



Contents lists available at ScienceDirect

The Saudi Dental Journal

journal homepage: www.ksu.edu.sa
www.sciencedirect.com

Original Article

Deformation and retentive forces variations of the additively manufactured cobalt-chromium and titanium alloys dental clasps

Kawkb M. El-Tamimi^a, Dalia A. Bayoumi^b, Rafif Alshenaiber^{c,*}, Ibrahim Aljulyfi^c,
Mohamed M.Z. Ahmed^d, Mohammed E. El-Sayed^a^a Department of Removable Prosthodontics, Faculty of Dentistry, Suez Canal University, 41522 Ismailia, Egypt^b Department of Dental Biomaterials, Faculty of Dentistry, Suez Canal University, 41522 Ismailia, Egypt^c Department of Prosthetic Dental Sciences, College of Dentistry, Prince Sattam Bin Abdulaziz University, AlKharj 16245, Saudi Arabia^d Department of Mechanical Engineering, College of Engineering at Al Kharj, Prince Sattam Bin Abdulaziz University, Al Kharj 11942, Saudi Arabia

ARTICLE INFO

Keywords:

Additive manufacturing
Co-Cr clasps
Ti clasps
Retentive force
Removable partial denture

ABSTRACT

This in vitro study aimed to evaluate the additive manufacturing (AM) of cobalt chromium Co-Cr and titanium Ti alloy clasps for clinical use. After scanning the Ni-Cr die of the first molar, Akers' clasps were designed using computer-aided design/ computer-aided manufacturing (CAD/CAM). The clasps were manufactured from Co-Cr-W dental alloy and Ti-6Al-4V alloy powder using AM machines. Then, they were divided into two groups. The initial retentive force of the clasps was measured using a universal testing machine. Cyclic loading of the clasps was carried out by a specially designed insertion-removal testing apparatus in wet condition up to 5000 cycles. Retentive force was measured at 1000, 2000, 3000, 4000, and 5000 cycles. Moreover, the intaglio surface of each clasp was scanned using the scanner; and superimposition between the pre- and post-cycling clasp files was performed to evaluate deformation after cyclic loading. The fitting surfaces of retentive clasp tips were examined with a scanning electron microscope (SEM). Finally, it has been found that the initial retentive force for the Co-Cr group was 10.81 ± 0.37 N, and for the Ti group was 5.41 ± 0.18 N. Additionally, during the testing periods, both Co-Cr and Ti clasps continued to lose retentive force within the cycles of placement and removal. This effect was more prominent in the Co-Cr than in the Ti clasps. The distances between pre- and post-cycling in the retentive arm were -0.290 ± 0.11 mm and -0.004 ± 0.01 mm in Co-Cr and Ti alloys, respectively, and in the reciprocal arm were -0.072 ± 0.04 mm and -0.032 ± 0.04 mm in Co-Cr and Ti alloys, respectively. The retentive force required to remove the Ti clasps was found to be significantly lower than those required to dislodge the Co-Cr clasps. Co-Cr and Ti clasps lost significant amounts of retentive force from the initial use to the 3.5-year periods of simulated clinical use.

1. Introduction

For over a century, removable partial dentures (RPDs) have been supported, braced, and retained by clasps made from cast dental alloys, including Nickel-chromium (Ni-Cr), (Co-Cr), and Ti (Campbell et al., 2017). However, Co-Cr alloys has been considered the preferred metal for the frameworks of RPDs, despite their restrictions when used for clasps that include distortion and eventual fracture (Campbell et al., 2017; Jiao et al., 2009; Popescu et al., 2017). Titanium is characterized by biocompatibility, outstanding corrosion resistance, high mechanical strength, and adequate weight; therefore, it has been used in the medical

and dental fields (Chen et al., 2020; Ibrahim et al., 2020; Lin et al., 2014; Liu et al., 2017; Ohkubo et al., 2008, 2017; Srimanepong et al., 2004; Takayama et al., 2009). Nevertheless, utilization of Ti in denture frameworks is not widespread due to its common casting errors (Baltag et al., 2002; Eisenburger and Addy, 2002; Watanabe et al., 1997).

The main technique applied for producing metallic dental restorations was conventional casting. However, the advancement in digital technology and the creation of (CAD/CAM) procedures made the marked turning point by bringing about the automated production processes (Van Noort, 2012). Such processes have become recently possible because of the advent of (AM) (Agarwala et al., 1995). To fulfill

* Corresponding author.

E-mail addresses: kowkb_eltamimi@dent.suez.edu.eg (K.M. El-Tamimi), dalia_bayoumi@dent.suez.edu.eg (D.A. Bayoumi), r.alshnaiber@psau.edu.sa (R. Alshenaiber), i.aljulyfi@psau.edu.sa (I. Aljulyfi), moh.ahmed@psau.edu.sa (M.M.Z. Ahmed), mohamed_ezzat@dent.suez.edu.eg (M.E. El-Sayed).<https://doi.org/10.1016/j.sdentj.2024.04.001>

Received 12 November 2023; Received in revised form 1 April 2024; Accepted 15 April 2024

Available online 16 April 2024

1013-9052/© 2024 THE AUTHORS. Published by Elsevier B.V. on behalf of King Saud University. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Table 1

Nominal chemical composition of both Co-Cr (Starbond simple Pulver 30, Scheftner dentistry, Germany) and Ti-6Al-4V (TC4, BLT, China) alloys.

Co-Cr Alloy		Ti-6Al-4V Alloy	
El.	Wt. %	El.	Wt.%
Co	61	Ti	90
Cr	27.5	Al	5.5–6.75
W	8.5	V	3.5–4.5
Si	1.6	Fe	>0.3
C, Fe, Mn	>1%	C	>0.08
		N	>0.05
		H	>0.015
		O	0.08–0.015

the demands of rapid manufacturing (RM) and rapid prototyping (RP) (Kruth et al., 2005), selective laser melting (SLM) has been preferred to make alloys (Van Noort, 2012). Structures with high strength and near full density are produced if the processing parameters are optimized (Jamshidi et al., 2020).

SLM Co-Cr removable partial denture (RPD) framework demonstrated more fit accuracy than that of the conventional casting techniques (Rues et al., 2023; Williams et al., 2006). Numerous investigations also claimed that Co-Cr alloy specimens, made via SLM, outperformed casting specimens in terms of fatigue endurance (Kajima et al., 2016), corrosion resistance (Xin et al., 2014), and biocompatibility (Hedberg et al., 2014). Whether Ti clasps are made via casting, laser melting, or milling, they must be extremely accurate to provide support and retention in clinical settings (Mahmoud, 2007; Saito et al., 2002). In fact, a study by (Tan et al., 2019) investigated the effects of SLS and SLM techniques, and casting on the behavior of commercial pure (CP) Ti clasps. They found no significant differences regarding the accuracy of the inner surface among these processes.

The routine daily procedure of insertion/removal and repetitive clasp bending during mastication movement is supposed to be endured by RPDs frameworks. However, RPDs frameworks may experience persistent deformation or even fatigue failure because of such pressure on the long term (Behr et al., 2012; Mahmoud, 2007 a; Mahmoud et al., 2007b; Saito et al., 2002; Tan et al., 2019). One of the properties attached to titanium, which has created interest in RPDs, is its low modulus of elasticity that allows positioning the clasps in more cervical, and thus more esthetic areas, without producing excessive loads on the abutment teeth (Jang et al., 2001; Shimpo, 2008). The retentive forces and deformation of the casted and machined Co-Cr and Ti clasps were examined individually in previous studies. However, there is currently limited information available on comparing the retentive force and deformation of SLM clasps manufactured from Co-Cr and Ti alloys.

Therefore, this *in vitro* study examined the initial retentive force, variations in retentive force up to 5000 insertion/removal cycles, and deformation of both SLM Co-Cr and Ti alloys clasps. The null hypothesis is that there is no difference in retentive force and deformation between SLM clasps made from Co-Cr or Ti alloys.

2. Materials and methods

The nominal composition of the two alloys provided by the manufacturer is listed in (Table1).

2.1. Sample size calculation

The computation of the sample size was adopted from earlier studies published on measuring retentive forces of clasps (Arda and Arian, 2005; Jayesh et al., 2014), and performed using G*Power version 3.1.9.2 (Faul et al., 2007). The obtained sample size is found to be 10 samples for each group.

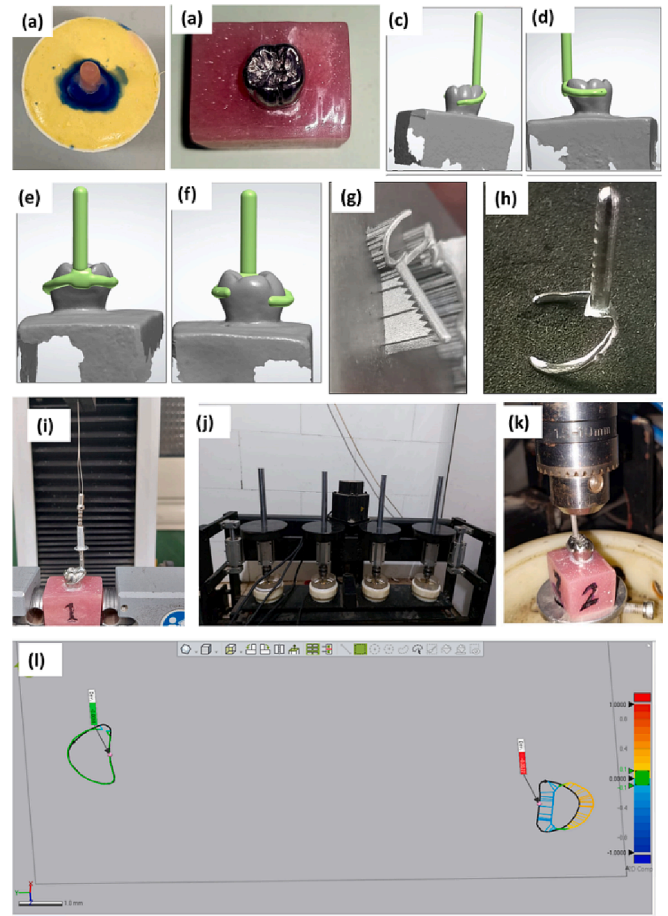


Fig. 1. (a) Top view of Polyether mold and wax pattern; (b) Top view of finished metal die in acrylic block; (c) Buccal; (d) Lingual; (e) Mesial; (f) Distal views of the CAD designed Akers clasps; (g) As printed and before finishing; (h) Finished clasp; (i) The universal testing machine used in the retentive forces test with the clasp and die assembly; (j) Chewing simulator setup; (k) Positioning of the clasp on the die; and (l) Superimposition between the pre- and post-cycling clasps.

2.2. Die fabrication

An artificial mandibular first molar (KaVo, Biberach, Germany) with a buccal undercut of 0.50 mm was selected for this investigation. The occlusal rest was prepared using the following standards in accordance with the support principles: rounded triangle shape measuring 2.5 mm in length, 2.5 mm in width, and 2 mm in depth, positioned mesially at lower-than-90-degree angle created by the minor connector and the occlusal rest. Furthermore, a 4 mm mesial guiding plane was constructed using a handpiece fastened to the vertical spindle of the surveyor (Nouvag AG CH-9403 Goldach) to standardize the insertion path.

A polyether impression material (Impregum Penta; 3M ESPE, USA) was used to duplicate the chosen molar. The die was made by pouring heated liquid wax (Crowax, Renfert GmbH, Hilzingen, Germany) into the polyether mold (Fig. 1a). Then, Ni Cr alloy (4 all Ivoclar) was utilized to cast the die. After the die was prepared, the parallelism of guiding planes was assessed. Finally, the metal die was embedded in auto-polymerizing acrylic resin (Acrostone, Cairo, Egypt) using custom-made copper holders, with a diameter of 15 mm and 20 mm in height, as shown in (Fig. 1b).

2.3. Clasp design

A dental laboratory scanner (Scanlab, Galvo Scanner, Germany) was

Table 2
The retentive forces of Co-Cr and Ti studied samples presented via mean, standard deviation, and percentage of change.

Number of cycles	Co-Cr				Ti				p-value
	Mean	SD	DMRTs	%Change	Mean	SD	DMRTs	%Change	
0	10.81	0.37	A	–	5.41	0.18	F	–	0.050*
1000	9.74	0.27	B	–9.8746	4.90	0.10	F	–9.47	0.103 ns
2000	8.70	0.52	C	–9.6563	4.21	0.37	G	–12.73	<0.001***
3000	7.62	0.19	D	–9.9893	3.38	0.88	H	–15.35	0.016*
4000	6.60	0.55	E	–9.4343	2.84	0.11	I	–9.981	<0.001***
5000	5.11	0.51	F	–13.78	2.51	0.21	I	–6.186	0.071 ns
p-value	<0.001***				<0.001***				

*, **, ***, significant at $p < 0.05$, <0.01 , and <0.001 ; NS nonsignificant at $p > 0.05$.

used to digitally scan the die. Akers’ clasps were designed using (CAD) software (3Shape, Copenhagen, Denmark) on a scanned die. The reciprocal arm was placed on the lingual tooth surface, while the retentive arm was placed on the buccal tooth surface. As shown in (Fig. 1c, d, e, and f), the retentive arm length is 8 mm; retentive arm shoulder width is 1.8 mm; tip width is 1.5 mm; retentive arm shoulder thickness is 1.3 mm; and tip thickness is 1.1 mm, respectively. To maintain appropriate long-term retentive force, the retentive arms were placed in the 1/2 undercut area of the abutment tooth (Shimpo, 2008); and the clasp tips were placed 0.5 mm at undercut depth. Eventually, the design was saved as an STL file.

2.4. Clasp printing

Using a 3D printer (Vulcanech VM120, Germany), the specimens were processed to produce Co-Cr clasps using 10 to 30 μm of Co-Cr-W dental alloy powder type 5 (Starbond simple Pulver 30, Scheftner dentistry, Germany). The powder alloy was melted to produce the pre-designed clasp by tracing high-energy laser beams across a powder bed of tightly packed powdered material. The printer has the following parameters: layer thickness of 0.02 mm; melting speed of 1100–1200 mm/s; and laser spot diameter of 0.08–0.1 mm. at 1150C, a homogenization process lasted for 30 min.

Ti grade 5 Ti-6Al-4V powder (TC4, BLT, China) and a 3D printer (A160 BLT, China) were used to construct the Ti specimens. The SLM specifications reported by the manufacturer were as follows: particle size between 15 to 45 μm ; 25–100 μm of powder layer thickness; 200 W of fiber laser; focus diameter approximately 75 μm ; working atmosphere of argon; no pre-heating process; hatch distance of 0.105 mm; check-board hatch style; scan speed of 1250 mm/s; offset to original contour of 0.0825 mm; and power supply of 1.5 kW.

The as-printed clasp is shown in (Fig. 1g). It should be noted that there are no print supports on the fitting surface of the clasp arms or clasp tips. After printing, supports and fins were cut and removed, as clarified in (Fig. 1h).

2.5. Initial retentive forces measuring

The clasp and the die were fixed on the universal testing machine (Instron model 3345 universal testing machine), as shown in (Fig. 1i). The calculated data were recorded using computer software (Blue Hill Universal Instron England). Furthermore, the tensile force mode was applied at a crosshead speed of 10 mm/min. The retentive force was measured as the maximum load required for totally removing the clasp from the die. Initial retentive forces (N) were calculated by averaging the values of retentive forces for the first 15 times.

2.6. Changes in retentive forces

To perform the fatigue test, through removal and insertion cycling, ROBOTA chewing simulator integrated with thermo-cyclic protocol operated on servo-motor (Model ACH-09075DC-T, Ad- Tech-

Technology co., LTD., Germany) was used (Fig. 1j) (El-Tamimi et al., 2022). The machine allows the placement of the clasp to its pre-determined terminal position, and its subsequent removal from the die, which stimulates the placement and removal of the clasp. Next, each clasp was placed on the die and fixed to the upper part of a machine with a vertical rod. The test conditions were maintained at room temperature and a wet environment using artificial saliva. The clasp was placed on the die under a load of 1.0 kg, and then removed from the die at a crosshead speed of 950 mm/min every time. These insertion/removal motions were repeated up to 5000 times (Fig. 1k). A total of 5000 cycles of vertical movements repetition, parallel to the longest axis of the tooth and to the axis of insertion of the clasps, were performed to simulate 3.5 years of usage of the RPD, as if the patient performs four cycles of insertion and removal of the RPD per day (Anes et al., 2023).

In addition, tensile testing was performed using the universal testing machine after 1000, 2000, 3000, and up to 5000 insertions/removal times. Variations in retentive forces were measured by the mean value of 15 tensile tests each time. Moreover, the decreased retentive forces for 5000 cycles were calculated by subtracting the retentive force of 5000 cycles from the initial retentive force.

2.7. Deformation measurements

To assess the deformation of both the retentive and reciprocal clasp arms of each clasp, all completed clasps were lightly coated with anti-glare spray (D-Scan, Dentify GmbH, Schenffelstr, Germany). The intaglio surface of each clasp was scanned using the scanner, creating an STL file for the intaglio surface of each clasp (pre). Next, the post-mechanical testing clasps were scanned. Using special 3D inspection and metrology software (Geomagic Control X; 3D systems), superimposition between the pre- and post-cycling clasp files was performed using the initial alignment and the best-fit algorithm to evaluate deformation after cyclic loading. A 2D comparison was carried out between the studied groups, followed by recording the deviation labels between the pre- and the post-cycling clasp files (Fig. 1l).

2.8. SEM investigation

The fitting surfaces of the retentive clasp tips were examined by (SEM) model Prisma E (Thermo Fisher Company) attached to EDX unit to assess surface topography. SEM examination of each sample was operated at an accelerating voltage of 30 KV. The examination of the clasps was done at different magnifications. After that, representative images of different samples were selected.

2.9. Statistical analysis

Data was collected and handled using Microsoft Excel 2016. The normality of data was checked using the Shapiro-Wilk normality test to determine whether the data are parametric or nonparametric. The difference between Ti and Co-Cr alloys at each point was checked using independent samples *t*-test at 0.05 level. The difference between points

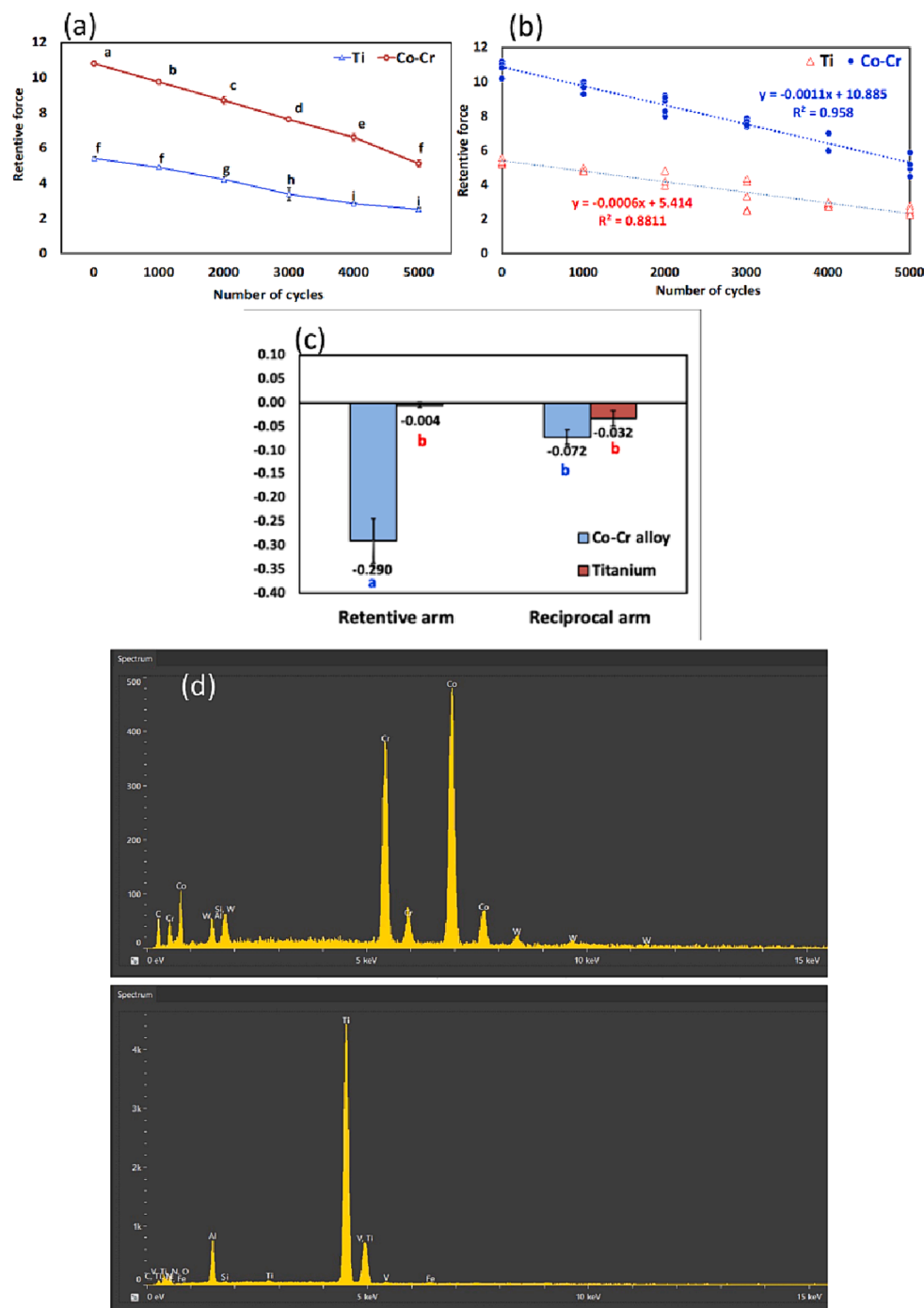


Fig. 2. (a) The retentive forces of both Co-Cr and Ti alloys studied samples presented via mean and standard error. Points with different letters are significantly different according to DMRTs; (b) Regression trendline presenting the interrelationship between cyclic loading and retentive force of both Co-Cr and Ti alloys; (c) Deviation distance in mm in retentive and reciprocal arm between pre- and post-cyclic loading in Co-Cr alloy versus Ti alloy; and (d) EDS analysis of Co-Cr and Ti-6Al-4T clasps.

was assessed using a paired samples *t*-test. One-way ANOVA was also applied to evaluate the difference between different time points. Duncan's Multiple Range post hoc test was used to further compare subgroups. Furthermore, linear correlation and simple linear regression were used to assess the relationship between time points and deviation. Data analysis was performed using IBM SPSS version 29.

3. Results

3.1. Initial retentive forces

The initial retentive forces of the clasps are displayed in (Table 2). The initial retentive forces are 10.81 ± 0.37 N for the Co-Cr group, and 5.41 ± 0.18 N for the Ti group. The initial retentive forces of Co-Cr are significantly greater than those of Ti.

Table 3
Deviation distance in mm in retentive and reciprocal arms between pre- and post-cycling in Co-Cr alloy versus Ti alloy.

Deviation distance (mm)	Pre- and post-cycling		p-value
	Co-Cr alloy	Ti	
Retentive arm	−0.290 ± 0.11 a	−0.004 ± 0.01b	0.001***
Reciprocal arm	−0.072 ± 0.04b	−0.032 ± 0.04b	0.224 ns
p-value	0.018*	0.033*	

*, **, ***, significant at $p < 0.05$, < 0.01 , and < 0.001 ; NS nonsignificant at $p > 0.05$.

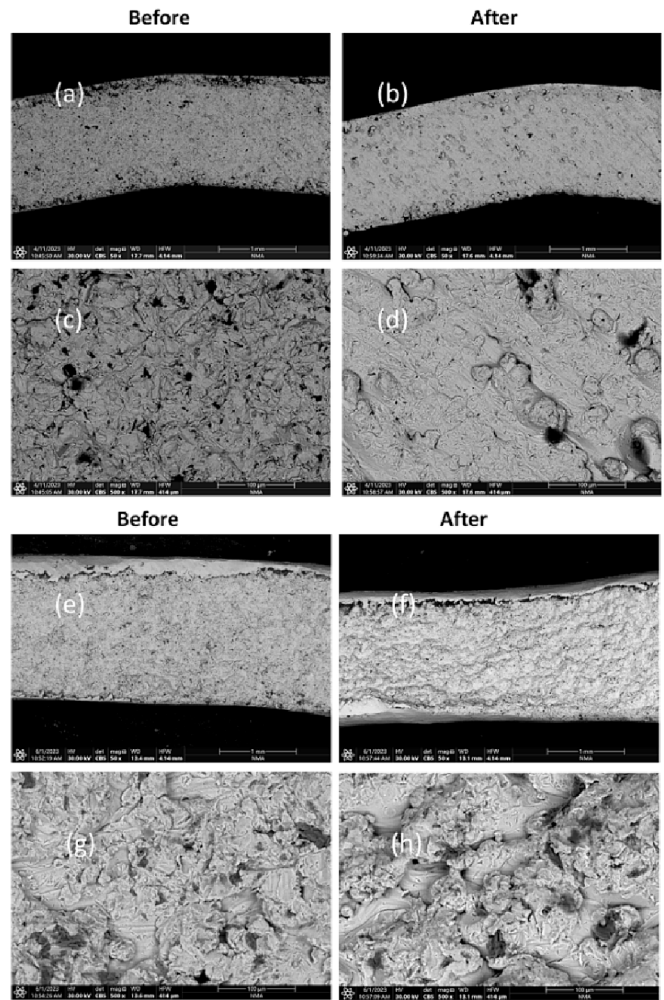


Fig. 3. (a, b, c, d): Different magnifications SEM micrographs of the inner surface of SLM Co-Cr before (left) and after (right) cyclic loading; (e, f, g, h): Different magnification SEM micrographs of the inner surface of SLM Ti-6Al-4 alloy clasp before (left) and after (right) cyclic loading.

3.2. Changes in retentive forces

The retentive forces of both the Co-Cr and Ti alloys studied samples are presented via mean and standard error in Table 2 and (Fig. 2 a and b). The retentive forces of Co-Cr at 0, 1000, 2000, 3000, 4000, and 5000 have recorded an average of 10.81 ± 0.37 , 9.74 ± 0.27 , 8.70 ± 0.52 , 7.62 ± 0.19 , 6.60 ± 0.55 , and 5.11 ± 0.51 , respectively. The change between the time points is significant at 0, 2000, 3000, and 4000 cycles. On the other hand, it is non-significant at 1000 and 5000 cycles, as revealed by one-way analysis of variance ($p < 0.001$). The retentive forces of Ti at 0, 1000, 2000, 3000, 4000, and 5000

cycles have recorded an average of 5.41 ± 0.18 , 4.90 ± 0.10 , 4.21 ± 0.37 , 3.38 ± 0.88 , 2.84 ± 0.11 , and 2.51 ± 0.21 , respectively. The change between the time points is highly significant, as revealed by one-way analysis of variance ($p < 0.001$). In addition, means and points with different letters are significantly different according to Duncan's Multiple Range Test (DMRTs).

3.3. Deformation results

As shown in (Table 3 and Fig. 2c), the distance in mm between pre- and post-cycling in the retentive arm recorded -0.290 ± 0.11 and -0.004 ± 0.01 in Co-Cr and Ti alloys, respectively. The difference between Co-Cr and Ti alloys in the retentive arm is highly significant, as revealed by the independent samples *t*-test. The distance in mm between pre- and post-cycling in the reciprocal arm recorded -0.072 ± 0.04 and -0.032 ± 0.04 in Co-Cr and Ti alloys, respectively. The difference between Co-Cr and Ti alloys regarding the reciprocal arm is non-significant, as reflected by the independent samples *t*-test. The difference in Co-Cr alloy between the retentive and reciprocal arms is significant, as revealed by the *t*-test (0.018*). The difference in Ti alloy between retentive and reciprocal arms is significant, as shown by the independent samples *t*-test (0.033*).

3.4. Surface morphology

The surface morphology of the dental clasps has been investigated before and after cycling loading using SEM. (Fig. 3) shows different magnification SEM micrographs of the Co-Cr and Ti-6Al-4V clasps before and after cycling. The SEM micrographs presented in (Fig. 3 a, b, c, d) are of Co-Cr clasps before and after cyclic loading. Besides, (Fig. 3 e, f, g, h) of Ti-6Al-4V show the features of the fabricated AM parts, where the surfaces look rough, and apparent irregularities can be observed. The SEM images of the inner surfaces of the Co-Cr clasps show smoother surfaces and less irregularities, in comparison to the Ti clasps (Fig. 3). Ti showed a more granular surface with irregular features (Fig. 3e, f, g, h). Wear streaks have been found after cyclic loading, which is more obvious in Co-Cr images because of their smoother surfaces (Fig. 3a, b, c, d). EDS analysis of both alloys is presented in (Fig. 2d), where the nominal chemical composition of the alloys can be confirmed.

4. Discussion

SLM has received remarkable attention regarding producing dental prostheses. In this study, RPD clasps were fabricated by using SLM with Co-Cr and Ti alloys. Retentive forces and deformation were evaluated before and after 5000 cycles of insertion and removal, which simulated 3.5 years of clinical use. There were differences in retentive force and deformation between SLM clasps made from Co-Cr and Ti alloys. Thus, the null hypothesis was rejected. In addition, higher forces were needed to remove the Co-Cr clasps from their dies, in comparison to the Ti clasps. The initial retentive force of the Co-Cr group was 10.81 ± 0.37 N, while the initial retentive force of the Ti group was 5.41 ± 0.18 N. This agrees with previous studies which reported that the average retentive forces were 12.18 ± 3.17 N and 6.68 ± 2.15 N. for the cast Co-Cr alloy and Ti clasps, respectively (Jayesh et al., 2014; Takahashi et al., 2020). These results are due to the high stiffness of the Co-Cr alloy compared to the Ti alloy. During the testing period, both Ti and Co-Cr clasps continued to lose retentive force within the cycles of placement and removal. This effect was more prominent in Co-Cr than in Ti clasps, represented by higher regression in (Fig. 2b); comparable results were observed (Kim et al., 2004). These findings are consistent with the clinical observation that Co-Cr clasps need adjustment at follow-up appointments. The permanent deformation of the clasp arm may explain the decline in the

retentive force. That is relevant to the tendency of Co-Cr clasps to undergo plastic deformation after repeated seating and removal, which is associated with their complex microstructure and elemental composition (Anusavice et al., 2012; Tonelli et al., 2023). These results coincide with deformation measurements in the present study; the retentive arm of the Co-Cr clasps produced significantly more deformation than Ti clasps. Similar results were found in another study (Mahmoud et al., 2005 a). These findings demonstrated an advantage of the Ti clasp that reduced permanent deformation in case of accidental overloading, which could happen clinically in case of using a different insertion path.

Moreover, SEM images of the Ti samples revealed more irregularities than the Co-Cr samples, which could be related to the characteristics of the powder used for 3D printing. Surface morphology and microstructures were affected by processing parameters such as laser power, scan spacing laser speed, and layer thickness (Tonelli et al., 2023). Fatigue strength and surface roughness are affected by building direction (Kajima et al., 2016). Powder of titanium and cobalt-chromium alloys showed dissimilar physical and chemical properties, which would require different printing parameter settings to produce dense structures. Furthermore, even with the same material, the optimum parameters might be different from one machine to another (Ghasemi-Tabasi et al., 2020). However, the lowest measured retentive force (2.5 N) represented an acceptable amount of retention (Peng et al., 2020). Therefore, further research on the clinical efficacy of the SLM Co-Cr and Ti clasps is needed.

This study had a limitation that the two materials, Ti and Co-Cr alloys, were printed using different machines. To verify the findings of the current study, the authors advise utilizing the same printer whenever feasible in the future.

5. Conclusions

Based on the conducted study on the deformation and retentive forces of the Co-Cr and Ti6Al-4 V clasps, the following conclusions about SLM clasps can be drawn: First, the mean retentive force required to remove the Ti clasps was found to be remarkably lower ($P < 0.001$) than that required for the removal of the Co-Cr clasps. Second, Co-Cr and Ti clasps lost significant amounts of retentive force from the initial to the 3.5-year periods of simulated clinical use ($P < 0.001$). Additionally, Co-Cr showed a higher loss in retentive force than Ti. Third, Co-Cr clasps reflected notable deformation after 3.5 years of simulated clinical use. In contrast, Ti clasps did not show significant deformation after 3.5 years of simulated clinical use.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was supported by funding from Prince Sattam bin Abdulaziz University, project number (PSAU/2023/R/1445).

References

- Agarwala, David, Bourell, Joseph, Beaman, Harris, Marcus, M., Barlow, J., Haase, P., Weiss, W., Prabhu, G., Manriquez-Frayre, J., Zong, G., Wu, Y., Tran, N., Lee, I., Das, S., McWilliams, J., Hysinger, C., Nelson, J., Subramanian, P., Vail, N. (1995). Introduction Direct selective laser sintering of metals. *Rapid Prototyping J.*, 1, 26–36.
- Anes, V., Neves, C.B., Bostan, V., Gonçalves, S.B., Reis, L., 2023. Evaluation of the retentive forces from removable partial denture clasps manufactured by the digital method. *Appl. Sci. (Switzerland)* 13 (14). <https://doi.org/10.3390/app13148072>.
- Anusavice, K.J., Shen, C., Rawls, H.R., 2012. *Phillips' science of dental materials*, 12th ed. Elsevier Health Sciences.
- Arda, T., Arikian, A., n.d. An in vitro comparison of retentive force and deformation of acetate resin and cobalt-chromium clasps.
- Baltag, I., Watanabe, K., Kusakari, H., Miyakawa, O., 2002. Internal porosity of cast titanium removable partial dentures: Influence of sprue direction on porosity in circumferential clasps of a clinical framework design. *J. Prosthet. Dent.* 88 (2), 151–158. <https://doi.org/10.1067/MPR.2002.127400>.
- Behr, M., Zeman, F., Math, D., Passauer, T., 2012. Clinical performance of cast clasp-retained removable. *Int. J. Prosthodont.* 25 (2).
- Campbell, S.D., Cooper, L., Craddock, H., Hyde, T.P., Nattress, B., Pavitt, S.H., Seymour, D.W., 2017. Removable partial dentures: The clinical need for innovation. In: *Journal of Prosthetic Dentistry*, Vol. 118, Issue 3, Mosby Inc., pp. 273–280, DOI: 10.1016/j.prosdent.2017.01.008.
- Chen, L.Y., Cui, Y.W., Zhang, L.C., 2020. Recent development in beta titanium alloys for biomedical applications. *Metals* 10 (9). <https://doi.org/10.3390/met10091139>.
- Eisenburger, M., Addy, M., 2002. Radiological examination of dental castings - a review of the method and comparisons of the equipment. *J. Oral Rehabil.* 29 (7), 609–614. <https://doi.org/10.1046/j.1365-2842.2002.00938.x>.
- El-Tamimi, K.M., Bayoumi, D.A., Ahmed, M.M.Z., Albaijan, I., El-Sayed, M.E., 2022. The effect of salinized nano ZrO₂ particles on the microstructure, hardness, and wear behavior of acrylic denture tooth nanocomposite. *Polymers* 14 (2). <https://doi.org/10.3390/polym14020302>.
- Faul, F., Erdfelder, E., Lang, A.-G., Buchner, A., 2007. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav. Res. Methods* 39 (2), 175–191. <https://doi.org/10.3758/BF03193146>.
- Ghasemi-Tabasi, H., Jhabvala, J., Boillat, E., Ivas, T., Drissi-Daoudi, R., Logé, R.E., 2020. An effective rule for translating optimal selective laser melting processing parameters from one material to another. *Addit. Manuf.* 36 <https://doi.org/10.1016/j.addma.2020.101496>.
- Hedberg, Y.S., Qian, B., Shen, Z., Virtanen, S., Odneval Wallinder, I., 2014. In vitro biocompatibility of CoCrMo dental alloys fabricated by selective laser melting. *Dent. Mater.* 30 (5), 525–534. <https://doi.org/10.1016/j.dental.2014.02.008>.
- Ibrahim, S.A., Selem, M.M., Ahmed, H.M., Hannora, A.E., 2020. Phase stability of mechanically alloyed Ti-Fe-Al alloys. *IOP Conference Series: Materials Science and Engineering* 973 (1). <https://doi.org/10.1088/1757-899X/973/1/012025>.
- Jamshidi, P., Aristizabal, M., Kong, W., Villapun, V., Cox, S.C., Grover, L.M., Attallah, M. M., 2020. Selective laser melting of ti-6al-4v: the impact of post-processing on the tensile, fatigue and biological properties for medical implant applications. *Materials* 13 (12), 1–16. <https://doi.org/10.3390/ma13122813>.
- Jang, K.S., Youn, S.J., Kim, Y.S., 2001. Comparison of castability and surface roughness of commercially pure titanium and cobalt-chromium denture frameworks. *J. Prosthet. Dent.* 86 (1) <https://doi.org/10.1067/mp.2001.116168>.
- Jayesh, R., Jasheel, A., Nayar, S., 2014. Comparative evaluation of retention force and porosity for titanium and cobalt-chromium clasp assemblies-an in vitro study. *World Appl. Sci. J.* 30 (6), 757–761. <https://doi.org/10.5829/idosi.wasj.2014.30.06.82249>.
- Jiao, T., Chang, T., Caputo, A.A., 2009. Load transfer characteristics of unilateral distal extension removable partial dentures with polyacetal resin supporting components. *Aust. Dent. J.* 54 (1), 31–37. <https://doi.org/10.1111/j.1834-7819.2008.01085.x>.
- Kajima, Y., Takaichi, A., Nakamoto, T., Kimura, T., Yogo, Y., Ashida, M., Doi, H., Nomura, N., Takahashi, H., Hanawa, T., Wakabayashi, N., 2016. Fatigue strength of Co-Cr-Mo alloy clasps prepared by selective laser melting. *J. Mech. Behav. Biomed. Mater.* 59, 446–458. <https://doi.org/10.1016/j.jmbbm.2016.02.032>.
- Kim, D., Park, C., Yi, Y., Cho, L., 2004. Comparison of cast Ti-Ni alloy clasp retention with conventional removable partial denture clasps. *J. Prosthet. Dent.* 91 (4) <https://doi.org/10.1016/j.prosdent.2004.02.015>.
- Kruth, J.P., Merckel, P., Van Vaerenbergh, J., Froyen, L., Rombouts, M., 2005. Binding mechanisms in selective laser sintering and selective laser melting. *Rapid Prototyping J.* 11 (1), 26–36. <https://doi.org/10.1108/13552540510573365>.
- Lin, W.S., Metz, M.J., Pollini, A., Ntounis, A., Morton, D., 2014. Digital data acquisition for a CAD/CAM-fabricated titanium framework and zirconium oxide restorations for an implant-supported fixed complete dental prosthesis. *J. Prosthet. Dent.* 112 (6) <https://doi.org/10.1016/j.prosdent.2014.06.012>.
- Liu, X., Chen, S., Tsoi, J.K.H., Matinlinna, J.P., 2017. Binary titanium alloys as dental implant materials-a review. In: *Regenerative Biomaterials*, Vol. 4, Issue 5, Oxford University Press, pp. 315–323, DOI: 10.1093/rb/rbx027.
- Mahmoud, A., 2007. Pre-overloading to extend fatigue life of cast clasps. *J. Dent. Res.* 86 (9), 868–872. <https://doi.org/10.1177/154405910708600912>.
- Mahmoud, A., Wakabayashi, N., Takahashi, H., Ohyama, T., 2005. Deflection fatigue of Ti-6Al-7Nb, Co-Cr, and gold alloy cast clasps. *J. Prosthet. Dent.* 93 (2), 183–188. <https://doi.org/10.1016/j.prosdent.2004.11.011>.
- Mahmoud, A., Wakabayashi, N., Takahashi, H., 2007. Prediction of permanent deformation in cast clasps for denture prostheses using a validated nonlinear finite element model. *Dent. Mater.* 23 (3), 317–324. <https://doi.org/10.1016/j.dental.2005.10.012>.
- Ohkubo, C., Sato, Y., Nishiyama, Y., Suzuki, Y., 2017. Titanium removable denture based on a one-metal rehabilitation concept. In: *Dental Materials Journal*, Vol. 36, Issue 5, Japanese Society for Dental Materials and Devices, pp. 517–523, DOI: 10.4012/dmj.2017-137.
- Ohkubo, C., Hanatani, S., Hosoi, T., 2008. Present status of titanium removable dentures - a review of the literature. *J. Oral Rehabil.* 35 (9), 706–714. <https://doi.org/10.1111/j.1365-2842.2007.01821.x>.
- Peng, T.-Y., Ogawa, Y., Akebono, H., Iwaguro, S., Sugeta, A., Shimoe, S., 2020. Finite-element analysis and optimization of the mechanical properties of polyetheretherketone (PEEK) clasps for removable partial dentures. *J. Prosthodont. Res.* 64 (3), 250–256. <https://doi.org/10.1016/j.jpor.2019.07.012>.

- Popescu, I.N., Vidu, R., Bratu, V., 2017. Porous metallic biomaterials processing (review) part 1: compaction, sintering behavior, properties and medical applications. *Sci. Bull. Valahia University - Materials and Mechanics* 15 (13), 28–40. <https://doi.org/10.1515/bsmm-2017-0015>.
- Rues, S., Tasaka, A., Fleckenstein, I., Yamashita, S., Rammelsberg, P., Boehm, S., Schwindling, F.S., 2023. Fit and retention of cobalt-chromium removable partial denture frameworks fabricated with selective laser melting. *J. Functional Biomater.* 14 (8) <https://doi.org/10.3390/jfb14080416>.
- Saito, M., Notani, K., Miura, Y., Kawasaki, T., 2002. Complications and failures in removable partial dentures: A clinical evaluation. *J. Oral Rehabil.* 29 (7), 627–633. <https://doi.org/10.1046/j.1365-2842.2002.00898.x>.
- Shimpo, H., 2008. Effect of arm design and chemical polishing on retentive force of cast titanium alloy clasps. *J. Prosthodont.* 17 (4), 300–307. <https://doi.org/10.1111/j.1532-849X.2007.00289.x>.
- Srimaneepong, V., Yoneyama, T., Wakabayashi, N., Kobayashi, E., Hanawa, T., Doi, H., 2004. Deformation properties of Ti-6Al-7Nb alloy castings for removable partial denture frameworks. *Dent. Mater. J.* 23 (4), 497–503. <https://doi.org/10.4012/dmj.23.497>.
- Takahashi, K., Torii, M., Nakata, T., Kawamura, N., Shimpo, H., Ohkubo, C., 2020. Fitness accuracy and retentive forces of additive manufactured titanium clasp. *J. Prosthodont. Res.* 64 (4), 468–477. <https://doi.org/10.1016/j.jpor.2020.01.001>.
- Takayama, Y., Takishin, N., Tsuchida, F., Hosoi, T., 2009. Survey on use of titanium dentures in Tsurumi University Dental Hospital for 11 years. *J. Prosthodont. Res.* 53 (2) <https://doi.org/10.1016/j.jpor.2008.08.011>.
- Tan, F.B., Song, J.L., Wang, C., Fan, Y.B., Dai, H.W., 2019. Titanium clasp fabricated by selective laser melting, CNC milling, and conventional casting: a comparative in vitro study. *J. Prosthodont. Res.* 63 (1), 58–65. <https://doi.org/10.1016/J.JPOR.2018.08.002>.
- Tonelli, L., Ahmed, M.M.Z., Ceschini, L., 2023. A novel heat treatment of the additively manufactured Co28Cr6Mo biomedical alloy and its effects on hardness, microstructure and sliding wear behavior. *Progress in Additive Manufacturing* 8 (2), 313–329. <https://doi.org/10.1007/s40964-022-00334-2>.
- Van Noort, R., 2012. The future of dental devices is digital. In: *Dental Materials*, Vol. 28, Issue 1, Elsevier Inc., pp. 3–12, DOI: [10.1016/j.dental.2011.10.014](https://doi.org/10.1016/j.dental.2011.10.014).
- Watanabe, I., Watkins, J.H., Nakajima, H., Atsuta, M., Okabe, T., 1997. Effect of pressure difference on the quality of titanium casting. *J. Dent. Res.* 76 (3) <https://doi.org/10.1177/00220345970760031001>.
- Williams, R.J., Bibb, R., Eggbeer, D., Collis, J., 2006. Use of CAD/CAM technology to fabricate a removable partial denture framework. *J. Prosthet. Dent.* 96 (2) <https://doi.org/10.1016/j.prosdent.2006.05.029>.
- Xin, X.Z., Chen, J., Xiang, N., Gong, Y., Wei, B., 2014. Surface characteristics and corrosion properties of selective laser melted Co-Cr dental alloy after porcelain firing. *Dent. Mater.* 30 (3), 263–270. <https://doi.org/10.1016/j.dental.2013.11.013>.