Effects of selective laser melting process parameters on the accuracy of the intaglio surface of maxillary removable partial denture frameworks

Hu Chen
Center of Digital Dentistry, Peking University School and Hospital of Stomatology and National Center of Stomatology and National Clinical Research Center for Oral Diseases and National Engineering Research Center of Oral Biomaterials and Digital Medical Devices and Beijing Key Laboratory of Digital Stomatology and NHC Research Center of Engineering and Technology for Computerized Dentistry, Beijing, China

Kenan Ma
Center of Digital Dentistry, Peking University School and Hospital of Stomatology and National Center of Stomatology and National Clinical Research Center for Oral Diseases and National Engineering Research Center of Oral Biomaterials and Digital Medical Devices and Beijing Key Laboratory of Digital Stomatology and NHC Research Center of Engineering and Technology for Computerized Dentistry, Beijing, China and Institute of Medical Technology, Peking University Health Science Center, Beijing, China

Yongsheng Zhou
Department of Prosthodontics, Peking University School and Hospital of Stomatology and National Center of Stomatology and National Clinical Research Center for Oral Diseases and National Engineering Research Center of Oral Biomaterials and Digital Medical Devices and Beijing Key Laboratory of Digital Stomatology and NHC Research Center of Engineering and Technology for Computerized Dentistry, Beijing, China

Yong Wang
Center of Digital Dentistry, Peking University School and Hospital of Stomatology and National Center of Stomatology and National Clinical Research Center for Oral Diseases and National Engineering Research Center of Oral Biomaterials and Digital Medical Devices and Beijing Key Laboratory of Digital Stomatology and NHC Research Center of Engineering and Technology for Computerized Dentistry, Beijing, China, and

Yuchun Sun
Center of Digital Dentistry, Peking University School and Hospital of Stomatology and National Center of Stomatology and National Clinical Research Center for Oral Diseases and National Engineering Research Center of Oral Biomaterials and Digital Medical Devices and Beijing Key Laboratory of Digital Stomatology and NHC Research Center of Engineering and Technology for Computerized Dentistry, Beijing, China, and Institute of Medical Technology, Peking University Health Science Center, Beijing, China

Abstract

Purpose – This *in vitro* study aims to explore the effects of selective laser melting (SLM) process parameters on the accuracy of the intaglio surface of cobalt–chromium alloy (Co–Cr), commercially pure titanium (CP Ti) and titanium alloy (Ti–6Al–4V) maxillary removable partial denture (RPD) frameworks and optimize these process parameters.

Design/methodology/approach – Maxillary RPD framework specimens designed on a benchmark model were built. The process parameters, including contour scan speed and laser power, infill scan speed and laser power, hatch space, build orientation and metallic powder type, were arranged through the Taguchi design. Three-dimensional deviations of the clasps area, connector area and overall area of maxillary RPD frameworks were analyzed by using root mean square (RMS) as a metric. One-way analyses of variance with the above RMSs as the dependent variable were carried out ($\alpha = 0.05$).

The current issue and full text archive of this journal is available on Emerald Insight at: **https://www.emerald.com/insight/1355-2546.htm**

Rapid Prototyping Journal
28/9 (2022) 1625–1635

[DOI 10.1108/RPJ-11-2021-0324]

This work was supported by National Key R&D Program of China [2019YFB1706900], Capital's Funds for Health Improvement and Research [2022-2Z-4106], Beijing Training Project for the Leading Talents in S&T [Z191100006119022], National Key Program of National Natural Science Foundation of China [51705006], and Open Fund of Shanxi Province Key Laboratory of Oral Diseases Prevention and New Materials [KF2020-04].

Authors contribution: Hu Chen and Kenan Ma contributed equally to this article and should be considered co-first authors.

Received 26 November 2021
Revised 20 February 2022
Accepted 16 March 2022

Findings – Maxillary RPD frameworks built horizontally had a more accurate intaglio surface than those built at other orientation angles; CP Ti or Ti–6Al–4V maxillary RPD frameworks had a more accurate intaglio surface than Co–Cr ones; the Maxillary RPD framework built with a higher infill scan speed and lower infill laser power had the more accurate intaglio surface than the one built with other levels of these two process parameters.

Originality/value – A novel benchmark model for evaluating the accuracy of the intaglio surface of maxillary RPD frameworks manufactured by SLM is proposed. The accuracy of the intaglio surface of maxillary RPD frameworks can be improved by adjusting SLM process parameters. The optimal setting of process parameters concerning the accuracy of the intaglio surface of maxillary RPD frameworks was given.

Keywords Maxillary removable partial denture frameworks, Selective laser melting, Process parameters, Accuracy

Paper type Research paper

1. Introduction

The manufacturing methods of removable partial denture (RPD) metal frameworks mainly include traditional casting, casting from 3D-printed resin patterns, numerical control milling and selective laser melting (SLM). SLM is becoming the mainstream manufacturing technology of RPD frameworks in dental laboratories for mass manufacturing and materials economy. Dental metallic powder includes cobalt-chromium alloy (Co–Cr), titanium-6 aluminum-4 vanadium alloy (Ti–6Al–4V) and commercially pure titanium (CP Ti) (Tamimi and Hirayama, 2019; Sakaguchi *et al.*, 2019). The errors of RPD frameworks result from the digital impression, liner space settings when designing RPD frameworks, SLM building, etc., which affect the intaglio surface adaption, retention, and stability of RPD in the patient's mouth and consequently have attracted much attention in clinical practice and research.

The accuracy of clasps in contact with rigid abutment teeth is a priority. The retention of RPD frameworks is highly related to the accuracy of clasps. Clasps have higher accuracy requirements than major connectors in contact with resilient mucosae. The three-dimensional deviation between Co–Cr Akers clasps built by SLM and the design data was -3.20 to $52.40\,\mu$m. Co–Cr Akers clasps built by SLM had higher accuracy than milled ones and those manufactured by digital light processing and casting (Tasaka *et al.*, 2019). There was no significant accuracy difference between the intaglio surface of CP Ti Akers clasp arms and that of milled ones or cast ones (Tan *et al.*, 2019). The accuracy of major connectors also attracts the researchers' attention. The study by Chen *et al.* (2019) showed that the mean gap between the major connector of Co-Cr maxillary RPD frameworks built by SLM and resin casts was 0.15–0.33 mm, whereas the mean gap was 0.15–0.28 mm for cast Co–Cr maxillary RPD frameworks.

Because both clasps and connectors are integral parts of RPD frameworks, the deformation of connectors will affect the accuracy of clasps. Tasaka *et al.* (2020) showed statistical accuracy differences between rests, proximal plates, connectors, and clasp arms of SLM-built Co-Cr RPD frameworks and the counterpart of those manufactured by polymer jetting and casting. According to Soltanzadeh *et al.* (2019), although the adaption of SLM-built Co-Cr maxillary RPD frameworks from direct digital impressions was worse than that of cast ones from traditional impressions, it was clinically accepted. Of the maxillary RPD framework components, the intaglio surface adaption of major connectors was the worst, and that of rests and reciprocal plates was the best (<0.05 mm). Ye *et al.* (2017) found that the mean gap between occlusal rests of SLM-built Co–Cr RPD frameworks and patients' natural teeth were significantly greater than that between occlusal rests of cast Co–Cr RPD frameworks and natural teeth but clinically accepted. The *in vivo* study of Lee *et al.* (2017) confirmed that the type of partial edentulism did not affect the adaption of RPD, which was different from the conclusion of Chen *et al.* (2019). Lee *et al.* (2017) also believed that there were accuracy differences between various components of RPD.

There are two main ways to evaluate the accuracy of RPD frameworks: aligning the scan data of RPD frameworks with the design data and then analyzing the 3D deviation or measuring the gap between the intaglio surface of RPD frameworks and dental casts. However, due to physical limits, a complete surface of RPD frameworks consisting of both the intaglio surface and the polishing one can not be acquired though a single scan, and combining multiple scans will introduce errors. Second, some other geometrical features usually need creating for virtually superimposing SLM-built RPD frameworks on the dental cast (Soltanzadeh *et al.*, 2019). Consequently, a benchmark model simulating and simplifying geometrical features of dental casts was created in this study.

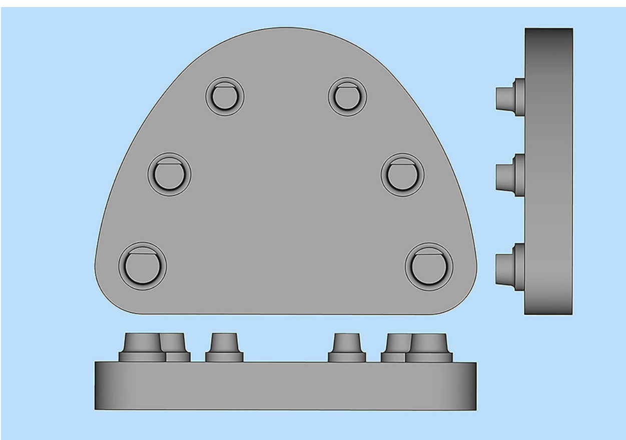
To further improve RPD frameworks' accuracy, it is necessary to investigate the effect of SLM process parameters on the accuracy of RPD frameworks. SLM process parameters mainly refer to the build orientation of parts, scan speed, laser power, scan pattern, hatch space, etc. Xie *et al.* (2020) pointed out that the mean gap between CP Ti Akers clasp arms built horizontally and the tooth analog was $33.4\,\mu$m. The adaption of CP Ti Akers clasps arms built horizontally was better than that of CP Ti Akers clasp arms built vertically or at the orientation angle of 45°. Hwang *et al.* (2021) considered that CP Ti maxillary RPD frameworks built vertically had higher accuracy than those built horizontally. The effects of laser process parameters on the accuracy of RPD frameworks have not been thoroughly investigated. Laser process parameters indeed affect not merely the dimensional accuracy of parts (Vandenbroucke and Kruth, 2007; Pal *et al.*, 2019) but the warpage and distortion of parts. Xia *et al.* (2018) had such results that Co–Cr cubic specimens built with a 550-mm/s scan speed and 115-W laser power had more minor height errors than those built with other levels of these two process parameters. Pal *et al.* (2019) concluded that the linear energy density, or the ratio of laser power to scan speed and hatch space, affects the side and height dimensional errors of Ti–6Al–4V cubic specimens. It is found out of practice that the distortion of maxillary RPD frameworks is more common than that of mandibular RPD frameworks. This study focuses on building errors of maxillary RPD frameworks. This paper aims to explore the effects of the contour scan speed, contour laser power, infill laser speed, infill laser power, hatch space and building orientation on the accuracy of CP Ti, Ti–6Al–4V and Co–Cr maxillary RPD frameworks. The null hypothesis is that SLM process parameters have no effect on the accuracy of maxillary RPD frameworks.

2. Material and methods

2.1 Design of the benchmark model and maxillary RPD framework specimen

The benchmark model mainly consisted of an extruded base, six cones and six cylinders. A fillet was generated for the edge between each cone and the cylinder beneath it. A cylinder, cone and fillet constituted a tooth abutment to simulating canine, first premolar and first molar. All tooth abutments were trimmed with parallel planes to simulate guide planes. After modeling the benchmark model in CAD software Solidworks 2013, it was saved as a standard tessellation language (STL) file (Figure 1). The upper surface of the benchmark model was triangulated with a smaller target edge length in reverse engineering software Geomagic Studio 2014. All errors of this STL file got repaired in data and build preparation software Magics 21. The Z-axis of the model was set as the insertion path, and this model was not blocked out in the dental CAD software Dental System Premium 2019 [Figure 2(a)]. Akers clasps were designed on abutments 17 and 27 (canine); half and half clasps were designed on abutments 15 and 25 (premolar); circumferential clasp arms were designed on buccal surfaces of abutments 13 and 23 (molar). The anterior–posterior palatal strap connected all clasps and retention grids [Figure 2(b)]. The liner space between the surveyed model and the maxillary RPD framework specimen was 0 mm, and the thickness of stippled wax was 0.2 mm. Other parameters were set at the default values recommended by the software vendor.

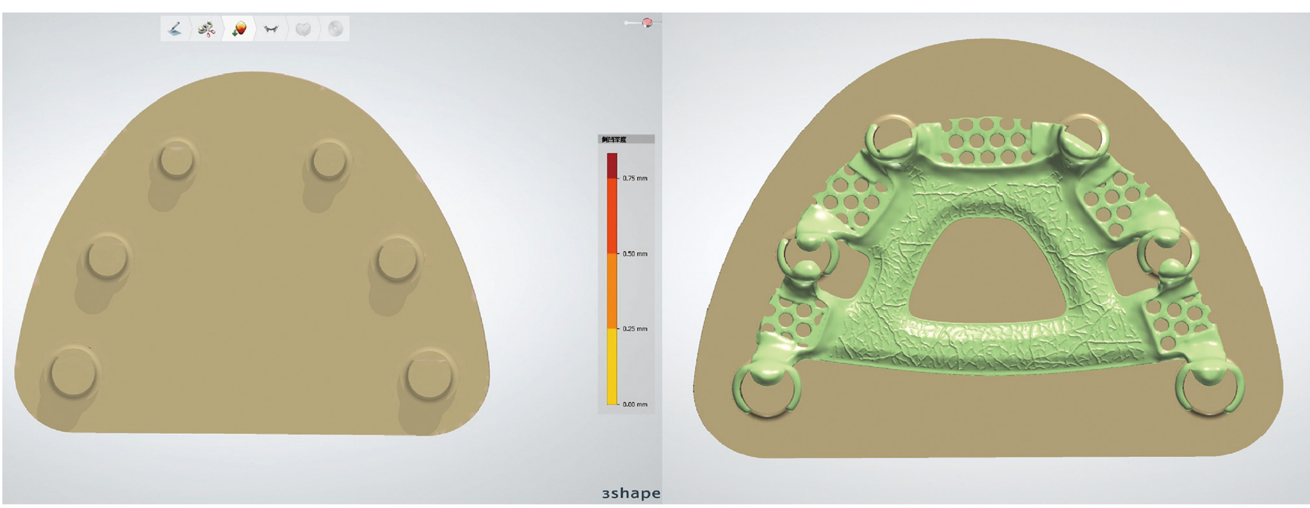
Figure 1 Benchmark model



2.2 Taguchi design

The factors studied in this experiment were as follows: contour scan speed $v_{contour}$, infill scan speed $v_{contour}$, contour laser power $P_{contour}$, infill laser power P_{infill}, infill hatch space h, build orientation θ and metallic powder type Met. The factors and their levels were shown in Table 1. Figure 3 shows the build orientations of maxillary RPD framework specimens. The maxillary RPD framework specimens with 0° of θ were built horizontally, and those with 90° of θ were built vertically. All maxillary RPD framework specimens were oriented with canine clasps at the bottom and molar clasps at the top except the ones built horizontally. The polishing surface of maxillary RPD framework specimens was always closer to building platforms than their intaglio surface. The particle size of Co–Cr alloy (Jinyuan Co, Ltd, China) ranges from 23 to 63 μm, and both the particle size of CP Ti (Falcontech Co, Ltd, China) and that of Ti–6Al–4V (Falcontech Co, Ltd, China) were 15–52 μm, which were provided by the manufacturers. The main chemical components of Co–Cr, CP Ti and Ti–6Al–4V (Falcontech Co, Ltd, China) powder are shown in Table 2. A Taguchi design table was generated in the statistical analysis software SPSS statistics 26. Forty-nine groups of experiments were arranged, and each group of experiments was repeated.

Figure 2 Design workflow of maxillary RPD framework specimen



(a) **(b)**

Notes: (a) Unblock-out benchmark model; (b) designed maxillary RPD framework specimen

Table 1 Factors and levels for the Taguchi design

Factors	Levels
Contour scan speed (mm/s)	300, 450, 600, 750, 900
Infill scan speed (mm/s)	600, 750, 900, 1050, 1,200
Contour laser power (W)	60, 75, 90, 105, 120
Infill laser power (W)	90, 105, 120, 135, 150
Infill hatch space (mm)	0.05, 0.065, 0.08, 0.095, 0.110
Build orientation (°)	0, 22.5, 45, 67.5, 90
Metallic powder type	Co–Cr, CP Ti, Ti–6Al–4V

2.3 Building and postprocessing of specimens

Each group of maxillary RPD framework specimens was oriented at the specified angle according to the Taguchi design, and single prism support structures were generated automatically and manually in slicer software P3DS (Profeta Co, Ltd, China) [Figure 4(a)]. The layer thickness was constant (0.03 mm). Co–Cr, CP Ti or Ti–6Al–4V alloy were used to build the maxillary RPD framework according to the Taguchi design. The Co–Cr specimens were built in the Tr150 system (Profeta Co, Ltd, China) under the atmosphere of nitrogen. CP Ti and Ti–6Al–4V specimens were built in the Ti150 system (Profeta Co, Ltd, China) under the atmosphere of argon. The maximum laser power of Nd: YAG fiber lasers equals 300 W, and the beam-spot size is 50–80 μm. The laser beam width was 0.065 mm for all specimens. The spot compensation when scanning the contour area was set as 0.07 mm. The laser beam contoured the layer along its perimeter twice, and then infill hatch lines were scanned. The laser speed and power when scanning the contour area and the laser speed, power and hatch space when scanning the infill area were set according to the Taguchi design. The meander strategy was used for hatching. The rotation angle of scanning patterns between layers was 67° to obtain a low-temperature gradient in the bulk volume and ensure the build parts' high final density and isotropic properties. The heat treatment recommended by the machine manufacturer involves heating up to the annealing temperature of the metal at a rate of 15°C/min, holding temperature for 60 min and cooling until reaching room temperature. The annealing temperature was 1,190°C for Co-Cr alloy, 650°C for CP Ti and 850°C for Ti–6Al–4V. After maxillary RPD framework specimens were cut from building platforms [Figure 4(b)] and support structures were removed,

Table 2 Main chemical components of SLM metallic powder

Metallic powder	Chemical element (weight%)
Co–Cr	Co, (60–64)%; Cr, (26–30)%; W, (7.5–9.5)%
CP Ti	Ti $\geq$99.10%
Ti–6Al–4V	Ti $\geq$88.56%; Al, (5.50–6.75)%; V, (3.50–4.50)%

specimens were ground but not polished for removal of residual supports, nodules and burrs using tungsten carbide burs at a speed of 20,000–30,000 r/min. All specimens were sandblasted with 100 μm white fused alumina particles under the pressure of 0.4–0.6 MPa [Figure 4(c)].

2.4 3D deviation analysis

Digital scans of the intaglio surface of all printed specimens were obtained by using a lab scanner 3Shape D2000 (Figure 5). In Geomagic Studio 2014, all printed specimens' intaglio surface was initially aligned with the original design data through the *N*-point alignment command. Curves were drawn on the design data to select the clasps area, including the proximal plates, rests, and clasp arms, and the major connector area, and then projected onto each printed specimen. The selected clasps area of each printed specimen was aligned with that of the design data through the best fit alignment command. Root mean square (RMS) representing the 3D deviation between the clasps area of each printed specimen and that of the design data (RMS_{cla}) and the one between the major connector area of each printed specimen and that of the design data (RMS_{con}) were calculated in 3D inspection and metrology software Geomagic control 2014 (Figures 6 and 7). Afterward, each printed specimen's overall area, including the clasps area and major connector area, was best-fit aligned with the design data. RMS between the overall area of each printed specimen and that of the design data (RMS_{ove}) was calculated (Figure 8).

2.5 Statistical analysis

Tests for normality were carried out in a statistical analysis system, SAS 9.4. Shapiro–Wilk test results showed that RMS_{con} followed a normal distribution, whereas RMS_{cla} and RMS_{ove} did not. A Box–Cox transformation of RMS_{cla} and RMS_{ove} was performed. The transformed RMS_{cla} ($\lambda\,RMS_{cla}$) and RMS_{ove} ($\lambda\,RMS_{ove}$) followed

Figure 3 Build orientations of maxillary RPD framework specimens

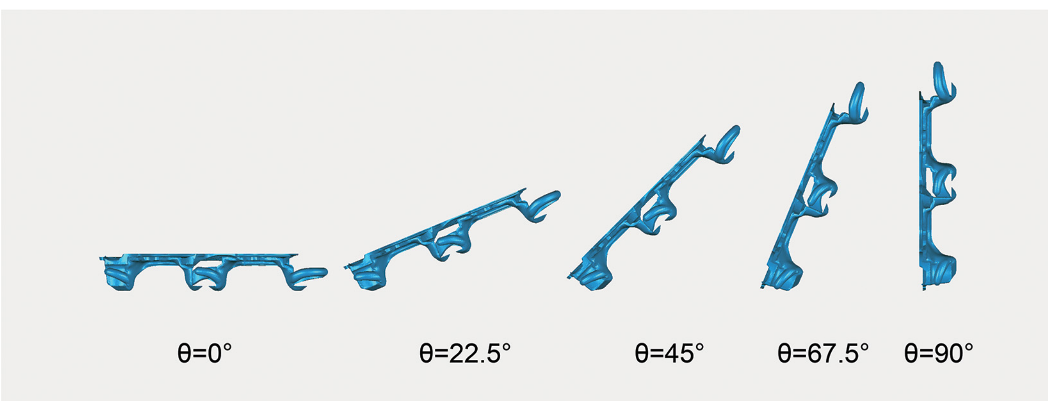


Figure 4 SLM building workflow of maxillary RPD framework specimens

Notes: (a) Support generation; maxillary RPD framework specimen before removal of supports (b) and (c) after grinding and sandblasting

Figure 5 Digital scan of the intaglio surface of maxillary RPD framework specimen

a normal distribution. Main-effects analyses of variance (ANOVA) with λ RMS_{cla}, RMS_{con} and λ RMS_{ove} as the dependent variables, respectively, and $v_{contour}$, $P_{contours}$, v_{infill}, P_{infill}, h, θ and Met as classification variables were carried out. All ANOVAs were significant ($P < 0.05$). The least-squares means for different levels of the significant process parameters and the comparisons between them were plotted in the data analysis and graphing software Origin 2020b.

3. Results and discussion

The RMSs of all groups of maxillary RPD frameworks were in the range of 0.034–0.303 mm for clasps, 0.050–0.411 mm for major connectors and 0.053–0.255 mm for the overall area. The contour scan speed, infill scan speed, infill laser power, hatch space, build orientation and metallic powder type had significant effects on the accuracy of clasps' intaglio surface ($P < 0.05$), and the contour laser power had no significant effects ($P > 0.05$). Of the significant process parameters, the build orientation had the most effects, and the metallic powder type had the second most

Figure 6 3D color-coded mapping of 3D deviation between intaglio surface of clasps area of the built specimen and that of design data

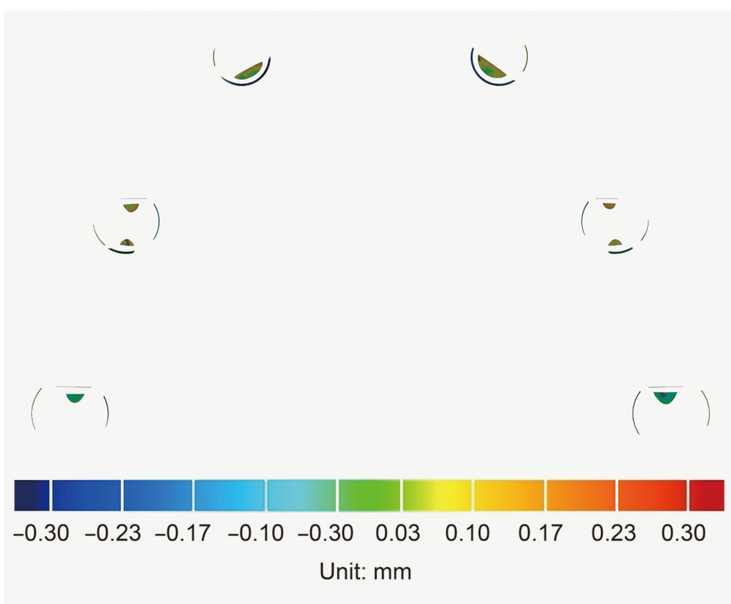


Figure 7 3D color-coded mapping of 3D deviation between intaglio surface of major connector area of the built specimen and that of design data

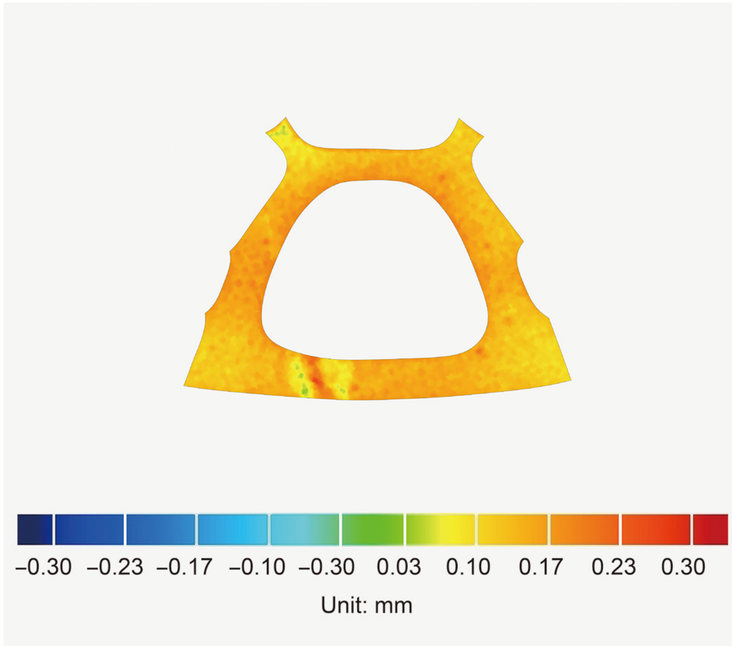
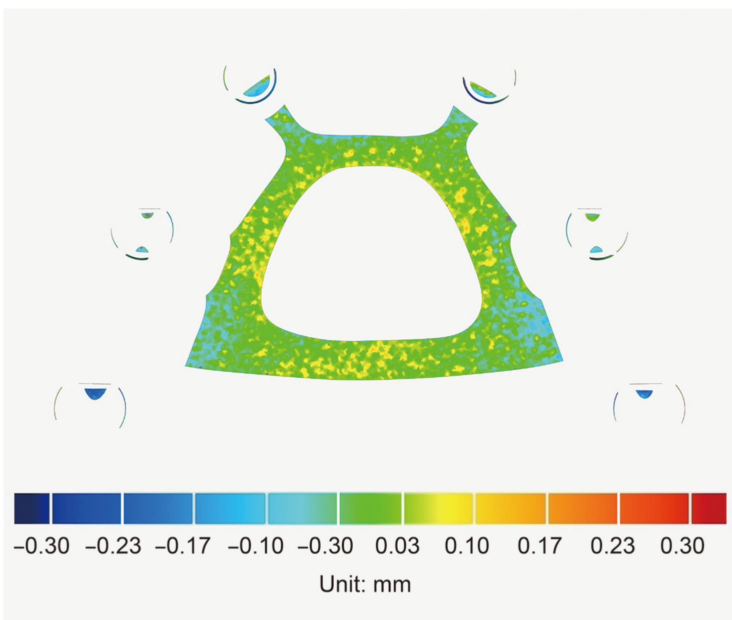


Figure 8 3D color-coded mapping of 3D deviation between intaglio surface of overall area of built specimen and that of design data



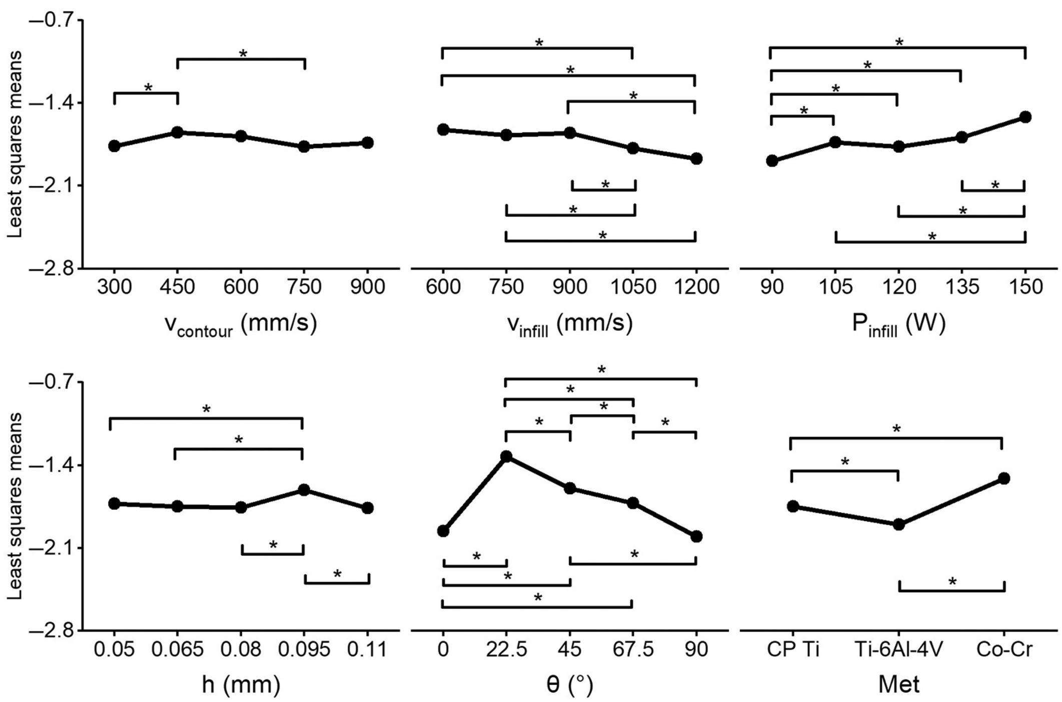
effects (Table 3). The accuracy comparisons of the intaglio surface of the clasps area between maxillary RPD frameworks built with different levels of a significant process parameter when other process parameters were kept constant are shown in Figure 9. Clasps of maxillary RPD frameworks built with a 300-mm/s or 750-mm/s contour scan speed had a more accurate intaglio surface than those of maxillary RPD frameworks built with a 450-mm/s contour scan speed ($P < 0.05$) when other process parameters were kept constant. Clasps of maxillary RPD frameworks built with a 1,050-mm/s or 1200-mm/s infill scan speed had a more accurate intaglio surface than those of the maxillary RPD frameworks built with a 600-mm/s, 750-mm/s or 900-mm/s infill scan speed ($P < 0.05$) when other process parameters were kept constant. Clasps of maxillary RPD frameworks built with a 90-W infill laser power had a more accurate intaglio surface than those of maxillary RPD frameworks built with a 105-W, 120-W or 135-W infill laser power ($P < 0.05$), and clasps of maxillary RPD frameworks built

Table 3 ANOVA for 3D deviation of the intaglio surface of clasps

Source	Df	Sum of squares	Contribution (%)	*F*	*P*
Model	26	12.076	89.7	23.90	<0.001*
$v_{contour}$	4	0.253	1.9	3.25	0.017*
v_{infill}	4	0.700	5.2	9.00	<0.001*
$P_{contour}$	4	0.124	12.4	1.60	0.185
P_{infill}	4	1.366	10.2	17.57	<0.001*
h	4	0.240	1.8	3.09	0.021*
θ	4	7.204	53.5	92.66	<0.001*
Met	2	2.189	16.3	56.31	<0.001*
Error	71	1.380	10.3		
Corrected total	97	13.456			

Notes: $v_{contour}$, contour scan speed; $P_{contour}$, contour laser power; v_{infill}, infill scan speed; P_{infill}, infill laser power; h, hatch space; θ, building orientation; Met, metallic powder type. *Mean difference significant ($P < 0.05$)

Figure 9 Least squares means of λ RMS_{cla} for significant process parameters



Notes: $v_{contour}$, contour scan speed; v_{infill}, infill scan speed; P_{infill}, infill laser power; h, hatch space; θ, build orientation; Met, metallic powder type. *Mean difference significant ($P<0.05$)

with a 150-W infill laser power had the less accurate intaglio surface when other process parameters were kept constant ($P < 0.05$). Clasps of maxillary RPD frameworks built with a 0.095-mm hatch space had a less accurate intaglio surface than those of maxillary RPD frameworks built with a 0.050-mm, 0.065-mm, 0.080-mm or 0.110-mm hatch space ($P < 0.05$) when other process parameters were kept constant. Clasps of maxillary RPD frameworks built with a 0° or 90° orientation angle had a more accurate intaglio surface than those of maxillary RPD frameworks built with a 22.5°, 45.0° or 67.5° orientation angle ($P < 0.05$) when other process parameters were kept constant. Clasps of Ti–6Al–4V maxillary RPD frameworks had the most accurate intaglio surface ($P < 0.05$), and those of Co–Cr maxillary RPD frameworks had the least accurate intaglio surface ($P < 0.05$) when other process parameters were kept constant.

The contour laser power, build orientation and metallic powder type had significant effects on the accuracy of the intaglio surface of major connectors ($P < 0.05$), and the contour scan speed, infill scan speed, infill laser power and hatch space had no significant effects ($P > 0.05$). The build orientation had the most effects on the significant process parameters, and the metallic powder type had the second most effects (Table 4). The accuracy comparisons of major connector's intaglio surface between maxillary RPD frameworks built with different levels of a significant process parameter when other process parameters were kept constant were shown in Figure 10. Major connectors of

Table 4 ANOVA for 3D deviation of the intaglio surface of major connectors

Source	Df	Sum of squares	Contribution (%)	F	P
Model	26	0.195	68.3	5.88	<0.001*
$v_{contour}$	4	0.004	1.2	0.69	0.602
v_{infill}	4	0.011	3.7	2.09	0.091
$P_{contour}$	4	0.015	5.3	2.99	0.024*
P_{infill}	4	0.005	1.6	0.92	0.457
h	4	0.004	1.5	0.83	0.513
θ	4	0.110	38.6	21.6	<0.001*
Met	2	0.046	16.3	18.2	<0.001*
Error	71	0.091	31.7		
Corrected total	97	0.286			

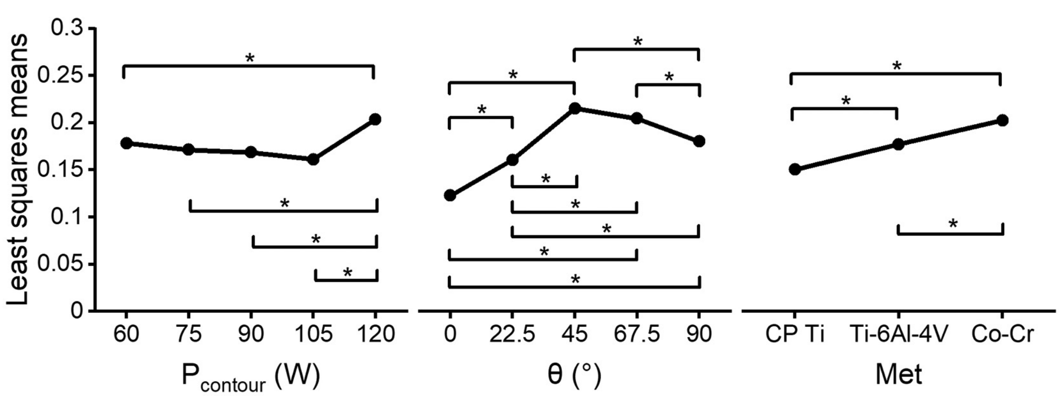
Notes: $v_{contour}$, contour scan speed; $P_{contour}$, contour laser power; v_{infill}, infill scan speed; P_{infill}, infill laser power; h, hatch space; θ, building orientation; Met, metallic powder type. *Mean difference significant ($P < 0.05$)

maxillary RPD frameworks built with a 120-W contour laser power had a less accurate intaglio surface than those of maxillary RPD frameworks built with a 60-W, 75-W, 90-W or 105-W contour laser power ($P < 0.05$) when other process parameters were kept constant. Major connectors of maxillary RPD frameworks built at 0° orientation angle had a more accurate intaglio surface than those of maxillary RPD frameworks built at 22.5°, 45.0°, 67.5° or 90° orientation angle ($P < 0.05$) when other process parameters were kept constant. Major connectors of CP Ti maxillary RPD frameworks had the most accurate intaglio surface ($P < 0.05$), and those of Co–Cr maxillary RPD frameworks had the least accurate intaglio surface ($P < 0.05$) when other process parameters were kept constant.

The contour scan speed, infill scan speed, infill laser power, hatch space, build orientation and metallic powder type had significant effects on the accuracy of the intaglio surface of maxillary RPD frameworks ($P < 0.05$), and the contour laser power had no significant effects ($P > 0.05$). Of the significant process parameters, the build orientation had the most effects and the metallic powder type had the second most effects (Table 5). The accuracy comparisons of the intaglio surface of the overall area between maxillary RPD frameworks built with different levels of a significant process parameter when other process parameters were kept constant were shown in Figure 11, which is similar to the accuracy comparisons of the intaglio surface of the clasps area between maxillary RPD frameworks.

The accuracy of the intaglio surface of maxillary RPD frameworks can be improved by adjusting SLM process parameters. Of SLM parameters, the build orientation had the most effects, the metallic powder type had the second most effects, and laser process parameters had the least effects. The build orientation not merely has effects on the support generation and postprocessing but affects the stress distribution of maxillary RPD frameworks (Kajima *et al.*, 2018; Hwang *et al.*, 2021). The major connector of maxillary RPD frameworks built at a lower orientation angle had a more accurate intaglio surface than that of maxillary RPD frameworks built at a higher orientation angle. The lower residual stress accumulated in the bulk volume of maxillary RPD frameworks due to the fewer layers built at a lower orientation angle. Besides the build orientation, the support structures can help reduce the deformation of maxillary RPD frameworks (Kajima *et al.*, 2018). More detailed and further research on it is needed. Clasps of maxillary RPD frameworks built horizontally or vertically had a more accurate intaglio surface than those of maxillary RPD frameworks built at other orientation angles. Almost no support was generated on intaglio

Figure 10 Least squares means of RMS_{con} for significant process parameters



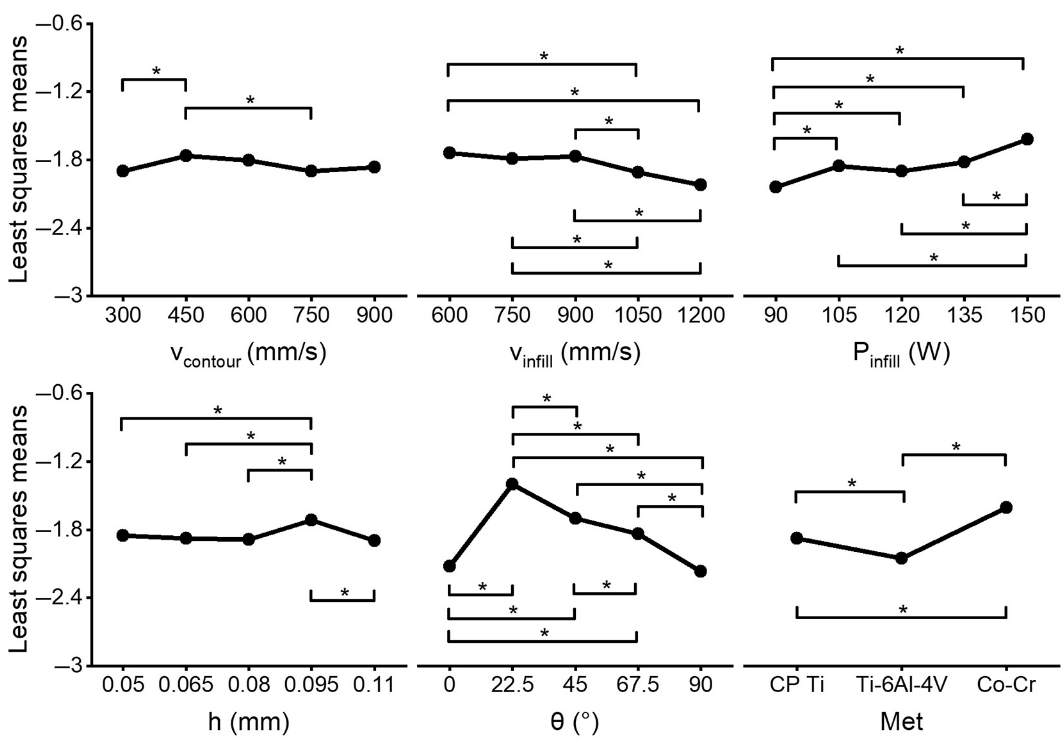
Notes: $P_{contour}$, contour laser power; θ, build orientation; Met, metallic powder type. *Mean difference significant ($P < 0.05$)

Table 5 ANOVA for 3D deviation of the intaglio surface of removable partial denture frameworks

Source	Df	Sum of squares	Contribution (%)	*F*	*P*
Model	26	15.733	89.5	23.34	<0.001*
$v_{contour}$	4	0.321	1.8	3.09	0.021*
v_{infill}	4	0.927	5.3	8.94	<0.001*
$P_{contour}$	4	0.181	1.0	1.75	0.149
P_{infill}	4	1.746	9.9	16.83	<0.001*
h	4	0.312	1.8	3.01	0.024*
θ	4	9.404	53.5	90.69	<0.001*
Met	2	2.843	16.2	54.84	<0.001*
Error	71	1.841	10.5		
Corrected total	97	17.574			

Notes: $v_{contour}$, contour scan speed; $P_{contour}$, contour laser power; v_{infill}, infill scan speed; P_{infill}, infill laser power; h, hatch space; θ, build orientation; Met, metallic powder type. *Mean difference significant ($P < 0.05$)

Figure 11 Least squares means of λ RMS_{ove} for significant process parameters



Notes: $V_{contour}$, contour scan speed; V_{infill}, infill scan speed; P_{infill}, infill laser power; h, hatch space; θ, build orientation; Met, metallic powder type. *Mean difference significant ($P < 0.05$)

surfaces of proximal plates, and supports were generated on only the margin of intaglio surfaces of rests, whereas clasp arms needed more support when maxillary RPD frameworks were built horizontally. However, the least number of supports were generated on clasp arms, whereas the intaglio surface of proximal plates was supported by single prism supports when maxillary RPD frameworks were built vertically. Single prism supports, which were the most common in the SLM process, were used in this research. In this experiment, single prism support structures should be replaced by lightweight ones (Calignano, 2014), for example, tree supports. It is necessary to orientate maxillary RPD frameworks and apply proper support structures to reduce the overhang surface area of clasps' intaglio surface, the residual stress and the deformation of maxillary RPD frameworks (Hwang *et al.*, 2021). The build orientation affects the accuracy of the intaglio surface of RPD frameworks, the fatigue strength of clasps (Xie *et al.*, 2020; Kajima *et al.*, 2018), and the building efficiency of RPD frameworks. All the above factors need to be considered before orientating maxillary RPD frameworks in practice. This experiment also showed that more deformation of clasps appeared in annealed Co–Cr maxillary RPD frameworks than CP Ti or Ti–6Al–4V ones. There were less residual stress and deformation in CP Ti and Ti–6Al–4V maxillary RPD frameworks as they had a lower temperature gradient in the bulk volume due to the lower thermal conductivity of Ti than Co and Cr (Li and Sun, 2011). The deformation of Co–Cr maxillary RPD frameworks can be reduced using preheating the build platform, improving the annealing process, etc.

Laser process parameters also had effects on the accuracy of clasps besides the build orientation and metallic powder type. The laser beam contoured the layer and then scanned hatch lines. The contour area was much smaller than the infill area of the slices of maxillary RPD frameworks. The results showed that the infill scan speed and laser power had more effects on the accuracy of clasps than contour scan speed and laser power. To reduce the dimension errors in the build plane, the contours of the slice of maxillary RPD frameworks were offset. But thermophysical properties, such as thermal conductivity and melting point of Co, Cr and Ti, are different from each other. The spot compensation should have been determined by the single-track width of the Co–Cr alloy, CP Ti and Ti–6Al–4V at the same linear energy density and laser beam diameter rather than kept constant. The rotation angle of scanning patterns between layers was 67° to obtain a low-temperature gradient in the bulk volume and reduce the distortion of maxillary RPD frameworks resulting from residual stress (Le Roux *et al.*, 2018; Xing *et al.*, 2018). It could be seen that the combination of the high infill scan speed and low infill laser power contributed to the high accuracy of the intaglio surface of clasps. Due to the low-temperature gradient in the maxillary RPD frameworks built with a low linear energy density and consequently (Xing *et al.*, 2018), the deformation of clasps was reduced. Clasps, the major connector, retention grids of a maxillary RPD framework have different accuracy requirements. Clasps in contact with teeth have the highest accuracy requirements, whereas retention grids wrapped in the denture base resin have the lowest accuracy requirements. Different settings of the scan speed and laser power can be used for different featured components of RPD frameworks to ensure both the building efficiency of RPD frameworks and the accuracy of the intaglio surface of clasps, which might be one of the future research directions. But it will not be easy to automatically identify these featured components only through analyzing STL data. Perhaps clasps, the major connector, retention grids were labeled during the CAD procedures, and then each labeled component of an RPD framework was built with different settings of the scan speed and laser power. Unlike the infill scan speed and laser power, the hatch space had more minor effects on the accuracy of the intaglio surface of clasps. There is an exponential relationship between the density and porosity of build parts and the volumetric energy density $E = P/(v^{*} h^{*} t)$, where P is laser power, v is scan speed, h is hatch space and t is layer thickness (Simchi, 2006). A low volumetric energy density due to a high scan speed and low laser power would help reduce the density and increase the porosity of RPD frameworks (Elsayed *et al.*, 2019). The optimal volumetric energy density is approximately 150–200 J/mm^3 for Co–Cr alloys (Tonelli *et al.*, 2020). Wang *et al.* (2019) recommended that the optimal range of the laser power is 200–250 W and that of scan speed is 850–1,150 mm/s for dense Ti–6Al–4V parts. The study by Gong *et al.* (2014) showed that the porosity of Ti–6Al–4V parts built with a 1,200-mm/s laser speed and 80-W laser power was more than 5%. However, Hwang *et al.* (2021) showed that the porosity of CP Ti parts built with a 1,200-mm/s scan speed and 90-W power was 0.81%. The density and porosity have direct effects on the resiliency and fatigue properties of clasps. It is one of the future research directions to improve the accuracy of clasps of maxillary RPD frameworks and, meanwhile, to maintain the resiliency and fatigue strength of clasps by adjusting SLM process parameters. Of course, the surface roughness, hardness, porosity, density, tensile properties and bending properties of SLM-built parts must meet the requirements of Standard YY/T 1702–2020.

Limitations of the present study included that only the main effects of process parameters were studied, and the interaction effects were not included in the Taguchi design. Second, the geometrical feature of the palatal vault was not simulated in the benchmark model. The support bars usually need to be designed to connect the different straps of curved anterior-posterior straps of maxillary RPD frameworks. Finally, only circumferential clasps were studied, and bar clasps were not. For Kennedy Class I or II partial edentulism, rest, proximal plate and I bar clasp assembly was often used on the most distal abutment tooth.

4. Conclusions

The effects of laser process parameters, build orientations and metallic powder type on the accuracy of the intaglio surface of maxillary RPD frameworks were investigated. Taguchi design method and ANOVA were used to generate an experimental plan, identify the most significant parameters and find the optimal setting of process parameters that can produce maxillary RPD frameworks which have the most accurate intaglio surface. Based on the findings of this *in vitro* study, the following conclusions were drawn:

- The accuracy of the intaglio surface of maxillary RPD frameworks can be improved by adjusting SLM process parameters. Of SLM parameters, the build orientation had the most effects, the metallic powder type had the second most effects and laser process parameters had the least effects.
- The maxillary RPD framework built at a lower orientation angle had a more accurate intaglio surface than the one built at a higher orientation angle. Almost no support is generated on intaglio surfaces of proximal plates, and supports were generated on only the margin of intaglio surfaces of rests when a maxillary RPD framework was built horizontally. Besides, the deformation of the major connector of a maxillary RPD framework was reduced when built at a lower orientation angle.
- Both clasps and the major connector of a CP Ti or Ti–6Al–4V maxillary RPD frameworks had a more accurate intaglio surface than those of the Co–Cr one. Because CP Ti and Ti–6Al–4V maxillary RPD frameworks had a lower temperature gradient in the bulk volume during building due to the lower thermal conductivity of Ti than Co and Cr.
- The maxillary RPD framework built with a higher infill scan speed and lower infill laser power had a more accurate intaglio surface than the one built with other levels of these two process parameters. A low linear energy density helped to reduce the deformation of clasps of maxillary RPD frameworks.

References

Chen, H., Li, H., Zhao, Y., Zhang, X., Wang, Y. and Lyu, P. (2019), "Adaptation of removable partial denture frameworks fabricated by selective laser melting", *The Journal of Prosthetic Dentistry*, Vol. 122 No. 3, pp. 316-324.

Elsayed, M., Ghazy, M., Youssef, Y. and Essa, K. (2019), "Optimization of SLM process parameters for Ti6Al4V medical implants", *Rapid Prototyping Journal*, Vol. 25 No. 3, pp. 433-447.

Gong, H., Rafi, K., Gu, H., Starr, T. and Stucker, B. (2014), "Analysis of defect generation in Ti–6Al–4V parts made using powder bed fusion additive manufacturing processes", *Additive Manufacturing*, Vols 1/4, pp. 87-98.

Hwang, S., An, S., Robles, U. and Rumpf, R.C. (2021), "Process parameter optimization for removable partial denture frameworks manufactured by selective laser melting", *The Journal of Prosthetic Dentistry*, doi: 10.1016/j.prosdent.2021.04.021.

Kajima, Y., Takaichi, A., Nakamoto, T., Kimura, T., Kittikundecha, N., Tsutsumi, Y., *et al.* (2018), "Effect of adding support structures for overhanging part on fatigue strength in selective laser melting", *Journal of the Mechanical Behavior of Biomedical Materials*, Vol. 78, pp. 1-9.

Le Roux, S., Salem, M. and Hor, A. (2018), "Improvement of the bridge curvature method to assess residual stresses in selective laser melting", *Additive Manufacturing*, Vol. 22, pp. 320-329.

Lee, J.-W., Park, J.-M., Park, E.-J., Heo, S.-J., Koak, J.-Y. and Kim, S.-K. (2017), "Accuracy of a digital removable partial denture fabricated by casting a rapid prototyped pattern: a clinical study", *The Journal of Prosthetic Dentistry*, Vol. 118 No. 4, pp. 468-474.

Li, L. and Sun, S. (2011), *Manual of Physical Properties of Metallic Materials*, China Machine Press, Beijing.

Pal, S., Kokol, V., Gubeljak, N., Hadzistevic, M., Hudak, R. and Drstvensek, I. (2019), "Dimensional errors in selective laser melting products related to different orientations and processing parameters", *Materiali in Tehnologije*, Vol. 53 No. 4, pp. 551-558.

Sakaguchi, R.L., Ferracane, J.L. and Powers, J.M. (2019), *Craig's Restorative Dental Materials*, Elsevier, St. Louis, MO.

Simchi, A. (2006), "Direct laser sintering of metal powders: mechanism, kinetics and microstructural features", *Materials Science and Engineering: A*, Vol. 428 Nos 1/2, pp. 148-158.

Soltanzadeh, P., Suprono, M.S., Kattadiyil, M.T., Goodacre, C. and Gregorius, W. (2019), "An in vitro investigation of accuracy and fit of conventional and CAD/CAM removable partial denture frameworks", *Journal of Prosthodontics*, Vol. 28 No. 5, pp. 547-555.

Tamimi, F. and Hirayama, H. (2019), *Digital Restorative Dentistry: A Guide to Materials, Equipment, and Clinical Procedures*, Springer International Publishing AG, Cham.

Tan, F., Song, J., Wang, C., Fan, Y. and Dai, H. (2019), "Titanium clasp fabricated by selective laser melting, CNC milling, and conventional casting: a comparative in vitro study", *Journal of Prosthodontic Research*, Vol. 63 No. 1, pp. 58-65.

Tasaka, A., Kato, Y., Odaka, K., Matsunaga, S., Goto, T., Abe, S. and Yamashita, S. (2019), "Accuracy of clasps fabricated with three different CAD/CAM technologies: casting, milling, and selective laser sintering", *The International Journal of Prosthodontics*, Vol. 32 No. 6, pp. 526-529.

Tasaka, A., Shimizu, T., Kato, Y., Okano, H., Ida, Y., Higuchi, S. and Yamashita, S. (2020), "Accuracy of removable partial denture framework fabricated by casting with a 3D printed pattern and selective laser sintering", *Journal of Prosthodontic Research*, Vol. 64 No. 2, pp. 224-230.

Tonelli, L., Fortunato, A. and Ceschini, L. (2020), "CoCr alloy processed by selective laser melting (SLM): effect of laser energy density on microstructure, surface morphology, and hardness", *Journal of Manufacturing Processes*, Vol. 52, pp. 106-119.

Vandenbroucke, B. and Kruth, J.P. (2007), "Selective laser melting of biocompatible metals for rapid manufacturing of medical parts", *Rapid Prototyping Journal*, Vol. 13 No. 4, pp. 196-203.

Wang, Z., Xiao, Z., Tse, Y., Huang, C. and Zhang, W. (2019), "Optimization of processing parameters and establishment of a relationship between microstructure and mechanical properties of SLM titanium alloy", *Optics & Laser Technology*, Vol. 112, pp. 159-167.

Xia, Y., Nei, Z., Yuan, J., Guo, L. and Zhang, Q. (2018), "Process and properties of selective laser melting cobalt chromium alloy", *Applied Laser*, Vol. 38, pp. 902-907.

Xie, W., Zheng, M., Wang, J. and Li, X. (2020), "The effect of build orientation on the microstructure and properties of selective laser melting Ti-6Al-4V for removable partial denture clasps", *The Journal of Prosthetic Dentistry*, Vol. 123 No. 1, pp. 163-172.

Xing, W., Ouyang, D., Li, N. and Liu, L. (2018), "Estimation of residual stress in selective laser melting of a Zr-based amorphous alloy", *Materials*, Vol. 11 No. 8, pp. 1-16.

Ye, H., Ning, J., Li, M., Niu, L., Yang, J., Sun, Y. and Zhou, Y. (2017), "Preliminary clinical application of removable partial denture frameworks fabricated using computer-aided design and rapid prototyping techniques", *The International Journal of Prosthodontics*, Vol. 30 No. 4, pp. 348-353.

Further reading

Calignano, F. (2014), "Design optimization of supports for overhanging structures in aluminum and titanium alloys by selective laser melting", *Materials & Design*, Vol. 64, pp. 203-213.

Corresponding author

Yuchun Sun can be contacted at: kqsyc@bjmu.edu.cn