Evaluation of the static frictional coefficients of Co-Cr and gold alloys for cone crown telescope denture retainer applications

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The static frictional coefficients (SFC) of a Co-Cr and a gold alloys were evaluated for the application of a cone crown telescope system in removable prosthesis. The SFCs of the Co-Cr alloy were lower than those of the gold alloy. The SFC of the gold alloy decreased by annealing at 85°C in air and was restored by re-polishing, although that of the Co-Cr alloy was stable irrespective of the annealing. The XPS analysis revealed the formation of a surface oxide layer on the gold alloy after annealing. The decrease in the SFC of the gold alloy may have been caused by the formation of an oxide layer on the surface due to annealing. The relationships among such factors as the retentive force, SFC and cone crown angle indicate that the angle of the Co-Cr alloy should be lower than that of the gold alloy based on the Körber's model.

Keywords: Co-Cr alloy, Retentive force, Static frictional coefficient

INTRODUCTION

A telescopic system with a cone crown is utilized in prosthetic treatment as the retainer for removable partial dentures and removable bridges. This system has also been used with overlay denture supported by dental implants¹⁻⁸. The clinical assessment of the cone crown telescope denture is excellent because of its clinical versatility, esthetic effect, and good prognosis⁹⁻¹¹. However, the expense and the heavy weight of the denture are disadvantages because the denture is constructed from gold alloys. These problems have therefore prevented the widespread use of the cone crown telescope system.

Co-Cr alloys which possess good biocompatibility, mechanical strength and a relatively low density provide an alternative to avoid these disadvantages. Co-Cr alloys have been applied for removable partial denture appliances for a long time. In addition, the mechanical properties and the castability of Co-Cr alloys have been improved by modifying the casting system to include investments. The alloys have been applied for both crowns and bridges. Therefore, Co-Cr alloys are also promising materials for cone crown telescope dentures. The retentive force of the cone crown telescope system should be clarified when Co-Cr alloys are considered for the cone crown telescope system as substitutes for gold alloys. Problems such as the collapse of cone crown telescope dentures or detachment of inner crowns may occur if the retentive force is not appropriate. In addition, abnormal occlusal force and inhomogeneous loading during the usage of the denture affect the periodontal tissue around the abutment, leading to the loss of the tooth^{12,13}. Therefore, the retentive force of the cone crown telescope system plays an important role in the long-

term prognosis of removable partial dentures.

The retentive force of the cone crown telescope system is influenced by the contact surface pressure, cone angle and static frictional coefficient (SFC)¹⁴. This is also affected by the thickness of the outer crown, height of the inner crown and inner crown diameter on the retentive force¹⁵⁻¹⁹. However, there are few reports on the SFC of gold alloys used in the cone crown telescope system at present. Therefore, the purpose of this study is to evaluate the SFC of a Co-Cr alloy and a gold alloy, and discuss the design of the cone crown telescope system containing a Co-Cr alloy. In addition, the effects of heat treatment on the SFC of both alloys were examined.

MATERIALS AND METHODS

Sample preparation

Wirobond 280 (BEGO, Bremen, Germany) and Degulor M (DENTSPLY SANKIN, Tochigi, Japan) were used for the SFC measurements as a Co-Cr alloy and gold alloy, respectively. The chemical composition and the properties of these alloys are listed in Tables 1, 2 and 3. The density of Wirobond 280 is half that of Degulor M. The mechanical properties of Wirobond 280 are comparable to those of Degulor M after casting and aging treatment.

Disc- and plate-shaped specimens were prepared for the SFC measurement of each casting alloy. The size of a disc specimen was 30 mm in diameter and 5 mm in thickness. The size of the plate specimen was 36 mm in width, 60 mm in depth, and 3 mm in thickness.

Wirobond 280 was cast using Bellavest SH (BEGO, Bremen, Germany) and Begosol HE (BEGO, Bremen, Germany) as the investment. The mold including wax pattern was kept for 30 minutes in air. The mold was

Table 1 Chemical composition of Wirobond 280

Alloy	Composition (mass %)					
	Co	Cr	W	Mo	Ga	Si, Mn
Wirobond 280	60.2	25.0	6.2	4.8	2.9	–

*The amount of Si and Mn is not announced in the specification sheet.

Table 2 Chemical composition of Degulor M

Alloy	Composition (mass %)						
	Au	Pt	Pd	Ag	Ir	Cu	Others
Degulor M	70.0	4.4	2.0	13.5	0.1	8.8	1.2

*A small amount of Zn and Sn may be contained in the alloy.

Table 3 Physical properties of Wirobond 280 and Degulor M

Alloys	Density (g/cm ³)	Melting point (°C)	Elongation (%)	Yield strength (MPa)	UTS (MPa)	Vickers hardness
Wirobond 280	8.5	1,360–1,400	14	540	680	280
Degulor M	15.7	900–970	17	620	740	235

heated at 900°C for 30 minutes in a muffle furnace. The mold was located in the casting machine after burning out the wax (Super Cascom, DENKEN, Kyoto, Japan) and heated to 1,500°C. Wirobond 280 was cast into the mold at 1,500°C in an Argon atmosphere and the mold was cooled in air.

Degulor M was cast using Cristobalite PF (Shofu, Osaka, Japan) as the investment. The mold including the wax pattern was kept for 30 minutes in air. The mold was heated at 700°C for 30 minutes in a muffle furnace. The mold was located in the casting machine after burning out the wax (Super Cascom, DENKEN, Kyoto, Japan) and heated to 970°C. Degulor M was cast into the mold at 970°C in Ar and the mold was cooled in air.

The top and bottom surfaces of plates and discs were polished to be parallel using surface grinder (PSG52EN, Okamoto Machine Tool Works, LTD, Gunma, Japan). The discs were manually buffed using the diamond paste of #1000 grid (SP-W, Asahi Diamond Industrial Co., Ltd, Tokyo, Japan). Optical microscope images of the surface of plate and disc of the Co-Cr and gold alloys after polishing are shown in Figure 1. Laser microscope was used for the evaluation of the surface roughness of the alloys. The surface roughness (R_a) of plate and disc of the Co-Cr alloy were 2.16 μm (SD 0.26) and 1.14 μm (SD 0.44), respectively. The surface roughness of the plate and disc of gold alloy were 2.09 μm (SD 0.17) and 1.07 μm (SD 0.24), respectively. Five sets of plates and discs of both alloys were prepared for the SFC measurements.

Treatment after polishing

Some processes were applied to the plates and discs of each alloy to examine the effect of heat treatment on the SFC: the as-polished discs and plates (condition 1) were immersed in ultra pure water at room temperature for 1 week (condition 2). After the immersion, the discs and plates were annealed at 85°C for 30 minutes (condition 3). The annealed discs and plates surfaces were polished with water proof emery papers up to #1000 grid using a rotating polisher machine (METASERV 2000, BUEHLER, Illinois, USA) (condition 4). The surface roughness of plate and discs of the Co-Cr alloy (condition 4) were 0.53 μm (SD 0.06) and 0.52 μm (SD 0.08), respectively. The surface roughness of the plate and disc of gold alloy (condition 4) were 0.53 μm (SD 0.08) and 0.58 μm (SD 0.05), respectively.

Evaluation of static frictional coefficient (SFC)

The evaluation of SFC was carried out using a tensile testing machine (AUTOGRAPH, Shimadzu, Kyoto, Japan) according to ASTM D1894²⁰. Figure 2 shows the schematic drawings of SFC measurement. Disc specimen was put on the plate which was fixed on the flat table. The total weight of the disc and weight was adjusted to 200 g. The peak load was measured at the beginning of sliding for the evaluation of SFC when the crosshead was moved at a speed of 5 mm/min. The SFC (μ) was calculated by the equation:

$$\mu = P/W \quad (1)$$

where P is the peak load and the W is the total weight of the disc and weight (200 g). The SFC measurements

Fig. 1 Optical microscopic images of the surface of disc and plate of the Co-Cr and gold alloys after polishing. (a) Co-Cr alloy plate ($R_a=2.16 \mu\text{m}$), (b) gold alloy plate ($R_a=2.09 \mu\text{m}$), (c) Co-Cr alloy disc ($R_a=1.14 \mu\text{m}$), and (d) gold alloy disc ($R_a=1.07 \mu\text{m}$).

Fig. 2 Schematic drawing of SFC measurement according to ASTM D1894 (the American Society for Testing Materials)²⁰⁾.

were performed at $22\pm1^\circ\text{C}$ and the humidity of $69\pm4\%$. Five sets of disc and plate were measured five times for each alloy. The surface of the disc and plate was cleaned and dried before SFC measurement using ethanol (Wako Chemical, Miyazaki, Japan). Statistically significant differences were evaluated by the *t*-test, One-way ANOVA and Tukey's HSD method. $p<0.05$ was considered to be statistically significant.

Surface analysis

X-ray Photoelectron Spectroscopy (XPS) was performed with an electron spectrometer (JPS-9010MC, JEOL, Tokyo, Japan). All binding energies noted in this report are relative to the Fermi level and all spectra were excited with the monochromatized Mg $K\alpha$ line (1,253.6 eV). Survey spectra were obtained over a range of 0–1,200 eV. The binding energy was calibrated using C 1s electron binding energy as 285.0 eV. The take-off angle for photoelectron detection was 90° from the surface of the specimen. The chemical states of elements were determined with their binding energies²¹⁾.

RESULTS

Static frictional coefficient of as-polished Co-Cr alloy and gold alloy

Figure 3 shows the SFC of as-polished Co-Cr alloy and gold alloy. The SFC of Co-Cr alloy is significantly lower than that of gold alloy (t -test, $p<0.001$). The difference of SFC is caused by the difference of the constituent elements because the surface roughness of both alloys is almost the same.

Static frictional coefficient of Co-Cr alloy and gold alloy after various treatments

Figures 4 and 5 show the SFC of Co-Cr alloy and gold

Fig. 3 The SFCs of as-polished Co-Cr alloy and gold alloy. Statistically significant differences were determined by the t -test. $p<0.05$ was considered to be statistically significant.

Fig. 4 The SFCs of the Co-Cr alloy after various treatments: Statistically significant differences were determined by One-way ANOVA and Tukey's HSD method. $p<0.05$ was considered to be statistically significant.

alloy after various treatments, respectively. Statistically significant differences were evaluated by the One-way ANOVA and Tukey's HSD method. The SFC of the Co-Cr alloy in condition 2 was slightly lower than that in condition 1, although no significant difference was observed ($p=0.186$). The SFC in condition 3 was lower than that of condition 1, although no significant difference was observed between conditions 2 and 3 ($p=0.056$). The SFC in condition 4 was slightly higher than that in the condition 1, although no significant difference was observed between conditions 1 to 3 and condition 4.

The SFC of the gold alloy in condition 2 was lower than that in condition 1. It should be noted that the SFC in condition 3 was significantly lower than that in condition 2. In addition, the SFC in condition 4 was higher than that in condition 3 and was as high as that in condition 1.

The changes of the SFCs of the Co-Cr alloy were smaller than those of the gold alloy when treatments were conducted in conditions 1 to 4. Therefore, the SFC of gold alloy is susceptible to treatments in conditions 1 to 4.

A surface analysis of Co-Cr alloy and gold alloy

Figure 6 shows the XPS survey spectra obtained from the Co-Cr alloy in the conditions 3 and 4. C, O, N, Co, Cr, Mo, Ga, W, Si, Mn, and S were detected in the Co-Cr alloy with XPS. C and N originated from the so-called "contaminant carbon and nitrogen". The elements, other than O and S, originated from the alloying elements. O originated from surface oxide and S may be incorporated into the alloy during the dental casting processes. There was no difference between these specimens.

Figure 7 shows the XPS spectra obtained from the

Fig. 5 The SFCs of the gold alloy after various treatments: Statistically significant differences were determined by One-way ANOVA and Tukey's HSD method. $p<0.05$ was considered to be statistically significant.

Fig. 6 XPS survey spectra of obtained from the Co-Cr alloy in the (a) condition 3 and (b) condition 4.

Fig. 7 XPS survey spectra of obtained from the gold alloy in the (a) condition 3 and (b) condition 4.

Fig. 8 XPS spectra of Cu 2p electron energy region obtained from the gold alloy in the (a) condition 3 and (b) condition 4.

Fig. 9 XPS spectra of Zn 2p electron energy region obtained from the gold alloy in the (a) condition 3 and (b) condition 4.

gold alloy in the conditions 3 and 4. C, O, N, Au, Pt, Pd, Ag, Sn, Cu, and Zn were detected in the gold alloy with XPS. C and N also originated from the so-called “contaminant carbon and nitrogen”. The elements, other than O were derived from the alloying elements. O originated from surface oxide. The unknown spectrum was observed at 815 eV. Figure 8 shows the XPS spectra of Cu 2p obtained from the gold alloy in the conditions 3 and 4. The Cu 2p spectrum in condition 3 was broadened to a higher binding energy region in comparison to that in condition 4. This was due to the overlap of some peaks from the valence of Cu⁰, Cu⁺ and Cu²⁺ in that condition 3. The binding energies of Cu²⁺ (933.5 eV)²²⁾ were higher than that of Cu⁺ (932.2 eV)²³⁾ and Cu⁰ (932.4 eV)²¹⁾, although it is difficult to separate these peaks. Figure 9 shows the XPS spectra of Zn 2p obtained from the gold alloy in conditions 3 and 4. Peaks originating from Zn 2p were

detected in condition 3. The Zn 2p spectrum in condition 3 seemed to be broadened to a higher binding energy. The binding energy of Zn²⁺ (1,021.7 eV)²¹⁾ was higher than that of Zn⁰ (1,021.4 eV)²¹⁾, although it is difficult to separate these peaks. However, these peaks were not detected in condition 4.

DISCUSSION

Effect of treatments on the static frictional coefficient of the Co-Cr alloy and the gold alloy

Amonton's law states that the SFC does not depend on the apparent contact area²⁴⁾. This law works when the surface roughness and the cleanness are in a similar range²⁵⁾. On the other hand, the SFC increases with decreasing the apparent contact area and with increasing circumference length²⁶⁾. These suggest that the surface roughness influences the SFC. When the

plastic deformation occurs at the real contact area, the new surface forms and the strong adhesion occurs between the materials. This contributes to the increase of the SFC. When the elastic deformation occurs at the real contact area, the effect of surface layer is large and the SFC is almost the same value, irrespective of the summation of the real contact area (*i.e.* roughness). If the surface roughness of the alloys in the condition 2 and 3 increases and the plastic deformation occurs at the real contact area, the SFC should increase owing to their treatments. However, the SFCs of the alloys decreased in the condition from 1 to 3. In addition, the SFC was almost the same, irrespective of the roughness difference between the condition 1 and 4. It is considered that the adhesion owing to the plastic deformation at the real contact surface should not occur for both alloys in the tested conditions.

Ludema *et al.*²⁷⁾ described that when oxygen is present, wear is very much lower, friction is significantly lower and the wear debris is mostly oxide. Thus, all the SFC value obtained in the tests was affected by the presence of oxygen. Generally, an oxide layer, which grows very slowly, forms on the alloy surface of gold alloys. Therefore, adhesion is dominant for the friction of the as-polished gold alloy although the surfaces are contaminated by air. XPS analysis revealed that Cu and Zn were oxidized during annealing even at 85°C, which is close to the polymerization temperature of a denture base resin and the vaporization temperature of ethanol. The gold alloy (type 4) contains Cu for strengthening and a small amount of Zn for deoxidization. These elements are easily oxidized during annealing and then the oxide layer containing Cu and Zn is formed on the surface. Accordingly, the SFC of the gold alloy decreased by annealing because the layer disturbs the adhesion of metals in the gold alloy.

On the other hand, oxides containing Cr_2O_3 and $\text{Co}(\text{OH})_3$ form immediately after polishing in Co-Cr alloys²⁸⁾. The oxides layer formation of Wirobond 280 is considered to be the same, based on the alloy composition (Table 1). The SFC was thought to be changed because of the dissolution $\text{Co}(\text{OH})_3$ in ultra pure water. However, there was no significant difference on the SFC between conditions 1 and 2. The SFC in condition 3 was slightly lower than those in the other conditions. This is presumably due to the stabilization of oxides on the surface during annealing. The SFCs of the Co-Cr alloy in each condition were lower than those of the gold alloy. The stable and thick oxide layer always exists at the surface and disturbs the adhesion of metals. Therefore, the change in the SFC of the Co-Cr alloy may be suppressed in each condition.

Effect of static frictional coefficient on the retentive force of cone crown telescope system

The retentive force in the cone crown telescope system is generated by the residual elastic strain in the outer crown. Figure 10 shows a schematic illustration of the

Fig. 10 Schematic drawing of the cone crown telescope system¹⁴⁾.

telescope system¹⁴⁾. The inner crown is inserted into the outer crown when the occlusal force (K) is applied firmly, and the elastic strain occurs due to the deformation of the outer crown. The elastic strain remains when the occlusal force is removed because of the existence of the inner crown. Therefore, the elastic strain is formed to generate the normal force (N) to the interface between the outer and inner crown. The retentive force (T_0) is expressed using the SFC (μ_0);

$$T_0 = \mu_0 N \quad (2)$$

The normal force (N) is expressed using the cone angle ($\alpha/2$);

$$N = K / \sin(\alpha/2) \quad (3)$$

The retentive force (T_0) is expressed using equations 2 and 3;

$$T_0 = \mu_0 K / \sin(\alpha/2) \quad (4)$$

Therefore, the retentive force is proportional to the SFC¹⁴⁾. The retentive force is controlled by the SFC and the cone angle from the design of cone crown telescope system. The SFC of the selected alloys should be evaluated before the cone angle is determined in order to obtain the same retentive force as the gold alloy. The SFC of the Co-Cr alloy was lower than that of the gold alloy (Fig. 3). Based on the figure and the experimental results, the cone angle of the Co-Cr alloy should be lower than that of the gold alloy. However, the SFC measurements were performed at $22 \pm 1^\circ\text{C}$ and the humidity of $69 \pm 4\%$ in this study. Although it is difficult to determine the exact value of the angle because the SFC depends on the oral circumstance in each patient²⁹⁾, further investigation of the SFC is still needed to discuss on the differences of the retentive force between the alloys in the oral circumstance.

CONCLUSION

The SFC of the Co-Cr alloy and the gold alloy were evaluated at $22\pm1^\circ\text{C}$ and the humidity of $69\pm4\%$. The SFCs of the Co-Cr alloy were lower than those of the gold alloy. The SFC of the gold alloy was decreased by annealing at 85°C in air and was restored by re-polishing, although that of the Co-Cr alloy was stable irrespective of the annealing. The XPS analysis revealed that the decrease of SFC of the gold alloy was caused by the formation of an oxide layer at the surface on annealing. The oxide layer of the Co-Cr alloy may suppress the change of the SFC in each condition. The cone angle should be considered when the alloy for the cone crown telescope system is changed from the gold alloy.

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