



Original Article

Mechanical and frictional properties of aesthetic orthodontic wires obtained by hard chrome carbide plating



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KEYWORDS

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Abstract *Background/purpose:* Although aesthetic wire coating has been increasing in demand, it has problems that changes in mechanical properties and increase in frictional force. The aim of this study was to evaluate the coating of the wire, as characterized by aesthetics, in terms of low and constant friction and mechanical properties.

Materials and methods: Hard chrome carbide-plated (HCCP) wires (HCCP group), commercially available polymer-coated wires (P group), rhodium-coated wires (R group), and uncoated wires (control group) were used. For all wire types, a stainless steel wire of dimensions 0.017 inch \times 0.025 inch was used. They were evaluated by three-point bending, friction testing, surface observation, and colorimetric testing.

Results: The HCCP group was not significantly different from the control group in terms of flexural strength (σ) and flexural modulus (E) (σ : $p = 0.90$, E : $p = 0.35$). However, it was significantly inferior compared to the three other groups in terms of the maximum static and kinetic frictional forces under both dry and wet conditions ($p < 0.05$). In the surface observation, scratches were observed on the wire after the friction test. In the colorimetric test, no significant difference was observed between the HCCP group and the R group ($p > 0.05$).

Conclusion: The mechanical properties of the HCCP wire were not significantly different compared to the control group. The frictional force of the HCCP wire was significantly lower than the other group. Therefore, the HCCP wire was suggested to increase the efficiency of tooth movement in clinics.

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Introduction

The use of aesthetic wires has increased in orthodontic treatment because of the increased number of patients who require good aesthetics as a prerequisite of their treatment. Here, “good aesthetics” refers to wires matching the tooth color. In order to obtain better aesthetics, orthodontic wires of colors similar to tooth colors have been introduced. However, because of the coating on the wire surface, it is necessary to consider how the coating may influence the orthodontic treatment.

Several problems involving the coatings of these coated wires have been identified. Kim and Cha reported that the friction coefficients of these coated wires are higher than those of uncoated wires.¹ Frictional forces between the brackets and the wire affect tooth movement. Reducing the coefficient of friction shortens the treatment period, reduces patient pain, and prevents anchorage loss.^{2–6}

It has been reported that the mechanical properties of some coated wires were significantly worse than those of uncoated wires.⁷ Deterioration in the physical properties of the wire adversely affects the orthodontic treatment. The load–deflection characteristics determine the nature of the wire and affect tooth movement. Deterioration of the mechanical properties of the wire also negatively affects the orthodontic treatment. When wires are subjected to deflection, the load–deflection properties determine the nature of tooth movement. These properties of the wire may be altered upon coating, because the diameter of the wire must be smaller than that of uncoated wires to compensate for the coating thickness.⁸

Some research has suggested that using surface treatments could reduce the friction between the brackets and the wire.^{9–11} Diamond-like carbon (DLC) is one coating that can reduce the frictional force between brackets and wire. However, the color of the DLC coating is black. Hard chrome carbide plating (HCCP) has been introduced in industrial applications because it offers properties like low friction, chemical inertness, high surface hardness, high wear resistance, and thin coating.¹²

The ionization potential of Cr is between those of Zn and Fe; Cr has basic properties compared to Ni, Sn, Pb, and Cu. Thus, Cr can easily form oxides in the atmosphere, depositing a dense oxide film primarily composed of Cr₂O₃ on the metal surface. Because the solubility of the oxide film is very low in the aqueous phase (pH 7), the chrome interior is protected and the metallic luster is maintained. When the metal Cr surface slides on other materials, the Cr₂O₃ of the coating surface becomes slightly worn. The wear particles act as a lubricant, making Cr a low-friction material.¹³ The aim of this study is to achieve the following objectives using HCCP processing of the wire: 1. good aesthetics, 2. immutable physical characteristics, and 3. low friction. Here, “immutable physical characteristics” means that the aesthetic wire does not differ in mechanical strength (flexural strength, flexural modulus) compared with the uncoated wire. Low friction means that the aesthetic wire has low friction as compared to the uncoated wire.

Materials and methods

Materials preparation

The base material of HCCP was a stainless steel wire of dimensions 0.017 inch (0.432 mm) × 0.025 inch (0.635 mm) (Stainless steel wire[®], CDB corporation, U.S.A.), which was subjected to electroplating. The metal was used as the cathode and the material for plating was used as the anode. For the plating bath, 250 g/L chromic anhydride was used (Fig. 1). First, the wire for HCCP was degreased to remove surface filth. Next, the wire was mounted on the jig. After anodic oxidation, electrodeposition of Cr is performed for 10 min. After electrodeposition, the hydrogen is removed and the wire is polished. A detailed description of the plating procedure was reported by Amifune and Fujiwara.¹⁴ For comparison, we obtained three commercial orthodontic wires from the market.

Uncoated wires (VIM STAINLESS STEEL Wire[®], ACME MONACO, U.S.A.) were used as the control group. As experimental groups, polymer-coated wires comprising epoxy resin (micro-coated stainless steel wire[®], G&H Wire Company, U.S.A.), Rh-coated wires (White stainless wire[®], Tomy International, Tokyo, Japan), and HCCP wires were used (Fig. 2a–d). Recently, various kinds of coatings have been developed; among these, polymer-coated and Rh-coated wires have been reported in various articles.^{1,15–17} Thus, there were 4 groups: uncoated wires (control group); polymer-coated wires (P group); Rh-coated wires (R group); and HCCP wires (HCCP group) (Table 1).

Three-point bending test

The three-point bending test was performed using a universal testing machine (AG-100N, Shimadzu, Kyoto, Japan). The crosshead speed for loading was 1.0 mm/min with a span length of 16 mm (Fig. 3). The flexural strength (σ) was calculated using the equation

$$\sigma = 3FL/2bh^2, \quad (1)$$

where L , b , h , and F are the span size, wire width, wire thickness, and maximum load, respectively. The flexural modulus E was calculated using the equation

$$E = (L^3/4bh^3) \times (\Delta F/\Delta S), \quad (2)$$

where ΔF is the variation of load, ΔS is variation of flexure, L is the span length, b is the specimen width, h is

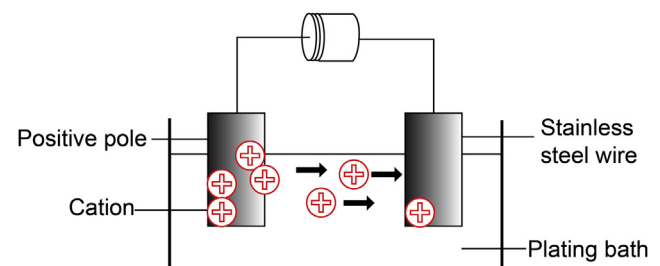


Figure 1 The electroplating method. The metal cations are attracted to the surface of the base material of the cathode.

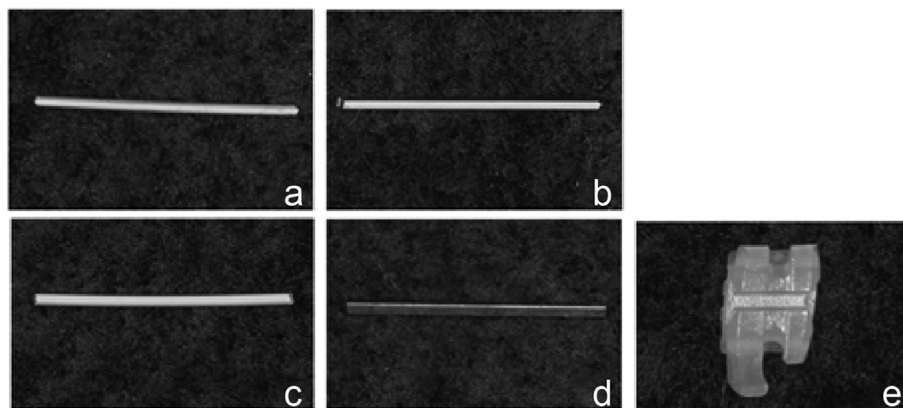


Figure 2 Types of stainless steel wires (0.017 inch × 0.025 inch) and testing bracket. a, HCCP wire; b, Rh-coated wires (White stainless steel wire®, Tomy International, Tokyo, Japan); c, polymer-coated wires (micro-coated stainless steel wire®, G&H Wire Company, U.S.A.); d, uncoated wires (VIM STAINLESS STEEL Wire®, ACME MONACO, U.S.A.) at 0.5× magnification.

the specimen thickness, and *F* is the maximum load. The wires were deflected by 2.00 mm under continuous monitoring of the force during loading and unloading. The experimental values of the four wires were averaged over 10 different specimens. All tests were carried out by the same person.

Friction test

A ceramic bracket (WIOCE®, CDB corporation, U.S.A.), with a 0.022 inch × 0.028 inch slot, 11° angulation, and 0° torque, was used for the upper canine (Fig. 2e). Brackets were mounted on an Al block (20 mm × 20 mm × 20 mm).

The surface of the Al block was roughened by sandblasting, and the brackets were mounted on the middle of the surface using the adhesive material Superbond (Sun medical, 571-2 Furutakacho, Moriyama city, Shiga, Japan). Both ends of the Al block were fixed with screws. The block was installed in a universal testing machine (AG-100N, Shimadzu, Kyoto, Japan). The arch wire was cut with a length of 5 cm at the rear straight part. The lower part of the wire was fixed with a weight of 150 g. A wire was ligated to the bracket and pulled out at the crosshead speed of 10 mm/min up to a distance of 5 mm (see Fig. 4). We considered it necessary to reproduce the intraoral environment; tests were also performed in wet conditions. In these tests, the

Table 1 List of wires used in this study.

Group	Section size (inch × inch)	Composition	Manufacturer
Control	0.017 × 0.025	Stainless steel	ACME MONACO
HCCP	0.017 × 0.025	Stainless steel	CDB corporation
R	0.017 × 0.025	Stainless steel	Tomy international
P	0.017 × 0.025	Stainless steel	G&H Wire Company

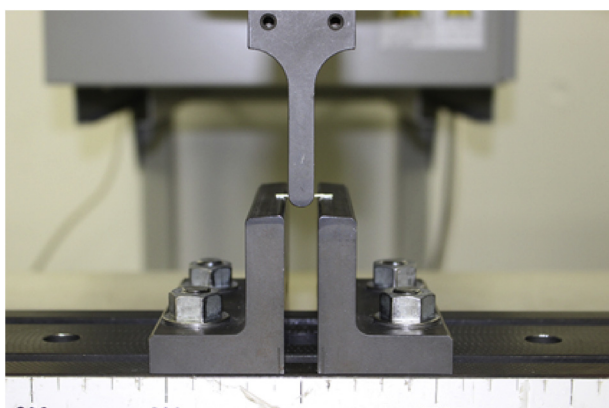


Figure 3 Three-point bending test machine (1× magnification).

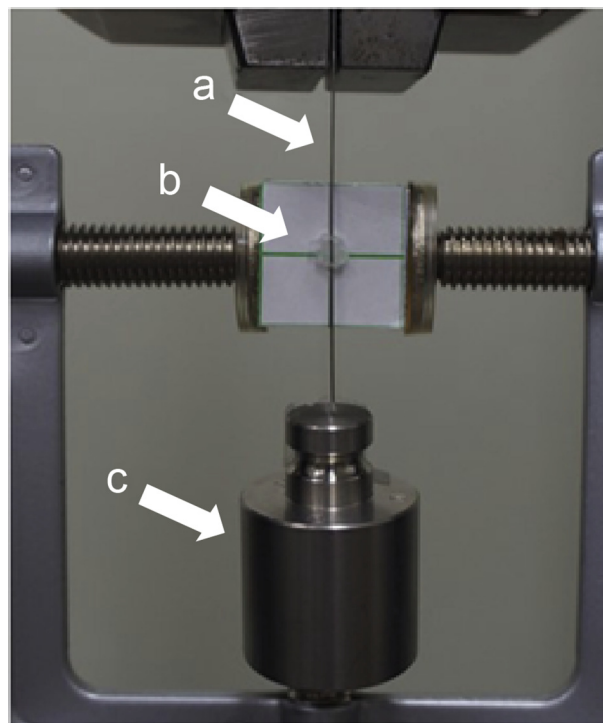


Figure 4 Friction test machine. a, wire; b, bracket; c, weight (150 g) 1× magnification.

bracket and wire were sprayed with a phosphate-buffered saline (PBS; pH = 7.4, NaCl: 138 mmol, KCl: 2.7 mmol, Na₂HPO₄: 10 mmol, KH₂PO₄: 1.76 mmol) solution immediately before measurements.¹⁸ Each bracket and wire was used only once in each experiment. All experiments were performed by the same person. The maximum static friction force was set as the maximum value during the first movement. The kinetic frictional force was set as the average value of the frictional force when the wire was moved by 1–5 mm.¹

Scanning electron microscopy

Scanning electron microscopy (SEM, Hitachi-800; Tokyo, Japan) was conducted to observe scratches and exfoliation of the wires, and to evaluate whether the structural integrity was maintained. SEM observations were performed on the wires before and after friction testing for comparison. The wire was cut to a length of 10 mm including the 5-mm portion in contact with the bracket.

Color measurement test

We measured the colors of the four groups of wires to investigate their aesthetics. In order to measure the small-diameter arch wires to accurately determine their color using colorimetry, samples with the minimum width of 3 mm are required. Therefore, in the present study, the technique described by da Silva et al. was used with slight modifications.¹⁸ Six wire segments were fixed tightly at both ends using utility wax (Fig. 5a). The colorimeter (Shade Eye, Shofu, Kyoto, Japan) used in this study is shown in Fig. 5b. A1 in the shade guide (VITAPAN[®], VITA, U.S.A) was used as a reference for white color. To measure the reference white color, the instrument tip was placed perpendicular to and in complete contact with the labial surface of the tooth.¹⁹ As per the research done by Inami et al., the color of each wire was measured three times.²⁰ Color parameters were expressed using the L^{*}a^{*}b^{*} color space system. The three axes in this three-dimensional color space were L^{*}, a^{*}, and b^{*}, with the L^{*}-axis denoting brightness, a^{*} representing the degree of redness (+a^{*}) or greenness (−a^{*}), and b^{*} representing the degree of yellowness (+b^{*}) or blueness (−b^{*}) of the studied object.²¹ The color difference between VA1 and each wire (ΔE^*ab) was calculated according to the following equation:

$$\Delta E^*ab = \left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2 \right]^{1/2}. \quad (3)$$

Statistical analysis

The mean values were calculated and expressed in terms of the standard deviation (SD). The results of the three-point bending test, friction test, and color measurement test were assessed using a one-way analysis of variance (ANOVA) to determine any overall differences. Post-hoc testing was conducted using Tukey's test and paired *t*-test to assess pairwise comparisons. Statistical significance was set at $p < 0.05$.

Results

Three-point bending test

Fig. 6a and b shows the flexural strengths and flexural moduli of the orthodontic wires, respectively, obtained using the three-point bending test. The flexural strengths of the control, HCCP, R, and P groups were 2903.8 (Ave.) ± 70.0 (S.D.), 2886.3 (Ave.) ± 24.5 (S.D.), 2834.7 (Ave.) ± 86.5 (S.D.), 2338.7 (Ave.) ± 26.8 (S.D.) MPa, respectively. The P group showed significantly lower flexural strength than the other three groups ($p < 0.05$). The flexural moduli of the control, HCCP, R, and P groups were 175.9 (Ave.) ± 5.9 (S.D.), 173.1 (Ave.) ± 2.2 (S.D.), 172.2 (Ave.) ± 2.4 (S.D.), 163.2 (Ave.) ± 3.8 (S.D.) GPa, respectively. Again, the P group showed a significantly lower flexural modulus than the other three groups ($p < 0.05$).

The effects of deflecting the wire to 2.00 mm during loading and unloading are shown in Fig. 7. In all the wires, the load increased with increasing deflection. The load–deflection curves of the control, HCCP, and R groups were linear up to 1.1 mm, while that of the P group was linear up to 0.8 mm, and the slope decreased thereafter. After unloading, the permanent distortions of the control, HCCP, R, and P groups were 0.28, 0.25, 0.27, and 0.38 mm, respectively.

Friction test

The maximum static frictional force of the HCCP group was significantly lower than those of the other three groups in both dry and wet conditions (Dry: control group: $p = 0.0076$, R group: $p < 0.001$, P group: $p < 0.001$; wet: control group: $p = 0.04$, R group: $p < 0.001$, P group: $p < 0.001$). The maximum static frictional forces of the R group were significantly greater than those of the other three groups in both dry and wet conditions. (Dry: HCCP group: $p < 0.001$, control group: $p < 0.001$, P group: $p < 0.001$; wet: HCCP group: $p < 0.001$, control group: $p < 0.001$, P group: $p < 0.001$). No significant difference in the maximum static frictional force was observed between the control group and the P group in both dry and wet conditions (Dry: $p = 0.89$; wet: $p = 0.64$) (Tables 2a, 2b, Fig. 8a,b). The kinetic frictional forces of the HCCP group were significantly lower than those of the other three groups in both dry and wet conditions (Dry: control group: $p = 0.049$, R group: $p < 0.001$, P group: $p = 0.0067$; Wet: control group: $p = 0.035$, R group: $p < 0.001$, P group: $p < 0.001$). The kinetic frictional forces of the R group were significantly greater than those of the other three groups in both dry and wet conditions (dry: HCCP group: $p < 0.001$, control group: $p < 0.001$, P group: $p < 0.001$; wet: HCCP group: $p < 0.001$, control group: $p < 0.001$, P group: $p < 0.001$). No significant difference in the kinetic frictional forces was observed between the control group and the P group in both dry and wet conditions (Dry: $p = 0.85$; wet: $p = 0.70$) (Tables 3a, 3b, Fig. 9a,b). A comparison of the maximum static frictional forces between dry and wet conditions revealed significantly lower friction in the control and R groups (control group: $p = 0.04$, HCCP group: $p < 0.09$, R group: $p = 0.02$, P group: $p = 0.13$) (Fig. 10a).

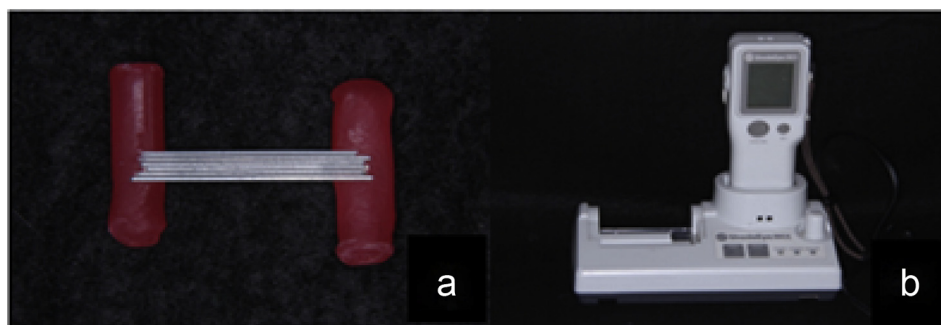


Figure 5 a, Wire sample devised for colorimetric measurement 0.5× magnification. b, The colorimeter (Shade Eye, Shofu, Kyoto, Japan) 1× magnification.

A comparison of the kinetic frictional forces between dry and wet conditions revealed significantly lower friction in the P group (control group: $p = 0.20$, HCCP group: $p < 0.08$, R group: $p = 0.11$, P group: $p = 0.04$) (Fig. 10b).

SEM observation

Prior to the friction test, the uncoated wire surface of the control group was smooth in all the studied samples

(Fig. 10, A-1). There were very small protrusions on the wire surfaces in the HCCP group (Fig. 11, B-1). The wire surfaces of the P group had small cracks (Fig. 11, C-1). The wire surfaces of the R group showed protrusions (Fig. 11, D-1). After the friction test, cracks were observed on the coating surface in the P group (Fig. 11, C-2), while scratches were seen on the surfaces in the control group, R group, and HCCP group (Fig. 11, A-2, B-2, and D-2, respectively).

Color measurement

Table 4 shows the ΔE^* score of each group; a small ΔE^* score indicates that the color is close to VA1. The ΔE^* scores of the control, HCCP, R, and P groups were 17.42 (Ave.) \pm 0.17 (S.D.), 11.60 (Ave.) \pm 0.53 (S.D.), 12.88 (Ave.) \pm 0.28 (S.D.), and 6.49 (Ave.) \pm 0.27 (S.D.), respectively. Thus, the P group showed a ΔE^* value significantly lower than those of the other three groups ($p < 0.05$).

Discussion

The flexural strength and flexural modulus of the HCCP wire were not significantly different from those of the control group (Fig. 6), indicating that there was no change in the mechanical properties of the wire by HCCP processing. Ryu et al. had examined the mechanical properties of white-coated arch wires for aesthetics; the white-coated wires were found to have inferior mechanical properties compared to the control wire.²² Muguruma et al. evaluated the mechanical properties of the coating covering aesthetic orthodontic arch wires, reporting that the aesthetic coated wires with smaller inner cores might produce less orthodontic force than expected.¹⁵ In this study, the flexural strength and flexural modulus of the P group were found to be significantly lower than those of the other groups. Since the HCCP wire shows no reduction in mechanical properties compared to the control group, it can be used like stainless steel wires in the clinical treatment.

During orthodontic treatment, the frictional force depends on various factors including the material, surface texture, and strength of ligation between the brackets and wires. The basic concept of friction follows the Amon-ton–Coulomb laws: 1) The frictional force does not depend

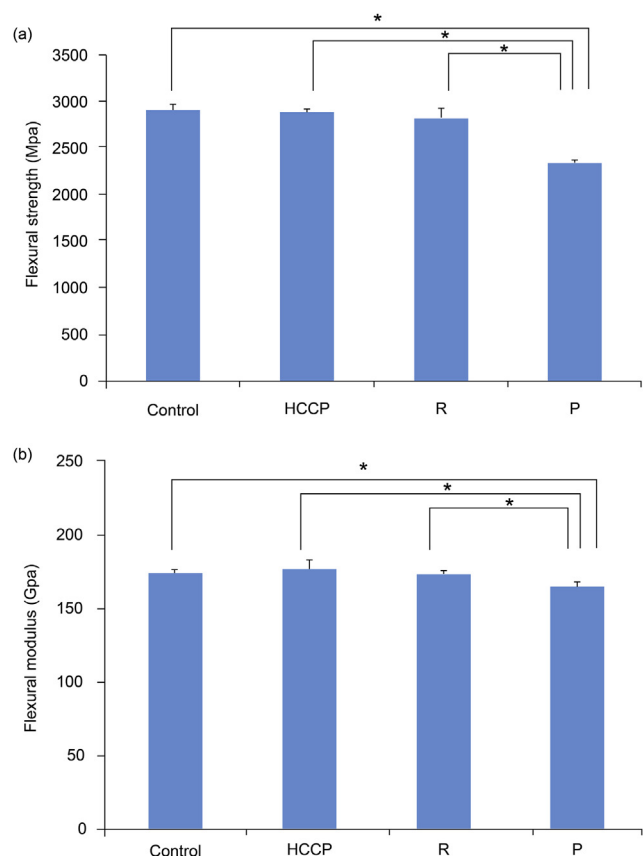


Figure 6 Flexural properties of four wires. a, Flexural strength; P group showed significantly lower flexural strength than other three groups ($p < 0.05$). b, Flexural modulus; P group showed significantly lower flexural strength than other three groups ($p < 0.05$).

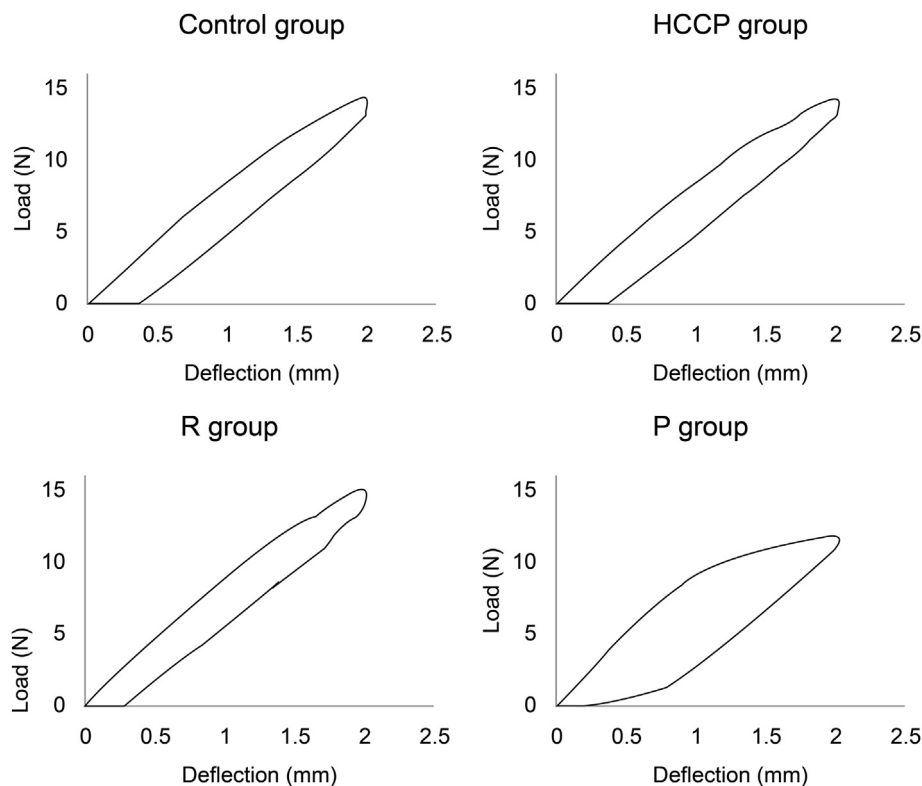


Figure 7 Typical load–deflection curves of the four wires. The middle portion of each wire was deflected to 2.00 mm.

on the apparent contact area; 2) The frictional force is proportional to the vertical load; 3) The frictional force is independent of the movement speed; 4) The static frictional force is larger than the kinetic frictional force. In the 18th century, the uneven theory was proposed, which attributed the generation of the frictional force to passage

Table 2a The mean and standard deviation of maximum static frictional forces in dry condition.

Name	Mean	SD
Control	147.15	18.51
HCCP	124.61	6.77
R	216.29	12.85
P	151.73	17.35
Tukey's test	HCCP < Control = P < R	

Table 2b The mean and standard deviation of maximum static frictional forces in wet condition.

Name	Mean	SD
Control	143.55	22.36
HCCP	121.41	10.72
R	210.21	11.03
P	147.13	13.00
Tukey's test	HCCP < Control = P < R	

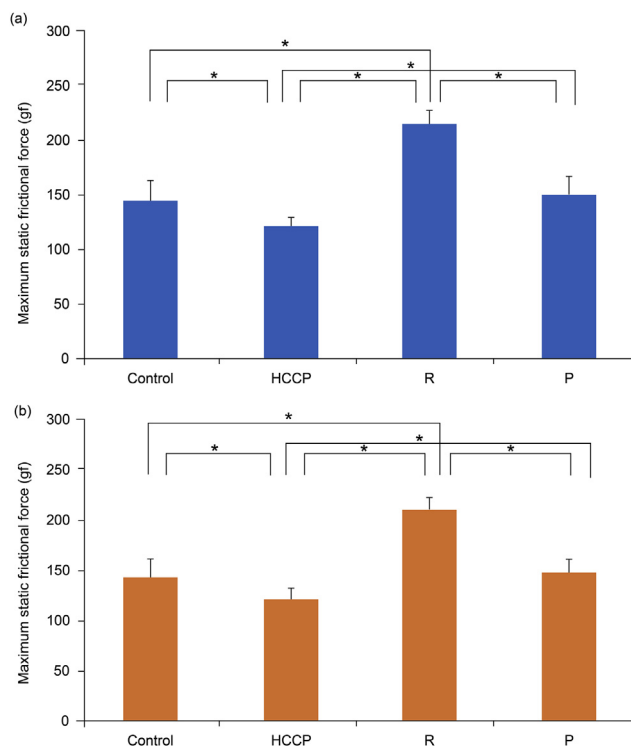


Figure 8 a, Maximum static frictional forces in dry condition (1 gf = 9.8 mN). b, Maximum static frictional forces in wet condition (1 gf = 9.8 mN).

Table 3a The mean and standard deviation of kinetic frictional forces in dry condition.

Name	Mean	SD
Control	124.5	20.50
HCCP	102.88	4.01
R	185.59	26.69
P	130.83	11.49
Tukey's test	HCCP < Control = P < R	

Table 3b The mean and standard deviation of kinetic frictional forces in wet condition.

Name	Mean	SD
Control	121.99	18.84
HCCP	100.28	5.01
R	182.83	26.30
P	127.94	11.13
Tukey's test	HCCP < Control = P < R	

over the irregularities on the surface of the object.²³ However, even when the surface of the metal was polished cleanly, the frictional force was found to increase. Thus, this theory was not a comprehensive one. In the 20th century, an adhesion theory was proposed instead of the

earlier uneven theory. The actual contact area is less than 10% of the apparent contact area. In the protruding part of the real contact part, the object plastically deforms and adheres. The shear force generated at this adhesion part was considered to be the cause of the frictional force.²⁴ Cohesion between ceramics and metals has also been reported to affect friction.²⁵ The surface roughness of the object is related to the change in the frictional force; however, the relationship is not a proportional one. Muguruma et al. evaluated the frictional force of the aesthetic orthodontic arch wire and reported that they were proportional to neither the surface roughness of the wire nor the frictional force.²⁶ In comparisons between the wet and dry conditions, the frictional force in the wet condition tended to be decreased. In the condition where moisture exists between the bracket slot and the wire, the frictional force decreases by lubricating action. The presence of saliva in the oral cavity may reduce the frictional force.

In this study, protrusions were confirmed in the SEM images of the wires of the HCCP group and the R group. However, the frictional force of the R group was larger than those of the other three groups, whereas the frictional force of the HCCP group was smaller than those of the other three groups. This implied that the real contact area of HCCP was small. It has been previously reported that microprojections reduce the real contact area and consequently reduce friction.²⁷

The color of the HCCP wire was not significantly different from that of the commercial aesthetic wire (R

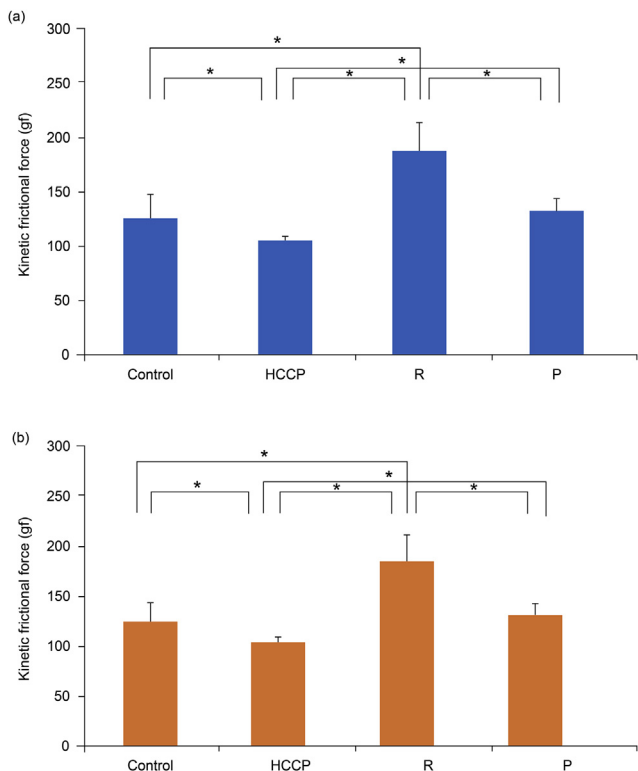


Figure 9 a, Kinetic frictional forces in dry condition (1 gf = 9.8 mN). b, Kinetic frictional forces in wet condition (1 gf = 9.8 mN).

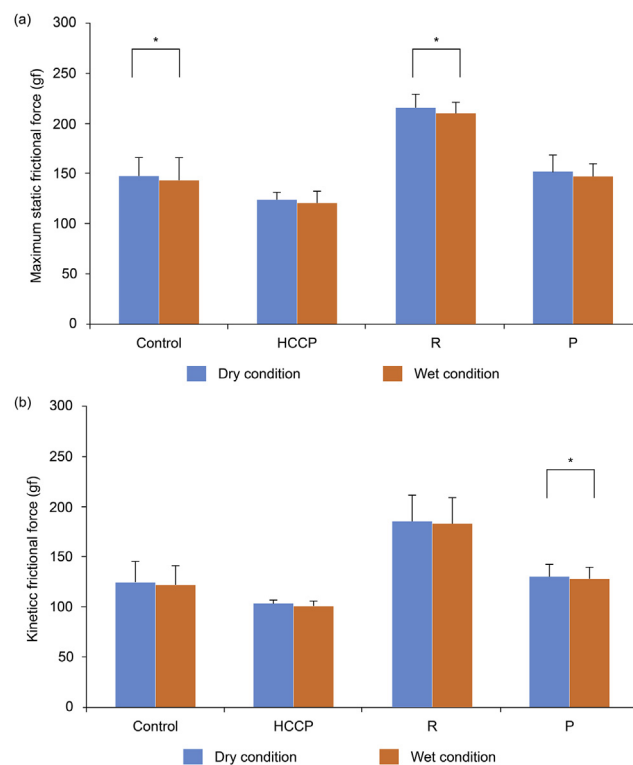


Figure 10 a, Maximum static frictional forces between dry and wet conditions (1 gf = 9.8 mN). b, Kinetic frictional forces between dry and wet conditions (1 gf = 9.8 mN).

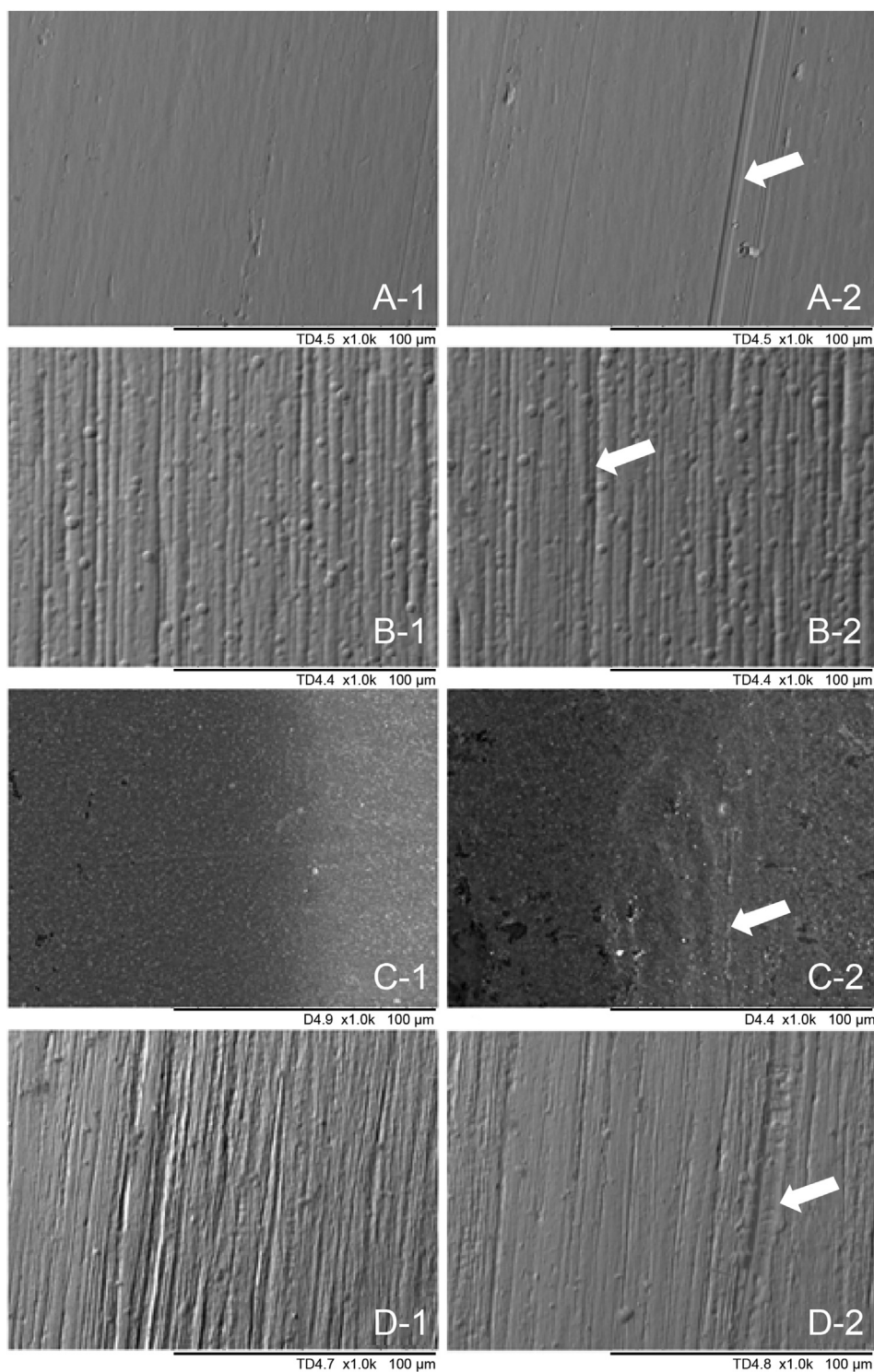


Figure 11 Micrographs of wires of dimensions 0.017 inch \times 0.025 inch at 1000 \times magnification. a, Control group; b, HCCP group; c, P group; d, R group.

group). The P group color was closest to VA1. The coatings of the HCCP group and R group were obtained by metal plating. On the other hand, the P group coating was a polymer coating, which is excellent in reproducing tooth color. However, it is known to have problems with durability.²⁸ Metal-plated wires, such as the HCCP and R groups, were white and shiny. Douglas et al. reported that the

predicted value at which 50% of dentists perceived a color difference was 2.6 ΔE^* .²⁹ The ΔE^* value of the HCCP group was greater than this (Table 4). Therefore, the color of the HCCP wire should be improved.

The results of the three-point bending tests suggest that HCCP does not change the mechanical properties of orthodontic wires. HCCP-coated wires were found to have

Table 4 The mean and standard deviation of ΔE^* scores.

Name	Mean (ΔE^*)	SD
Control	17.42	0.17
HCCP	11.60	0.53
R	12.88	0.28
P	6.49	0.27
Tukey's test	P < HCCP = R < Control	

less friction than other wires, which could promote smoother orthodontic treatment. The colorimetric test results suggest that the aesthetics of the HCCP wire were equivalent to those of R group wire. However, the color of the HCCP wire requires improvement, which will be addressed in future studies.

Conflicts of interest statement

The authors declare no conflict of interest.

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References

- Kim Y, Cha JY, Hwang CJ, Yu HS. Comparison of frictional forces between aesthetic orthodontic coated wires and self-ligation brackets. *Korean J Orthod* 2014;44:157–67.
- Andreasen GF, Quevedo FR. Evaluation of friction forces in the 0.022×0.028 edgewise bracket in vitro. *J Biomech* 1970;3:151–60.
- Redlich M, Mayer Y, Harari D, Lewinstein I. In vitro study of frictional forces during sliding mechanics of "reduced-friction" brackets. *Am J Orthod Dentofac Orthop* 2003;124:69–73.
- Drescher D, Bourauel C, Schumacher HA. Frictional forces between bracket and arch wire. *Am J Orthod Dentofac Orthop* 1989;96:397–404.
- Liu X, Ding P, Lin J. Effects of bracket design on critical contact angle. *Angle Orthod* 2013;83:877–84.
- Kapila S, Angolkar PV, Duncanson Jr MG, Nanda RS. Evaluation of friction between edgewise stainless steel brackets and orthodontic wires of four alloys. *Am J Orthod Dentofac Orthop* 1990;98:117–26.
- Kaphoor AA, Sundareswaran S. Aesthetic nickel titanium wires – how much do they deliver? *Eur J Orthod* 2012;34:603–9.
- Elayyan F, Silikas N, Bearn D. Mechanical properties of coated superelastic archwires in conventional and self-ligating orthodontic brackets. *Am J Orthod Dentofac Orthop* 2010;137:213–7.
- Kusy RP, Tobin EJ, Whitley JQ, Sioshansi P. Frictional coefficients of ion-implanted alumina against ion-implanted beta-titanium in the low load, low velocity, single pass regime. *Dent Mater* 1992;8:167–72.
- Farronato G, Maijer R, Caria MP, Esposito L, Alberzoni D, Cacciatore G. The effect of Teflon coating on the resistance to sliding of orthodontic archwires. *Eur J Orthod* 2012;34:410–7.
- Husmann P, Bourauel C, Wessinger M, Jäger A. The frictional behavior of coated guiding archwires. *J Orofac Orthop* 2002;63:199–211.
- Suzuki C. Hard chrome plating under oil-free conditions. *J Surf Finish Soc Jpn* 1988;35:336–40.
- Simpo R. Properties of hard chrome plating. *J Surf Finish Soc Jpn* 2014;65:123–8.
- Amifune H, Fujiwara H. *Gendai mekki kyohon*. Tokyo: Nikkan Kogyo Shimbunsha, 2011.
- Muguruma T, Iijima M, Yuasa T, Kawaguchi K, Mizoguchi I. Characterization of the coatings covering esthetic orthodontic archwires and their influence on the bending and frictional properties. *Angle Orthod* 2016 Oct 12. <https://doi.org/10.2319/022416-161.1> [Epub ahead of print].
- Katić V, Curković HO, Semenski D, Barsić G, Marusić K, Spalj S. Influence of surface layer on mechanical and corrosion properties of nickel–titanium orthodontic wires. *Angle Orthod* 2014;84:1041–8.
- Kim IH, Park HS, Kim YK, Kim KH, Kwon TY. Comparative short-term in vitro analysis of mutans streptococci adhesion on esthetic, nickel–titanium, and stainless-steel arch wires. *Angle Orthod* 2014;84:680–6.
- Stannard JG, Gau JM, Hanna MA. Comparative friction of orthodontic wires under dry and wet conditions. *Am J Orthod* 1986;89:485–91.
- da Silva DL, Mattos CT, Simão RA, de Oliveira Ruellas AC. Coating stability and surface characteristics of esthetic orthodontic coated archwires. *Angle Orthod* 2013;83:994–1001.
- Toshihiro I, Yasuhiro T, Naomi M, Masaru Y, Kazutaka K. Color stability of laboratory glass–fiber-reinforced plastics for esthetic orthodontic wires. *Korean J Orthod* 2015;45:130–5.
- O'Brien WJ, Hemmendinger H, Boenke KM, Linger JB, Groh CL. Color distribution of three regions of extracted human teeth. *Dent Mater* 1997;13:179–85.
- Ryu SH, Lim BS, Kwak EJ, Lee GJ, Choi S, Park KH. Surface ultrastructure and mechanical properties of three different white-coated NiTi archwires. *Scanning* 2015;37:414–21.
- Yamamoto Ryuji. Mechanism of friction and real contact area. *JTEKT Eng J* 2007;1003:2–8.
- Matsukawa H. Physics of friction. *J Surf Sci Soc Jpn* 2003;24:328–33.
- Ishigaki H. Friction and wear of ceramics. *Iron Steel Ind Jpn* 1986;9:13–8.
- Muguruma T, Iijima M, Brantley WA, Ahluwalia KS, Kohda N, Mizoguchi I. Effects of third-order torque on frictional force of self-ligating brackets. *Angle Orthod* 2014;84:1054–61.
- Ando Y, Tanaka T, Ino J, Kakuta K. Relations among friction and pull off forces and surface geometry in nano meter scale. *Jpn Soc Mec Eng* 1999;65:306–13.
- Rongo R, Ametrano G, Gloria A, Spagnuolo G. Effects of intraoral aging on surface properties of coated nickel–titanium archwires. *Angle Orthod* 2014;84:665–72.
- Douglas R, Steinhauer T, Wee S. Intraoral determination of the tolerance of dentists for perceptibility and acceptability of shade mismatch. *J Prosthet Dent* 2007;97:200–8.