had approximately five to 10 times significantly rougher surfaces than those of cast clasps. Especially, the surfaces of AM Ti-6Al-7Nb clasps were significantly roughest (approx. 12 µm) among cast and AM titanium clasps.

Recently, a single machine platform that integrates repeated laser sintering and high-speed milling for one-process molding has been developed\textsuperscript{21,24}. The surface roughness of Co-Cr Akers clasps fabricated by hybrid processing was evaluated and compared to those of cast Co-Cr and commercial pure (CP) titanium alloys. Surfaces remarkably smoother than those of cast clasps could be obtained by the hybrid processing.

3) Internal porosity and contamination
Schweiger \textit{et al.}\textsuperscript{25} evaluated the internal porosities of cobalt-chromium (Co-Cr) alloy clasps fabricated by DMLS as compared to conventionally cast clasps. DMLS clasps displayed a smaller volume and a more homogeneous distribution of internal porosities as compared to the cast specimens. Takahashi \textit{et al.}\textsuperscript{26} also verified the internal porosity and contamination of AM clasps using the three titanium alloys mentioned above. Nondestructive inspection revealed that cast titanium clasps had significantly greater porosities than did AM titanium clasps. Computerized tomography (CT) images showed many irregularly shaped porosities in all of the cast clasps, although there were few spherical small porosities in the thicker rest portion and no porosities in the clasp arm of the AM titanium clasps.

4) Retentive forces of AM clasp
Schweiger \textit{et al.}\textsuperscript{25} measured the retentive forces and survival times of DMLS and conventionally cast clasps. The mean initial retentive force values were 13.6 N (cast) and 15.7 N (DMLS), which significantly declined with aging for the cast group but not for the DMLS group. Survival was considerably higher for the DMLS group (93.8%) than for cast group (43.8%) after 65,000 cycles of aging. Nakata \textit{et al.}\textsuperscript{26} and Torii \textit{et al.}\textsuperscript{27} reported that the initial retentive forces of the hybrid processed clasps were comparable to or higher than those of conventional cast clasps. In addition, hybrid processed clasps showed little decrease of retentive forces with up to 10,000 insertion/removal cycles as compared to cast clasps.
also suggested that the durability of the retention of heat-treated clasps was significantly greater than for cast clasps. Based on every study, the long-term survival of AM clasps was considerably higher than or comparable to that of conventionally cast clasps.

Clinical investigation
The resin patterns of RPD frameworks were first designed and printed using CAD/CAM technology in 200420. The patterns were then cast with a dental alloy using the lost-wax technique. Later, RPD metal frameworks were directly manufactured using CAD-milling and AM techniques26–28. In 2006, RPD frameworks were directly fabricated using SLM with stainless steel and Co-Cr alloys27. SLM Co-Cr alloys showed comparable results to cast frameworks in terms of object accuracy and quality of fit. In contrast, stainless steel clasps showed a tendency to deform with repeated insertions and removals of frameworks.

Tregerman et al.29 compared the clinical fit of RPD frameworks produced by three manufacturing pathways—analog (physical impression and cast), combined analog-digital (the stone cast was scanned using a laboratory scanner and SLM), and digital (intraoral digital scan and SLM)—using a yes/no questionnaire. Three RPD frameworks were fabricated for each of the nine participants using each of the three techniques. Seven of the nine participants declared superior the fit of the framework was subjectively judged to be acceptable

DISCUSSION
Traditionally, the manufacture of RPDs has involved the fabrication of stone casts, the examination of the geometric characterization of the tooth and soft tissues relative to the path of placement, and the careful fabrication of the RPD framework using a direct waxing method. However, in recent years, three steps before denture design—namely, (1) taking physiology impressions, (2) scanning the stone cast using a laboratory scanner, and (3) intraoral digital scan—and three manufacturing methods after CAD —(1) conventional lost-wax casting, (2) fabricating resin or wax patterns by milling or AM, and then casting, and (3) directly manufacturing a metal framework by milling or AM—have been applied. Comparing methods of fabricating RPD frameworks is remarkably difficult, because the combined ways of taking impressions and manufacturing become really complicated in most studies.

Therefore, our review included the results for digital RPDs manufactured by direct and indirect AM techniques, the conventional casting technique, and combinations of the conventional and digital methods. Prosthodontic crucial items for RPD frameworks and clasps, namely, fitness accuracy, surface roughness, internal porosity, contamination, and retentive forces, were evaluated in this review.

In the AM technique, important factors for analyzing the dimensional accuracy of 3D-printed dental restoration were greatly influenced by the build direction and support configuration. Several authors31,32 emphasized the following points: (1) the optimal build direction offers higher accuracy, (2) the self-supporting geometry of the printed object leads to suitable printing, and (3) a minimal support structure maintains the stability of the object during the printing process. In addition, the size, shape, and melting temperature of the particles influence the surface quality of the printed pieces33–35. Preheating the particles close to the melting temperature can limit the energy input needed from the laser to sinter the particles and results in a more homogenous smooth surface34. Inability to control the melting temperature can result in the surface roughness of the printed object, which may explain the roughness observed on AM frameworks26–29.

AM RPD clasps showed distinct fitting irregularities, indicating comparable or worse fits compared to cast or milled clasps. In the present study, 95% of the clasp specimens had greater than 311 µm gap distance15. On the other hand, Tasaka et al.17 reported that overall discrepancies were smaller for the AM rest and clasp than for the 3D-printed pattern casting. The effects of clasp casting pattern distortion and shrinkage on tip displacement differ depending on the form of the clasp arm. Large discrepancies were observed at the center of ring and RPI clasp arms. As the long and thin clasps may be susceptible to distortion, caution should be exercised when using a casting pattern. To create a smooth surface on a framework manufactured using laser sintering, hybrid manufacturing by repeated laser sintering and high-speed milling has been developed24. Since the hybrid manufactured clasp was finally milled after the lamination layer reached a thickness of 500 µm, the same surface as that of the milling surface could be obtained.

As mentioned above, the surface roughness, fitness accuracy, and retentive force of the AM RPD frameworks with clasps were certainly verified in this review. However, the effect of anisotropy, supporting structures, and RPD designs on the properties of AM
frameworks were unclear. Moreover, AM machining and post treatment should be improved to obtain high-quality frameworks. For that, further study is necessary to develop a stable supply of AM removable denture frameworks for clinical use.

CONCLUSIONS

We tried to confirm the laboratory efficiencies of AM systems for RPD frameworks using a literature-based review. A total of 17 articles discussed the surface roughness, fitness accuracy, and retentive forces of AM frameworks and clasps. Within the limitations of this review, the following conclusions were drawn:

1. The surface roughness of AM RPD framework was inferior to those of cast and milled frameworks.
2. Between a conventional lost-wax cast and AM RPD framework, which has superior fitness accuracy could not be clarified. However, both methods reveal clinically acceptable fitness.
3. Compared with casting and AM, milling enabled the fabrication of RPD clasps with comparable or better fitness accuracy.
4. AM clasps showed superior consistency in retentive force values over time, as compared to that of conventionally cast clasps.
5. Clasps fabricated by repeated laser sintering and high-speed milling could provide smoother surfaces and more suitable retention than those clasps fabricated by AM.

REFERENCES

1) Ohkubo C, Sato Y, Nishiyama Y, Suzuki Y. Titanium removable denture based on a one-metal rehabilitation concept. Dent Mater J 2017; 36: 517-523.
2) ASTM International, Committee F42 on Additive Manufacturing Technologies, 2009. ISO/ASTM52900-S52915. Standard terminology for additive manufacturing—general principles— terminology. West Conshohocken: ASTM International, Committee F42 on Additive Manufacturing Technologies; 2009.
3) Revilla-León M, Ceballos L, Martínez-Klemm I, Özcan M. Discrepancy of complete-arch titanium frameworks manufactured using selective laser melting and electron beam melting additive manufacturing technologies. J Prostheth Dent 2018; 120: 942-947.
4) Strub JR, Rekow ED, Witkowski S. Computer-aided design and fabrication of dental restorations: Current systems and future possibilities. J Am Dent Assoc 2006; 137: 1299-1296.
5) Azari A, Nikzad S. The evolution of rapid prototyping in dentistry: A review. Rapid Prototyp J 2009; 15: 216-225.
6) Abduo J, Lyons K, Bennamoun M. Trends in computer-aided manufacturing in prostodontics: A review of the available streams. Int J Dent 2014; 2014: 783948.
7) Salmi M, Palheimo KS, Tuomi J, Ingman T, Mäkitie A. A digital process for additive manufacturing of occlusal splints: A clinical pilot study. J R Soc Interface 2013; 10: 20130203.
8) Martorelli M, Gerbino S, Giudice M, Ausiello P. A comparison between customized clear and removable orthodontic appliances manufactured using RP and CNC techniques. Dent Mater 2013; 29: e1-e10.
9) Chen H, Wang H, Lv P, Wang Y, Sun Y. Quantitative evaluation of tissue surface adaption of CAD-designed and 3D printed wax pattern of maxillary complete denture. Biomed Res Int 2015; 2015: 453968.
10) Wu J, Zhang C, Gao B, Wang X, Zhao X. A study on the fabrication method of removable partial denture framework by computer-aided design and rapid prototyping. Rapid Prototyp J 2012; 18: 318-323.
11) Giacomo GD, Silva J, Martines R, Ajzen S. Computer-designed selective laser sintering surgical guide and immediate loading dental implants with definitive prosthesis in edentulous patient: A preliminary method. Eur J Dent 2014; 8: 100-106.
12) Begum Z, Chideat P. Rapid prototyping —when virtual meets reality. Int J Comput Dent 2014; 17: 297-306.
13) Prabhu R, Prabhu G, Baskaran E, Arumugam EM. Clinical acceptability of metal-ceramic fixed partial dental prosthesis fabricated with direct metal laser sintering technique-5 year follow-up. J Indian Prosthodont Soc 2016; 16: 193-197.
14) Forrester K, Sheridan R, Phoenix R. Assessing the accuracy of casting and additive manufacturing techniques for fabrication of a complete palatal coverage metal framework. J Prosthodont 2019; 28: 811-817.
15) Soltanzadeh P, Supomo MS, Kattadiyil MT, Goodacre C, Gregorius W. An in vitro investigation of accuracy and fit of conventional and CAD/CAM removable partial denture frameworks. J Prosthodont 2019; 28: 547-555.
16) Ye H, Ning J, Li M, Niu L, Yang J, Sun Y, et al. Preliminary clinical application of removable partial denture frameworks fabricated using computer-aided design and rapid prototyping techniques. Int J Prosthodont 2017; 30: 348-353.
17) Tasaka A, Shimizu T, Kato Y, Okano H, Ida Y, Higuchi S, et al. Accuracy of removable partial denture framework fabricated by casting with a 3D printed pattern and selective laser sintering. J Prosthodont Res 2020; 64: 224-230.
18) Chen J, Ahmad R, Suenaga H, Li W, Sasaki K, Swain M, et al. Shape optimization for additive manufacturing of removable partial dentures —A new paradigm for prosthetic CAD/CAM. PLoS One 2015; 10: e0132552.
19) Kelljens HM, Mulder J, Kayser AF, Creugers NH: Fit of direct retainers in removable partial dentures after 8 years of use. J Oral Rehabil 1997; 24: 138-142.
20) Arnold C, Hey J, Schwyen R, Setz J. Accuracy of CAD-CAM-fabricated removable partial dentures. J Prostheth Dent 2018; 119: 586-592.
21) Torii M, Nakata T, Takahashi K, Kawamura N, Shimo H, Ohkubo C, et al. Fitness and retentive force of cobalt-chromium alloy clasps fabricated with repeated laser sintering and milling. J Prosthodont Res 2018; 62: 342-346.
22) Koike M, Greer P, Owen K, Lilly G, Murr LE, Gaytan SM, et al. Evaluation of titanium alloys fabricated using rapid prototyping technologies —electron beam melting and laser beam melting. Materials 2011; 4: 1776-1792.
23) Takahashi K, Torii M, Nakata T, Kawamura N, Shimo H, Ohkubo C. Fitness accuracy and retentive forces of additive manufactured titanium clasps. J Prosthodont Res 2020; 13: 1883-1958.
24) Nakata T, Shimo H, Ohkubo C. Clasp fabrication using one-process molding by repeated laser sintering and high-speed milling. J Prosthodont Res 2017; 61: 276-292.
25) Schweiger J, Güth J, Erdelt K, Edelhoff D, Schubert O. Internal porosities, retentive force, and survival of cobalt-chromium alloy clasps fabricated by selective laser-sintering. J Prosthodont Res 2020; 64: 210-216.
26) Williams RJ, Bibb R, Eggbeer D, Collis J. Use of CAD/CAM technology to fabricate a removable partial denture framework. J Prostheth Dent 2006; 96: 96-99.
27) Bibb R, Eggbeer D. Rapid manufacture of removable partial denture frameworks. Rapid Prototyp J 2006; 12: 95-99.
28) Gao B, Wu J, Zhao X, Tan H. Fabricating titanium denture base plate by laser rapid forming. Rapid Prototyp J 2009; 15: 133-136.
29) Tregerman I, Renne W, Kelly A, Wilson D. Evaluation of removable partial denture frameworks fabricated using 3 different techniques. J Prosthet Dent 2019; 122: 390-395.

30) Almuffeh B, Emami E, Alageel O, de Melo F, Seng F, Caron E. Patient satisfaction with laser-sintered removable partial dentures: a crossover pilot clinical trial. J Prosthet Dent 2018; 119: 560-567.

31) Alharbi N, Osman RB, Wismeijer D. Factors influencing the dimensional accuracy of 3D-printed full coverage dental restorations using stereolithography technology. Int J Prosthodont 2016; 29: 503-510.

32) Osman RB, Alharbi N, Wismeijer D. Build angle: Does it influence the accuracy of 3D-printed dental restorations using digital light-processing technology. Int J Prosthodont 2017; 30: 182-188.

33) Mitteramskogler G, Gmeiner R, Felzmann R, Gruber S, Hofstetter C, Stampfl J et al. Light curing strategies for lithography-based additive manufacturing of customized ceramics. Add Manuf 2014; 1-4: 110-118.

34) Stansbury JW, Idacavage MJ. 3D printing with polymers: Challenges among expanding options and opportunities. Dent Mater 2016; 32: 54-64.

35) Wilkes J, Hagedorn YC, Meiners W, Wissenbach K. Additive manufacturing of ZrO₂-Al₂O₃ ceramic components by selective laser melting. Rapid Prototyp J 2013; 19: 51-57.