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Deformation and retentive force following *in vitro* cyclic fatigue of cobalt-chrome and aryl ketone polymer (AKP) clasps

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ABSTRACT

Objective. To compare the retention force of individual clasps made from cobalt chromium (CoCr) or new aryl ketone polymer (AKP) material, Ultaire^{TM} AKP, following prolonged fatigue testing along ideal and non-ideal paths of removal and to assess 3D deformation of the active and passive clasp tips.

Methods. CoCr and AKP clasps were manufactured in their standard, respective processes, digitally scanned prior to testing, then cycled 15,000 times over an e.max analogue crown in artificial saliva. Retentive load was measured *in situ*, as a function of cycles. Clasps were rescanned to assess deformation and along with their antagonists subjected to SEM to assess localised wear.

Results. Distortion of the CoCr clasps was consistently larger than Ultaire^{TM} AKP clasps, irrespective of removal path. CoCr clasps had significantly higher retentive forces than AKP clasps, for both removal paths. Ultaire^{TM} AKP clasps showed a lower but relatively constant retentive force. The non-ideal path of removal affected retentive forces for both clasp materials. SEM showed localised removal of glaze for e.max crowns used with CoCr clasps.

Significance. Ultaire^{TM} AKP clasps showed significantly less permanent deformation and lower retentive force than CoCr clasps. Unlike CoCr, the Ultaire^{TM} AKP clasps did not work harden, nor had as large a reduction in retentive force and accompanying permanent deformation; the retentive force for the Ultaire^{TM} AKP clasps was consistent over 15,000 cycles of fatigue mimicking prolonged clinical use. The AKP material was more robust; showing minimal deformation even in non-ideal paths of removal, as many patients would routinely use.

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1. Introduction

Removable partial dentures (RPD) are widely used to replace missing teeth and lost alveolar tissue thereby restoring aesthetics and function. Two of the most common types of removable partial denture are ones made entirely of acrylic or where the replacement teeth are attached to an underlying metal framework. In this latter design, direct retention is provided by the use of clasps that engage undercuts on abutment teeth. Cobalt chrome (CoCr) is currently perceived as the most popular material for removable partial denture frameworks. However, the material has particular limitations when used for clasps, including work hardening, distortion and eventual fracture of clasp arms when they are stressed beyond their elastic limit [1–6]. In order to have clasps capable of yielding sufficient retentive force, cobalt chrome clasps have to work close to the elastic limit of the material. Thus, it is important that cobalt chrome dentures are designed with a single path of insertion/removal to ensure that the clasp arms only move over the 'correct' depth of undercut (bulbosity) on the abutment teeth. If the clasps are placed in too deep an undercut on the teeth, they may distort or fracture and the abutment teeth may be subjected to excessive forces. Similarly, if the path of displacement of the denture is different to the designed path of insertion/ removal (for instance if the patient drops one side of the denture before the other side when inserting the denture) then the depth of undercut (the amount of bulbosity) the clasp arm has to move over is increased. Moving a denture out on a path other than that path specifically designed by the dentist at manufacture will work harden, distort and eventually fracture cobalt chrome clasp arms.

Although there has been prior scientific literature on *in vitro* investigations of cobalt chrome and titanium denture clasp flexibility, they have centred on a single, ideal path of removal [7–9]. In this context, the current literature fails to shed light on the mechanism of failure of cobalt chrome clasps in real life.

High performance polymeric materials such as the recently introduced aryl ketone polymer (AKP) have the potential to engage and dissengage undercuts without being stressed beyond their elastic limit. This opens up the possibility of prolonged and improved retention (over many years) for the denture frameworks constructed from these new materials.

In vitro repeated removal and insertion of a single clasp over an analogue allows simulation of many years of use. The testing of clasps in this way allows comparison of the potential degradation of that retention over time. It also allows for a comparison of any permanent distortion of the clasps following prolonged cyclic testing, which would be expected to have a detrimental effect on clasp retention.

Standard protocols for previous investigations into the *in vitro* testing of clasp designs allow repeated insertion and removal of the clasps along an ideal path of insertion which is normally parallel to the long axis of the tooth [10–12]. Typically, the insertion and removal is repeated to simulate 3–5 years of use in a wear or masticatory simulator and removal forces recorded at nominal time intervals, *e.g.* every 1000 or 1500 cycles either directly or through samples being placed in a Universal Testing Machine and the retentive force measured before the tooth analogue/clasp assembly is fatigued further. Retentive force required to remove the clasp assembly at the start and end of the aging process is the normal primary outcome; little attempt has been made to measure permanent deformation of the clasp, let alone the active and passive clasp tips, at the end of the cycling process and to correlate this with loss of retentive force.

The aim of the current study was to compare the permanent deformation and loss of retention of Co-Cr and AKP clasps tested in repeated removal along both an ideal path of removal/insertion and one that varied from ideal, to more accurately simulate natural use by patients.

Table 1 – Comparison of the reported physical properties of the tested CoCr and AKP clasps.

	Sheralit-Cylindra	Ultaire^{TM} AKP
Tensile strength (N/mm^2)	675	91
Yield strength (N/mm^2)	441	47
Elongation limit (%)	9.3	>6%
Modulus of elasticity (N/mm^2)	197,000	3500

2. Materials and methods

2.1. *Abutment design*

A typodont first lower molar was prepared for an e.max crown (Ivoclar-Vivadent, Lichtenstein). This was scanned using an intra-oral scanner (Omnicam, Dentsply-Sirona, Bernsheim, Germany) and a crown designed to include a mesial rest seat, mesial guide plane, lingual flattened reciprocating profile and buccal bulbosity. The crown was milled and then rescanned and imported into inLab Partial Framework (v.16.0.0.7765 RC2, Sirona Dental Systems, Bernsheim, Germany).

2.2. *Clasp production*

Two groups of 32 3-arm clasps were fabricated in either CoCr (SHERALIT-CYLINDRA, SHERA Werkstoff-Technologie GmbH, Lemförde, Germany) or AKP (Ultaire^{TM} AKP, Solvay Dental 360, USA). A summary of their mechanical properties is given in Table 1. These were further divided into two groups [CoCr0, CoCr10] and [AKP0, AKP10] to represent samples tested along the ideal path of insertion and those tested at ten degrees angulation away from that ideal path.

The CoCr clasp was designed using inLab Partial Framework (v.16.0.0.7765 RC2, Sirona Dental Systems GmbH, Bernsheim, Germany). The clasps were printed on a Form 2 stereolithographic printer (Formlabs, MA, USA) using Formlabs Castable Resin such that the design was 0.6 mm thick and 1.2 mm wide at the tip of the clasp, and at the base 1.02 mm and 2.04 mm respectively. Print supports, necessary for a successful print, were not placed on any contact surface or clasp tips. These were cast into a phosphate bonded investment material (Sheracast, SHERA Werkstoff-Technologie GmbH, Lemförde, Germany) and finished following normal laboratory protocols.

The AKP clasp was designed using 3Shape Dental System (3Shape, Copenhagen, Denmark). The design was such that the clasp tips were 1.3 mm thick and 2.5 mm wide, and the base was 1.5 mm and 3.5 mm respectively. The clasps were milled using a DWX-51D 5-Axis Dental Milling Machine (Roland DGA, California, USA) using Millbox (Roland Edition v2017, CIMsystem s.r.l., Milan, Italy). Sprues were not placed anywhere on the clasp arms or on contact surfaces.

Prior to testing, all clasps were scanned in a dental model scanner (Rexcan DS2, Europac 3D, Crewe, UK) to confirm that the clasps produced were the same as their CAD files. To avoid scan artefact from reflections and glare, both the CoCr and AKP clasps were powdered using Cerec Optispray (Sirona Dental Systems GmbH, Bernsheim, Germany) prior to scanning. Each clasp was scanned twice, and rotated, repositioned, cleaned and re-powdered before the second scan to ensure complete scan coverage.

The two clasp scans were aligned in Meshlab [13]. Any spurious artefacts and noise were removed. The merged scans were resurfaced using a Poisson filter (depth 11). The final scan was aligned to the original CAD file using custom software and any differences between the final scan and CAD file quantified using the method described below.

2.3. *Analogue production*

Tooth analogues were milled from blocks of IPS e.max (Ivoclar-Vivadent, Lichtenstein) using a Sirona Cerec MC milling machine (Dentsply Sirona, PA, USA) according to the agreed design. The reason IPS emax was chosen was that it is a ceramic with claimed similar wear to enamel [14]. They were finished and glazed (IPS e.max CAD Crystall Glaze Paste, Ivoclar-Vivadent, Lichtenstein) according to manufacturer's guidelines. A new tooth analogue was used for each test.

2.4. *Cyclic testing*

The tooth analogues were secured into the angulation adaptor in the base of a dynamic testing machine (ElectroPuls^{TM} E3000 Dynamic Test Instrument, Instron, UK) using autopolymerising epoxy resin (Technovit, Hereaus Kulzer, UK), then cemented using RelyX^{TM} Ultimate Adhesive Resin Cement, (3 M, UK). The clasps were fitted to a specifically designed holder that sat vertically above the analogue, using a drill chuck setup. When brought together, the assembly was submerged in a bath containing artificial saliva [15] at a temperature of 37 °C maintained using a Companstat water circulator (Weiss Technik UK) and 15,000 cycles of dynamic vertical displacement at a speed of 10 mm/s were carried out such that the clasp engaged with the undercut on the analogue and was pulled sufficiently upwards to mimic its removal by a patient.

2.5. *Force measurement*

The retentive/removal force of the clasps over the analogues was recorded every cycle for the first 10 cycles, every 10th cycle for the next 90 cycles, and every 100th cycle thereafter by a load cell. Data was plotted as Removal Force (y-axis) *vs* log (number of cycles) (x-axis). Kruskal Wallis was used to look for differences between clasp material and angulation, where the force value was the average peak force of clasp removal per cycle across the entire 15,000 cycle range.

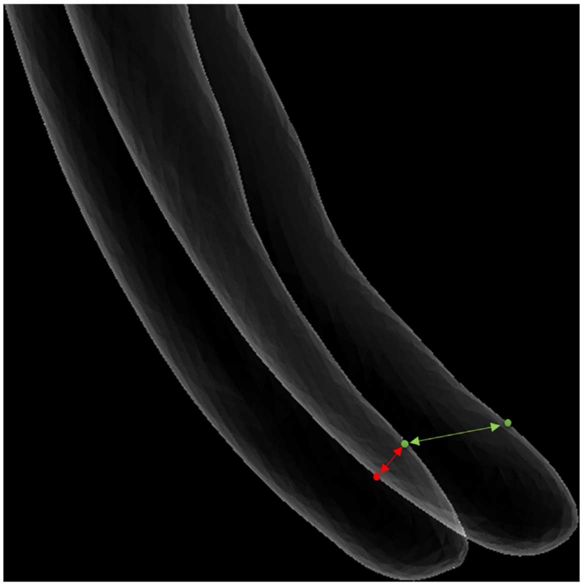

Fig. 1 – Correct method for comparing clasp tip distortion. The figure shows a plan view of a clasp tip which has distorted outwards following mechanical testing. If a standard surface comparison is used to measure the deviation of a point on the face of the POST clasp tip, the back of the PRE clasp arm will be measured to, and an underestimate of distortion given (red arrow). The correct measurement (green arrow) requires that each vertex on the PRE scan corresponds precisely to a topologically identical vertex on the POST scan.

2.6. *Deformation measurement*

In order to assess the three-dimensional deformation of both the active and passive clasp arms of each clasp, all pre-mechanical testing (PRE) clasp scans were aligned to their respective CAD files using the iterative closest point algorithm [16]. Next, each post-mechanical testing (POST) clasp scan was aligned to its (PRE) facsimile.

A naïve surface comparison (such as might be performed with Geomagic software) would not be suitable for comparing clasp tip distortions. This is because the closest point on the POST clasp scan to a point on the PRE clasp scan would be unlikely to be a topological match and would underestimate the degree of distortion. This is illustrated in Fig. 1.

To overcome this, a statistical deformable model of each clasp scan was calculated using Statismo [17] which had the effect of creating a set of clasp scans (PRE and POST) whose number of vertices in each mesh was identical, and each indexed vertex exactly corresponded to a similar vertex on the comparison mesh.

For each clasp arm (active and reciprocal), a point was identified 0.5 mm from the tip on the surface facing the tooth. A patch of points was then defined with a diameter of 0.5 mm from this key point. The mean distance between the corre-

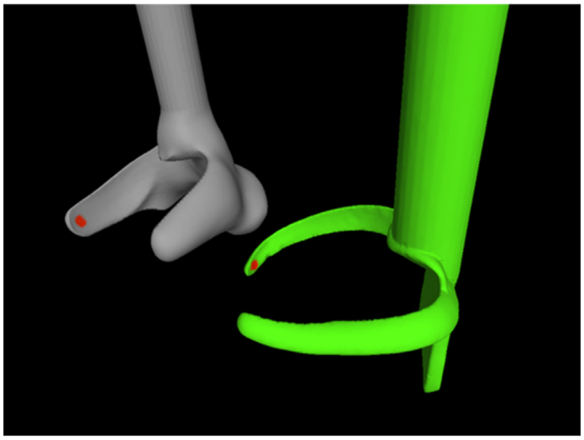

Fig. 2 – The patches used for distortion measurements. The faces of the active arms for an AKP (grey) and CoCr (green) clasp are shown. Each patch was centred 0.5 mm from the clasp tip, with a diameter of 0.5 mm. All vertices within the patch were measured from PRE to POST scan, and the mean distance of tip distortion calculated. The reciprocal arm patches were similarly identified.

Table 2 – Summary of retentive force (N) in terms of mean, maximum, minimum, standard deviation, initial and final force and for each of the four groups.

	AKP0	AKP10	CoCr0	CoCr10
Mean (N)	2.46	4.14	10.20	8.89
Max (N)	2.60	4.97	13.98	12.09
Min (N)	2.33	3.88	9.22	7.86
s.d. (N)	0.09	0.30	1.00	0.95
Initial (N)	2.55	4.73	11.97	10.36
Final (N)	2.49	3.92	9.22	7.92

Table 3 – Means and standard deviations for clasp tip distortions within each test group.

Group	Active clasp arm	Reciprocating clasp arm
AKP0	0.030 (0.024) mm	0.042 (0.030) mm
CoCr0	0.105 (0.095) mm	0.053 (0.079) mm
AKP10	0.019 (0.016) mm	0.021 (0.016) mm
CoCr10	0.319 (0.195) mm	0.047 (0.031) mm

sponding points in these patches on a pair of PRE and POST clasp meshes was recorded (Fig. 2).

This method robustly measured clasp tip deformation, where ’clasp tip’ was defined as the terminal 0.5 mm region on the inner surface of the clasp (in contact with the tooth). The active portion of a clasp arm is traditionally designed to be the terminal third of the arm, so our method confidently encapsulated only the most actively engaged portion of each arm.

For each of the four test groups (CoCr0, CoCr10, AKP0, AKP10) the mean and standard deviation for clasp tip distortion (active and reciprocal) was calculated ($n = 16$ in each group). Significance was assessed using ANOVA with post-hoc Bonferroni correction using SPSS Statistics (IBM, USA).

The repeatability (precision) of the combined workflow in scanning the clasps, building the deformable model and taking the measurements was tested as follows; one of the AKP clasps was randomly selected and the complete scanning, aligning, mesh deformation modelling and measurement workflow was applied. This gave 5 ostensibly identical results such that any differences in the deformation of the active and passive clasp faces could be deemed to be measurement error. All possible combination pairs of the 5 clasps were compared, yielding 10 pairwise comparisons, each comprising 2 measurements (active and reciprocal clasp distortion). The mean and standard deviation of these measured clasp tip distortions were recorded.

2.7. *Scanning electron microscopy*

In order to assess whether there was any superficial damage to the clasps or their analogues, scanning electron microscopy (SEM) was carried out using a Hitachi S-3400N SEM (Hitachi, UK). The active tips on intact clasps were imaged in low vacuum mode at magnifications between ×25 and ×2000. SEM imaging was also carried out to investigate if there was any wear of the glazed tooth analogues.

3. Results

3.1. *Removal forces*

The mean removal forces (N) for each of the four groups over 15,000 cycles are summarised in Table 2. CoCr0 had a significantly higher mean retentive force than CoCr10 and both CoCr groups had a significantly higher retentive force than their AKP counterparts; the AKP10 group had a significantly higher removal force than AKP0 ($p = 0.000$ for all tests). It is noteworthy that the standard deviations of the AKP groups are much smaller than for the CoCr groups.

More instructive than the mean force is the variation in removal force over 15,000 cycles as shown in Fig. 3 where Fig. 3a shows the removal force *vs* log(cycles) for AKP clasps and Fig. 3b shows the removal force *vs* log(cycles) for CoCr clasps.

3.2. *Clasp tip distortions*

The means and standard deviations for clasp tip distortions within each test group are shown in Table 3.

In all cases the CoCr groups distorted more than their AKP counterparts ($p < 0.01$). Example images showing overlaid PRE and POST clasp from each group are shown in Fig. 4 (median result from each group) and Fig. 5 (worst result from each group).

The mean measurement error for the full workflow when comparing the 5 scans of the same clasp was 28.5 μm (22.4 SD). This suggests that most of the measured AKP distortion can be accounted for in the noise of the measurement method itself.

3.3. *Scanning electron microscopy (SEM)*

Representative SEM’s of each clasp material, pre and post testing are shown in Fig. 6 for AKP10 and Fig. 7 for CoCr10. The

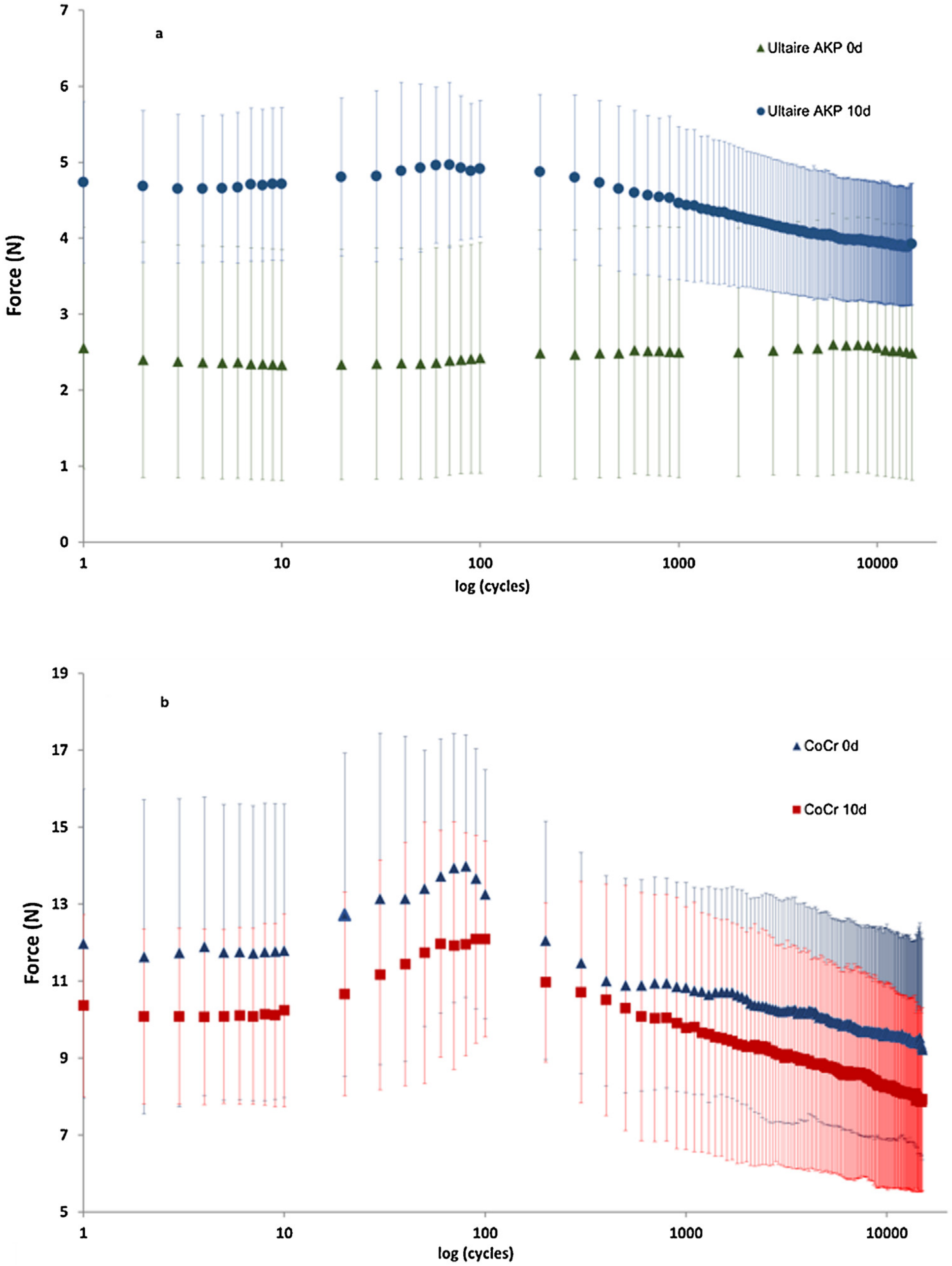

Fig. 3 – Summary graph of the removal force against log (cycles) plotted for each of the four groups. In Fig. 3a, AKP0 is represented by green triangles, AKP10 by blue circles. In Fig. 3b, CoCr0 is represented by blue triangles and CoCr10 by red squares. Standard deviation values for each data set are displayed in Table 3.

SEM's of matched glazed e.max crown surfaces for CoCr10 are shown in Fig. 8. SEM's of the antagonist e.max crown for AKP are not shown as there was no difference between the untested and post-tested images for either the AKP0 or AKP10 groups.

4. Discussion

In terms of the recorded removal forces, the larger forces needed to remove the CoCr clasps from the abutment crown are related to the initial high stiffness of the CoCr material compared to the polymeric AKP.

As shown in Fig. 3a, the retentive forces for the AKP groups were relatively low but consistent over the entire 15,000 cycles of the study, whilst the CoCr groups, shown in Fig. 3b underwent an initial sharp increase in force within the first hundred cycles followed immediately by a gradual reduction in removal force. It is likely that the initial increase in removal force for the CoCr groups could be attributed to work hardening. As the CoCr is plastically deformed through repeated engagement with the crown bulbosity, dislocations with the metal occur and additional dislocations are generated. The more

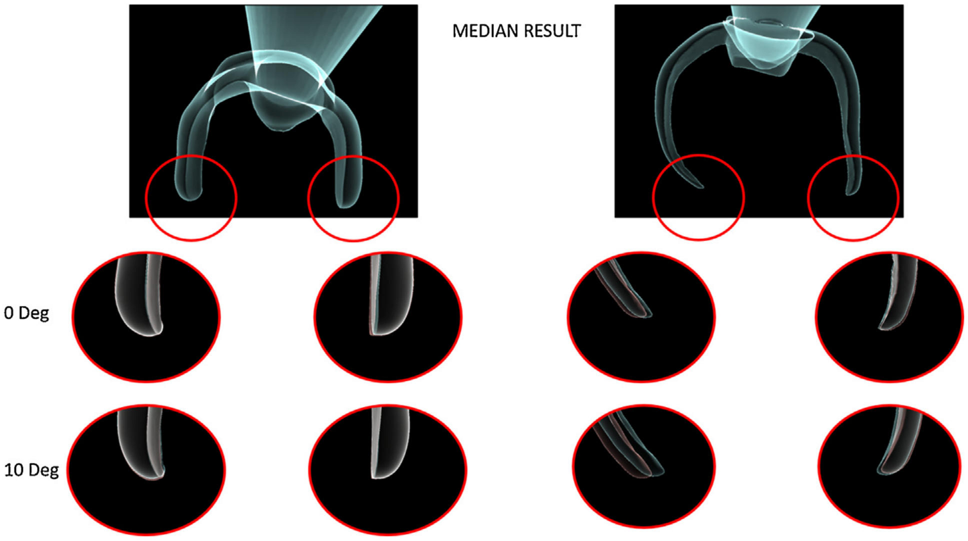

Fig. 4 – Example images showing overlaid PRE and POST clasp from each group (median result from each group). AKP on left of diagram, CoCr on the right of diagram. Differences in the design of the clasps can be seen in the top images.

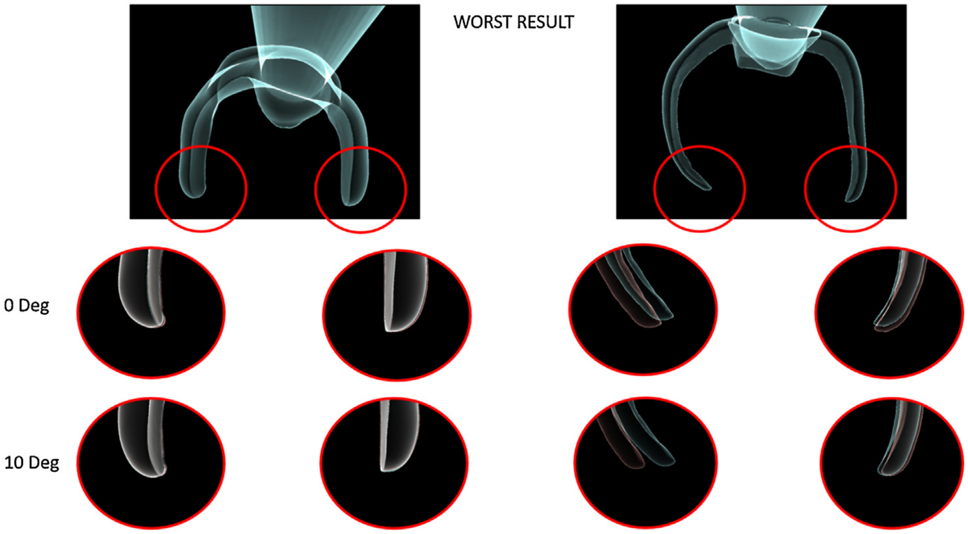

Fig. 5 – Example images showing overlaid PRE and POST clasp from each group (worst result from each group). AKP on left of diagram, CoCr on the right of diagram. Differences in the design of the clasps can be seen in the top images.

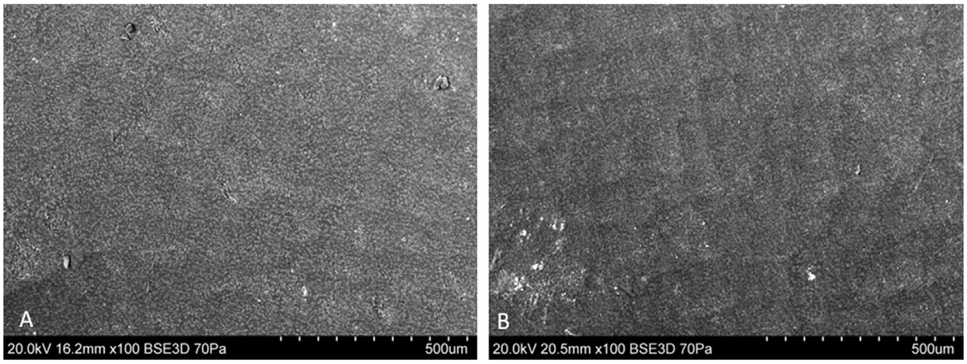

Fig. 6 – SEM of the AKP10 retentive arm surface (arm tip), (A) before fatigue testing, (B) after fatigue testing. Scale bar is 500 microns. There is no obvious wear, distortion or material loss at this scale.

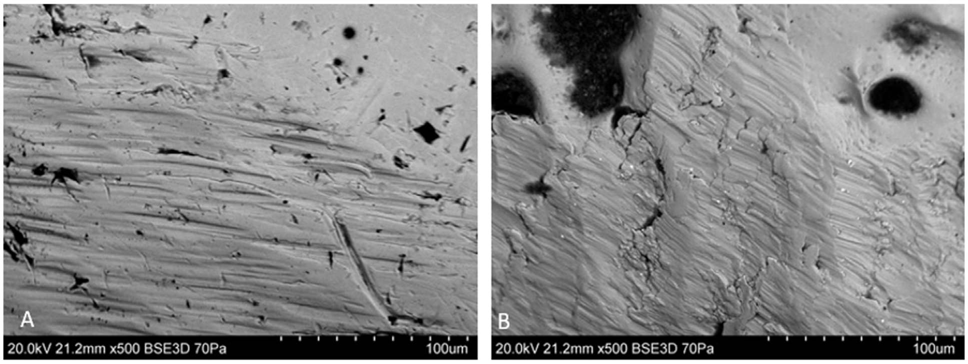

Fig. 7 – SEMs of the CoCr10 retentive arm surface (arm tip) (A) before fatigue testing, (B) after fatigue testing. Scale bar is 100 microns. There is no obvious wear, distortion or material loss at this scale.

dislocations within a material, the more they will interact and become pinned or tangled, decreasing their mobility and resulting in a strengthening of the CoCr material, with a concurrent reduction in its ductility. The removal force increased from 12.0 to14.0 N and 10.4 to 12.1 N for CoCr0 and CoCr10 respectively during the initial 100 cycles, corresponding to a patient wearing their denture for a period of only a few weeks [2].

It is interesting to note that the relative difference between AKP and CoCr retention force behaviour within the first 100 cycles was dramatic, as AKP0 and AKP10 showed a respective 5% reduction and 4% average increase in force while CoCr0 and CoCr10 showed an 11% and 17% average increase in force, respectively.

This initial short term increase for CoCr was followed by a gradual reduction in retentive force over the remaining 1̃5,000 cycles to 9.2 N and 7.9 N respectively; consistent with clinical observation of the need for a clasp adjustment at review appointments. It is possible that porosity could contribute to a loss of retention in the CoCr clasps. However, in this study, as also shown previously [18], no evidence of increased porosity or cracks was found in SEM observations of the Co-Cr alloy clasps after testing. Attrition of the inner surface of clasps and the outer surface of the abutment crowns could also cause a reduction in retention. This possibility cannot be discounted because SEM on crowns in both CoCr groups showed evidence of loss of glaze on the abutment ceramic crown.

The percentage reduction in retentive force for each of the four groups between the start and finish of the experiment was 2.35% and 17.1% for the AKP0 and AKP10 groups respectively and 22.97% and 23% for the CoCr0 and CoCr10 groups respectively. This suggests that the AKP10 group was in some ways behaving in a similar way to the CoCr clasps with a gradual tail off in retention. This small tail off for AKP10 could be

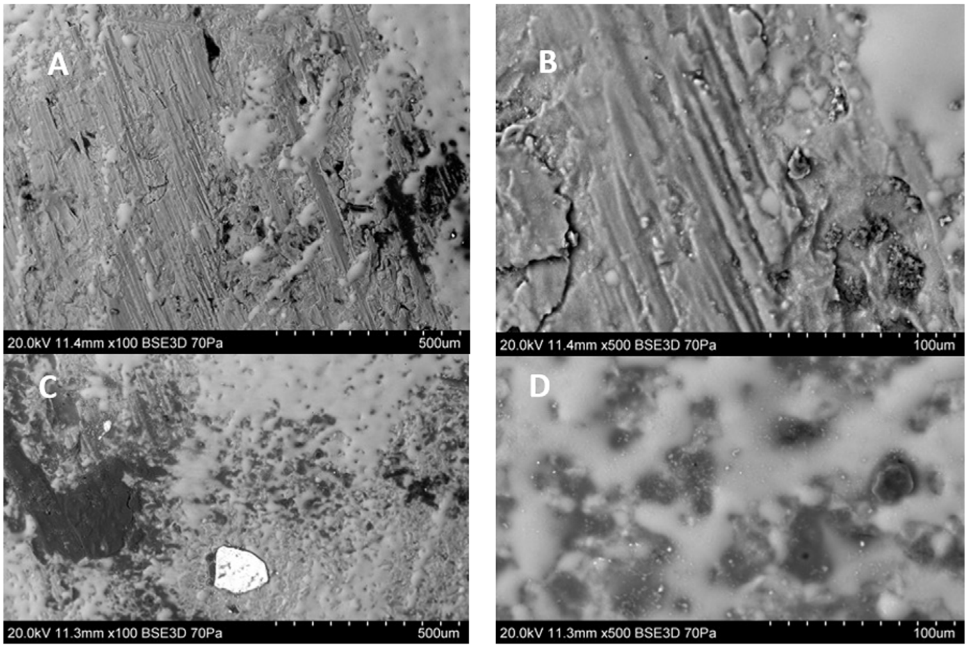

Fig. 8 – SEMs of glazed e.max crown antagonist for CoCr10 clasp showing obvious material loss of the glaze (light coloured material) due to the CoCr clasp sliding over the undercut (A and B) and the crown bulbosity (C and D). The glaze remained intact on control (untested) samples and on AKP antagonist samples.

attributed to conditioning of the clasp/crown or an increase in friction as the clasps engaged the glazed crown at an angle of 10° off vertical compared to the ideal path of removal in the AKP0 group. Increased friction could also explain why the retentive force itself was higher for the AKP10 group. Whilst the retentive force was higher for AKP10 there was no evidence from SEM that the clasp was causing any localised wear or removal of the glaze itself. This was very different behaviour to the much harder CoCr material which, although showing no signs of local material loss itself (Fig. 7) resulted in loss of glaze on the e.max crown antagonist (Fig. 8) as the clasp moved over the bulbosity of the crown.

This is the first study to test AKP clasps in this way; in terms of absolute forces measured, it is difficult to draw precise comparisons to other studies testing metallic and/or polymeric clasps as the materials and experimental set-ups are different between different studies and these differences cover the full range of experimental variables [19–21]. For example, Jiang et al. [22] reported a loss of initial retention of 29.9% for CoCr clasps using CoCr antagonists after 15,000 cycles, similar to the 23% reduction we noted. In contrast, whilst Tannous et al. [11] saw a similar initial increase in force for CoCr in their study using a CoCr antagonist, the initial and final removal forces were the same at the end of 15,000 cycles. They also made similar observations with regard to retentive forces using other polymeric clasp materials in that their retentive forces were both similar to the forces recorded in this study and uniformly less than that their CoCr control. Furthermore, no-one has previously attempted off-axis testing of single clasp/abutment assemblies, although the need for further studies, encompassing this approach has been recommended [11].

A limitation of the current study is that testing was carried out on single clasps only and the clinical retention of denture frameworks relies on a number of factors. For example, LaVere [23] showed through *in vitro* testing that the retention of commonly used clasp assemblies, *i.e.* moving on from single clasp testing to frameworks, was affected by clasp type, abutment material, artificial saliva and presence/absence of indirect retainers.

Scanning the clasps was difficult because dental scanners do not scan sharp corners or fine detail well. The scale and shape of the clasps made it challenging to build reliable 3D models. The use of statistical shape modelling has the disadvantage of introducing an additional data processing step. However, such techniques are well established in other contemporary fields such as monocular facial scanning [24], and this was found to translate well to dentistry. The dental literature is somewhat obtuse in its use of engineering comparison software when in many cases such an approach might be inappropriate. Here we showed a successful alternative analysis which yielded clinically relevant results, where traditional colour maps and surface distance measures would have been misleading.

It is likely that the operators became more skilled at the scanning task throughout the experiment. This would explain the unexpected result that the AKP10 group outperformed AKP0 in terms of distortions. In any event, the differences were small and not significant. Conversely, the degree of distortion of the CoCr clasps was consistently larger than the AKP. In fact, even the most favourable situation of a 10° path of insertion for the reciprocal arm (meaning it should move away from the tooth surface immediately upon removal) showed more distortion in CoCr than the least favourable AKP situation (10° path of insertion, active clasp). Whilst this extreme example was not statistically significant, it highlights the large difference in the distortion behaviour of the two materials – the maximum recorded deviation for CoCr was 789 microns whilst that for AKP was almost 10-fold less at 86 μm.

In all cases (AKP and CoCr), the reciprocating arms showed minimal mean distortions. The e.max crowns were designed with a flattened lingual surface, and the CAD design software allowed for precise identification of undercuts. The lack of distortion in all reciprocating arms might therefore be attributed to the method (CAD followed by either milling or 3D printing) rather than the material. One benefit of using newer framework materials such as AKP might simply be that the manufacturing process is more tightly controlled than wax patterning methods. It is conceivable that traditional manufacturing methods may inadvertently place the reciprocating arm in a slight undercut.

In addition, the patient may utilise an unintended path of insertion/withdrawal that introduces an undercut to the reciprocation. Whilst our protocol only enhanced the effective undercut of the active arm, the real-life situation might be a redistribution of the undercuts on both clasp arms. Regardless of where undercuts lie, the clinically important finding drawn from this study was that CoCr clasps consistently distorted when inserted and withdrawn from undercut regions whereas AKP clasps did not. This could be considered a notable drawback for CoCr, since by their very design, clasps must engage undercuts. Furthermore, despite the lower retentive forces, increasing clinical evidence points to AKP frameworks providing clinically acceptable levels of overall retention in a wide range of designs of removable partial dentures. This is rationalized in part by the fact that the retention of a removable partial denture relies on a number of factors in addition to the retentive forces created by clasps, *i.e.* the use of guide planes to limit the path of insertion/removal, along with the use of soft tissue undercuts. Hence, all of these factors need to be taken into account when planning the overall retention of the denture.

5. Conclusions

We have presented novel methods for testing the fatigue properties of CoCr and polymeric clasps and for assessing clasp deformation in both passive and active clasp tips in three dimensions. Using these methods, Ultaire^{TM} AKP clasps had a significantly lower average distortion than CoCr at both ideal and non-ideal (10° off vertical) angles of clasp removal. AKP showed overall lower retention forces than CoCr, but displayed much more stability over the 15,000 cycle lifetime.

Disclosure

This work was funded by Solvay Dental 360^{TM}. Ryan J. Murphy and Timothy J. Shary are employees of Solvay Dental 360^{TM}, holding the roles of Technology Manager and Research Engineer, respectively. Their scientific contribution to this work involved input of material properties, proper clasp design for the Ultaire AKP clasps, input into the analysis of the results, and assistance in creating the manuscript. No input was given by Solvay Dental 360TM into the experimental procedure, actual experimental execution or data creation.

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