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Friction and wear behaviors of dental ceramics against natural tooth enamel

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Abstract

The friction and wear behaviors of dental ceramics against the natural tooth enamel were investigated. In this study three dental ceramics, namely zirconia with both polished and rough surfaces, hot-forged lithium disilicate glass ceramics and silicates based veneer porcelain were involved with two metallic materials, gold–palladium alloy and Nickel–chromium alloy, as references. The tribological tests were carried out under artificial saliva lubrication condition by using freshly extracted natural teeth and samples with controlled surface roughness. The frictional coefficients versus reciprocating cycles were recorded. Scanning Electron Microscopy was used to observe the topography of worn teeth enamel surfaces and antagonists. The frictional coefficient of enamel against gold palladium alloy or Nickel–chromium alloy was the smallest. The frictional coefficient of enamel against polished zirconia or porcelain was between that of metal and glass-ceramic. Upon surface polishing, frictional coefficient between zirconia and enamel was radically decreased. Furrows and granular debris were observed on the worn surfaces of enamel while sliding against the rough zirconia or glass ceramic, indicating a abrasive wear mechanism. While chipping flake and pit-like structure after stripping and crack were observed on the enamel surface while sliding against polished zirconia or Nickel–chromium alloy, indicating a type of fatigue wear. It appeared that the friction and wear performances of zirconia could be improved significantly by adequate surface polishing. This observation indicated that attention must be paid to carefully design proper occlusal surface contours and correctly choose dental materials in clinical practice.

Keywords: Dental ceramics; Enamel; Friction; Wear; Surface; Microstructure

1. Introduction

Artificial dental restorations made of metal or porcelain fused to metal has been used in clinic for a long time. Although their biological safety has been proved by long-term in vivo application, the dental restorations often endure clinical failures, e.g. the progressive occlusal height reductions appears as a result of friction and wear between natural teeth and restorations under mastication cycles in oral environment. In clinical practice, excessive wear of opposite natural teeth is frequently observed when Nickel–chromium alloy (Ni–Cr alloy) is used for making crowns, whereas occlusal surface perforation of the crowns made of noble metal alloy may remain after long time service. The proper selection of restorative materials is thus important for preserving normal occlusal function.

Surface wear of enamel is a physiological process going with the opposite movement between upper and lower teeth through the uncountable mastication cycles in whole life. In the oral cavity, the wear between enamel mainly shows abrasive wear style.[1] The wear style changes to three body wear type with food addition. The properties of food, i.e. grain size and hardness, would affect the friction and wear procedure of natural teeth.[2] In addition, saliva acts as a lubricant significantly reducing the frictional coefficient and wear rate during the mastication process.[3]

What the clinicians care mostly is that how to avoid the pathological damage of natural teeth during the friction process between restorations and natural teeth. It is therefore of particular interest to carry out in vitro friction tests between dental materials and natural teeth.[3–6] The tribological behaviors between dental restorations and enamel are mainly determined by the mechanical properties and superficial microstructure as well as topography of the restoration materials. The friction and wear performances of dental crowns are directly affected by the surface finishing. In general, the frictional coefficient between enamel and polished restorations is smaller than that of rough restorations.[5,7] Additionally, the environmental influences should not be ignored.[7,8]

During the last two decades, ceramic materials, including veneer porcelains, glass ceramics and zirconia ceramics, etc.

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have been widely used in dental practice because of their aesthetics, chemical stability and biocompatibility. Initially, zirconia ceramic parts were just applied as the cores for manufacturing dental crowns in the form of bi-layer restorations, with veneer porcelain shells fused on them. Therefore, the porcelain made of softer amorphous silicates is the one that comes in contact with the natural tooth structure. Nowadays, by increasing the translucency of zirconia ceramics, full contour zirconia crowns are used to reestablish the posterior teeth. This type of ceramic restorations made of one single material by computer assistant design (CAD) and computer assistant machining (CAM) approach shows excellent mechanical properties. It has become a very attractive dental solution, because it can totally avoid the porcelain chipping problem commonly encountered in ceramic crowns of bi-layer structure.[9]

Taking into account the rigidity and elastic modulus of zirconia that are much higher than that of enamel,[10,11] a great worry has been brought in clinic: would natural teeth be damaged by excessive wear and/or stress concentration caused by mechanical mismatching between zirconia and natural enamel? So far, tooth pathological wear has not yet been confirmed due to the short application time of the full contour zirconia crowns. In vitro test was demanded for clarifying the actual damage patterns of enamel by the friction and wear between natural teeth and restorations made of, besides zirconia, also other dental ceramics. It is known that the friction and wear between dental ceramics and natural teeth are affected by the stress and chemical circumstance in oral environment. In normal procedure of chewing movement with saliva acting as a lubricant, the masticatory force is about 3–36 N, and the sliding distance between the bite contacted teeth is about 0.9–1.2 mm.[12,13] In vitro friction tests of dental ceramics have been carried out in the past by using steatite ceramics as a standard antagonist instead of enamel.[14] This does not reflect the exact oral conditions. The wear tests using natural teeth and dental materials are more desirable for collecting information that may guide clinical practice, as wear pairs under oral stress and chemical circumstances.

In the present work, the wear behaviors of the natural enamel against dental materials were characterized by in vitro friction tests under simulated oral stresses and chemical environment. The frictional coefficients between enamel and dental materials were calculated and compared. In addition, the effect of the surface roughness of zirconia restorations on the frictional coefficient and enamel wear performances was investigated.

2. Experimental procedures

2.1. Samples preparation

2.1.1. Natural enamel samples

Four premolars without obvious wear scar, extracted for orthodontic demand, were collected from a 13-year aged young male, and preserved in distilled water at 4 °C for sample preparation. Each tooth was embedded in epoxy resin (SY-668-3, SenMeiYa, China) after pulpless, with the enamel of buccal surface (at least 5 × 5 mm area) exposed. The enamel surface was then grounded by carborundum sand paper in water, gradually from 180 to 1500 mesh, and polished by 1 μm diamond sand paper. The final dimension of the epoxy resin block was 30 mm diameter and 10 mm thickness. The samples were stored in distilled water during the whole test process.

Table 1
The chemical composition of artificial saliva.

NaCl (g)	0.4
KCl (g)	0.4
$CaCl_2·2H_2O$ (g)	0.795
$NaH_2PO_4·2H_2O$ (g)	0.78
$Na_2S·9H_2O$ (g)	0.005
Urea (g)	1
Distilled (ml)	1000

2.1.2. Dental materials samples

Three types of dental ceramics and two types of metal alloys that are popularly used in dental practice were tested as antagonists. The test samples were fabricated to hemisphere, with the radius of 2 mm, to simulate the dimension of natural tooth cusp with the radius of 2–4 mm. Two zirconia ceramic samples were made from powder of 3Y-TZP (doped with 3 mol% Y_2O_3, TOSOH, Japan) by cold isostatic pressing (CIP) followed by pressure-less sintering (PLS) in air. The hemispherical geometry was produced by CAD/CAM grinding of pre-sintered blanks. One zirconia sample was polished, whereas the other was left with a sintered rough surface. The lithium disilicate glass ceramic sample (IPS Empress, Ivoclar, Switzerland) was made by hot press casting. The veneer porcelain sample (Rondo, Nobel Biocare AB, Gothenburg, Sweden) was shaped and sintered according to the recommendations of the dental laboratory procedure. The metallic samples, gold–palladium alloy (Au–Pd alloy) (Heraeus, Germany) and Ni–Cr alloy (Heraeus, Germany), were made by wax losing casting. All the samples were grounded by carborundum sand paper in water, gradually from 180 to 1500 mesh, and polished by 1 μm diamond sand paper.

2.2. Friction and wear tests

The wear pairs of the plates of natural teeth and balls of six kinds of dental materials were tested by a micro friction and wear testing apparatus (UMT-2, CETR, USA) in reciprocating ball on plat pattern style. Throughout the testing procedure the natural tooth was always immersed in artificial saliva, even while cleaning the samples before the experiment. The friction and wear tests were controlled by a computer. The relation between surface friction and displacement at every cycle was recorded. The frictional coefficient was automatically calculated and recorded by the UMT-2 control software.

The chemical composition of the artificial saliva that was used to simulate the actual oral condition was showed in Table 1.[15] The enamel samples were tested with antagonist made by 5 dental materials under constant static load, vertical load 4 N, and cyclic friction with back-and-forth movement pattern. Every enamel sample was tested with four different antagonists, each for 5000 cycles, at frequency 2 Hz and sliding displacement 1 mm.

2.3. Characterization of the worn surfaces

The wear scars on the worn surfaces of teeth enamel and on that of antagonist hemispheres were investigated by a scanning electron microscope (SEM, SSX-550, and Shimadzu, Japan). The widths of worn scars were also measured.

3. Results and discussion

The ideal restorative dental materials should have similar tribological behaviors with natural enamel, in regard to surface roughness, frictional coefficient and wear mechanism, so as to avoid excessively abrasion of natural teeth. The mechanical properties of dental ceramics, such as zirconia with flexural strength >1000 MPa, elastic modulus 210 GPa, and hardness 10 GPa, are far above that of human enamel with flexural strength 280 GPa, elastic modulus 94 GPa and hardness 3.2 GPa.[16,17] Presence of ceramic artificial crowns may change the normal wear process between natural teeth.

3.1. Friction behaviors

3.1.1. The frictional coefficient of natural enamel against artificial materials related not only to the mechanical property but also the microstructures of the materials

Frictional coefficient is a very important parameter that reflects the intrinsic interaction characteristics of tribology. An ideal dental restoration should have appropriate frictional coefficient with natural teeth for the benefit of chewing food without excessive abrasion of natural teeth. In the present study, the wear behaviors of enamel were studied directly by wear tests against different dental materials commonly used as antagonist. The enamel samples and antagonists were tested in artificial saliva under similar stress and sliding distance with human teeth to mimic the oral chemical environment.[18] The results showed that the frictional coefficients of enamel against dental materials were different in relation to the hardness, elastic modulus, and surface finishing of the materials.

Fig. 1 showed the frictional coefficient of natural enamel against two dental alloys and three dental ceramics plotted versus the number of cycles. It appeared that the average frictional coefficients of enamel against Ni–Cr and Au–Pd alloys were very similar, at the lowest value of ~0.2 among all the tested materials. The polished Zirconia and veneer porcelain showed high average frictional coefficient of ~0.55. The frictional coefficient of Empress Glass ceramic was a little higher, at 0.6l. The average frictional coefficient of enamel against rough zirconia was the highest, at 0.65.

Au–Pd alloy has been used as good material for artificial dental restorations for long time. Although its metallic color limits its use in clinic, many clinicians would like to choose Au–Pd alloy for posterior teeth restorations, owing to its prominent advantages of avoiding excessive wear abrasion of opposite teeth. Yet, Au–Pd crowns themselves sometimes

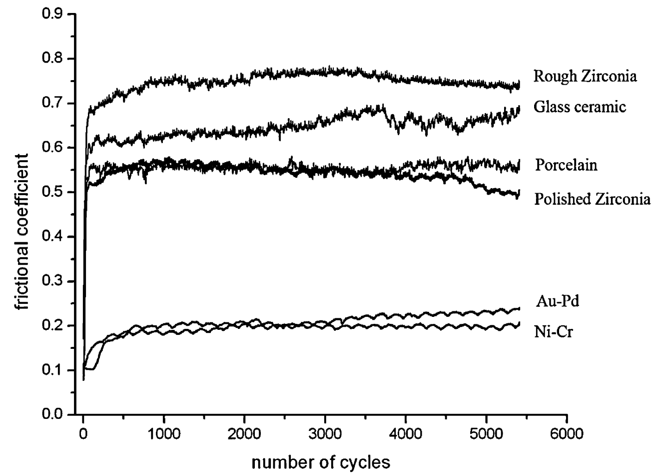

Fig. 1. The frictional coefficient of natural enamel against different dental materials plotted versus the number of cycles.

failed by perforation after long time friction against natural teeth.[19,20] Our results revealed a low frictional coefficient of enamel against Au–Pd alloy that was in consistence with previous observations.[21]

The observed frictional coefficient of enamel against Empress glass ceramics was higher than that against polished zirconia and porcelain, which was due to the microstructure of it. Empress glass ceramic sample was composed of the noodle shaped lithium disilicate crystalline grains embedded in a glass matrix. During the abrasive wear against enamel, the glass matrix was worn away more quickly than the lithium disilicate crystalline grains because of its lower strength and hardness. The accordingly increased surface roughness induced the highest frictional coefficient in this test.

3.1.2. The frictional coefficient strongly influenced by surface roughness of artificial materials

In our study, the observed frictional coefficient of enamel against rough zirconia was the biggest in the test groups, which is ~0.65, whereas that against polished zirconia was, reduced to ~0.5 almost the same as against veneer porcelain. The high strength and toughness of zirconia enabled it to resist surface damage under stress. So the surface of polished zirconia antagonist kept its fineness during long time frictional process, presenting a stable frictional coefficient over time. This point was also confirmed by the SEM observation of the zirconia worn surface.

3.2. Wear behaviors

Analyzing the frictional coefficient was not enough to understand the tribological properties of dental ceramics and natural teeth. Wear mechanism was clarified by the micro morphological analysis. At first, the worn type between enamel and dental material antagonists (including adhesive wear, abrasive wear, fatigue wear and corrosive) was indicated.[22] In this study, all the wear scars were obtained under neutral environments, supposing without chemical reaction layer between enamel and dental

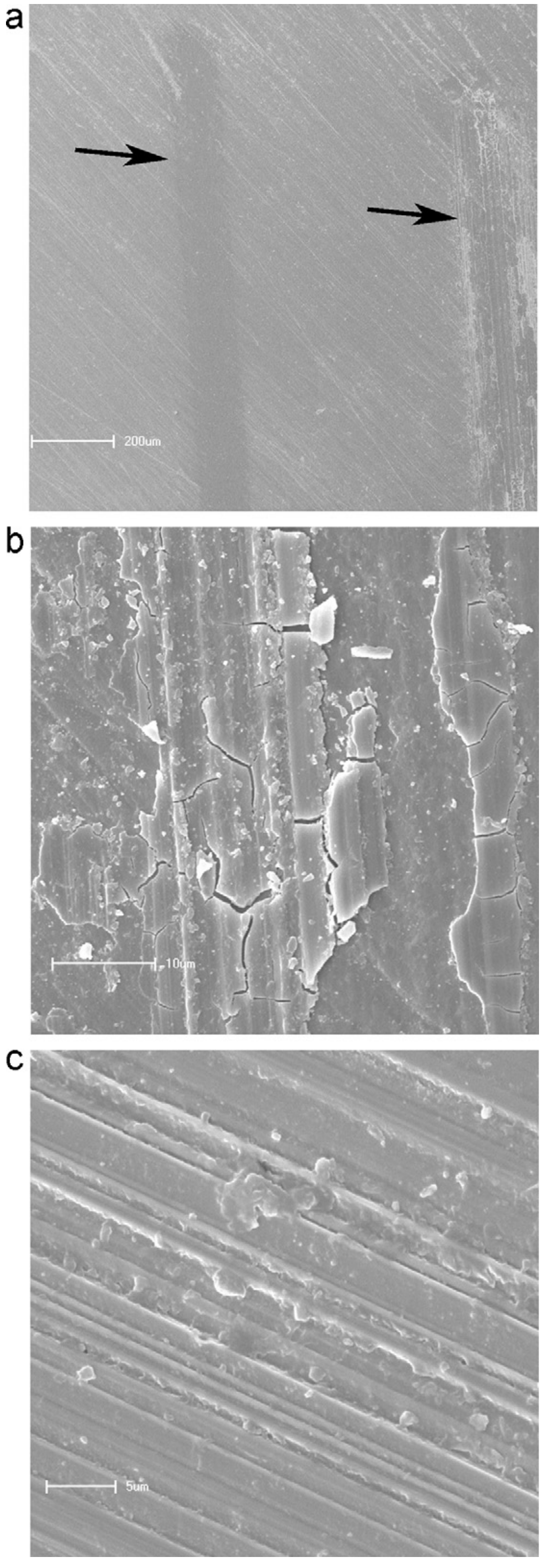

Fig. 2. SEM images of the worn surface of natural enamel after wear teats for 5400 cycles against two metal alloys (a), where the narrow and smooth scar marked by arrow in the left was produced against Au–Pd alloy, whereas wider scar in the right was produced against Ni–Cr alloy. The high magnification image of wear scar produced against Ni–Cr alloy revealed the presence of cracks and chipping of enamel (b). The high magnification image of the worn surface of Ni–Cr alloy antagonist showed the presence of small granules within the deep furrows that may be the enamel fragments chipped off (c).

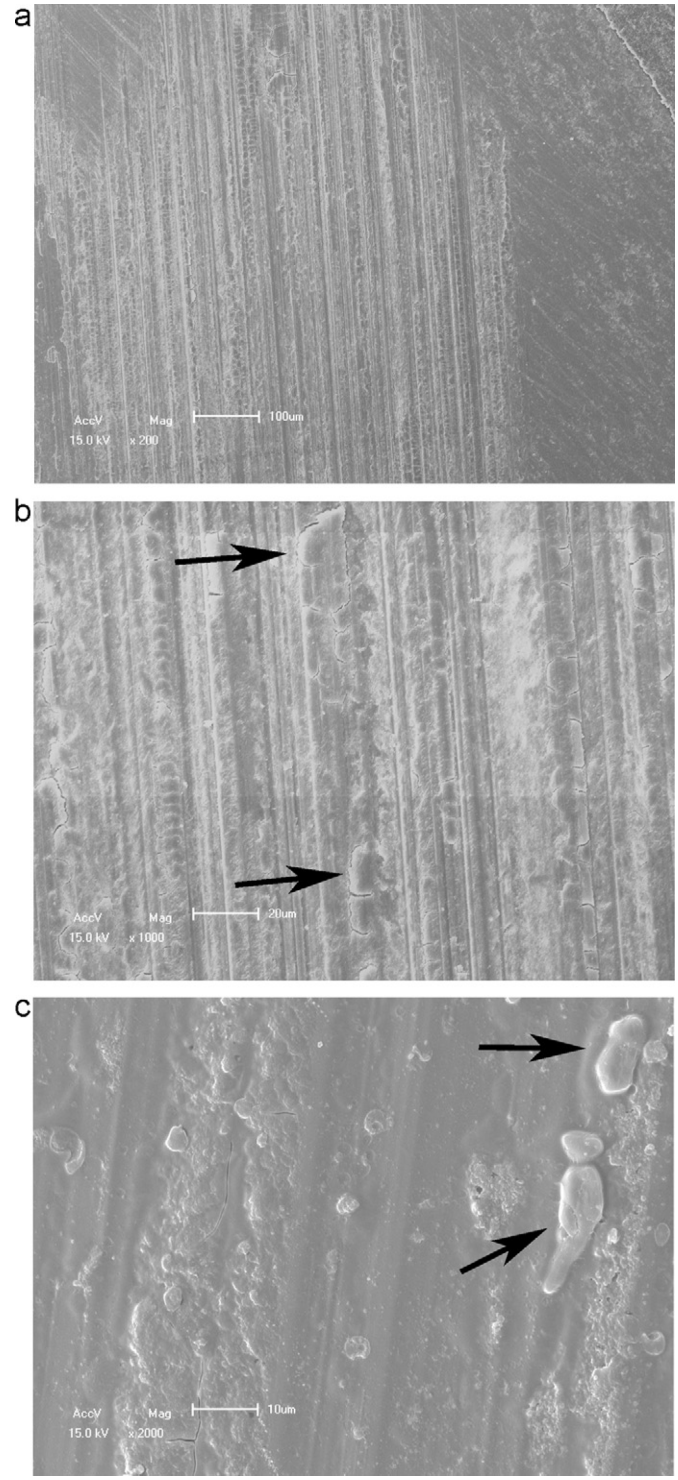

Fig. 3. SEM images of the worn surface of enamel after wear test for 5400 cycles against Empress showing the formation of rough parallel furrows (a). A high magnification image of "a" revealing the formation of small cracks (marked by arrows) within the furrows (b). The observed particles sticking on the on the surface of Empress antagonist was ascribed to the accumulation of chipped off enamel and glass ceramic particles (c).

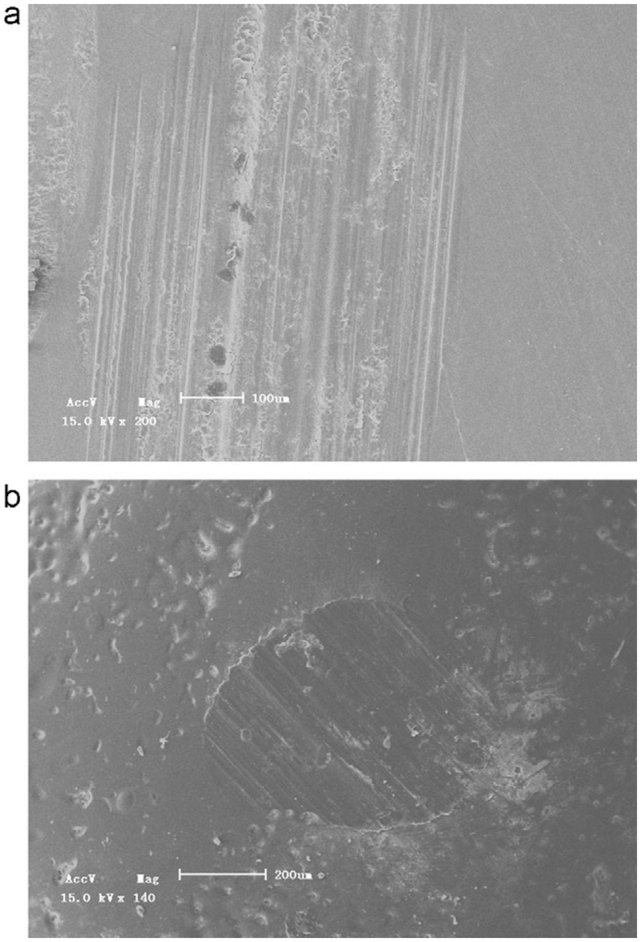

Fig. 4. SEM micrograph of the worn surface of enamel after wear test for 5400 cycles against porcelain showing the formation of parallel furrows (a). Similar paralleled furrows were also observed on the surface of porcelain antagonist (b).

materials. Therefore, corrosive wear was not considered in this study. Furthermore, the detail analysis of wear scars on the worn surfaces of enamel against dental materials was beneficial to exploring whether enamel abraded excessively during the frictional procedure between dental crowns and natural teeth and to understanding the damage process of the enamel.

3.2.1. The wear behaviors of teeth enamel

Table 2 showed the widths of wear scars on worn surface of enamel after friction test against different testing materials. The widths of the wear scars on the worn surface of enamel against Au–Pd alloy and Ni–Cr alloy were narrow and very similar. While the worn enamel against Empress and porcelain showed the biggest in width. The width of wear scar of enamel against rough zirconia was broader than that against polished zirconia. This tendency was consistent with the change of observed frictional coefficients.

Fig. 2 showed the microstructures of the wear scars on worn surface of enamel after friction test against different testing materials. The wear scar on the worn surface of enamel against Au–Pd alloy antagonist was narrow and smooth, seeing Fig. 2a, indicated the wear damage of enamel was mild. The smooth worn surface and narrow wear scar on it revealed an adhesive

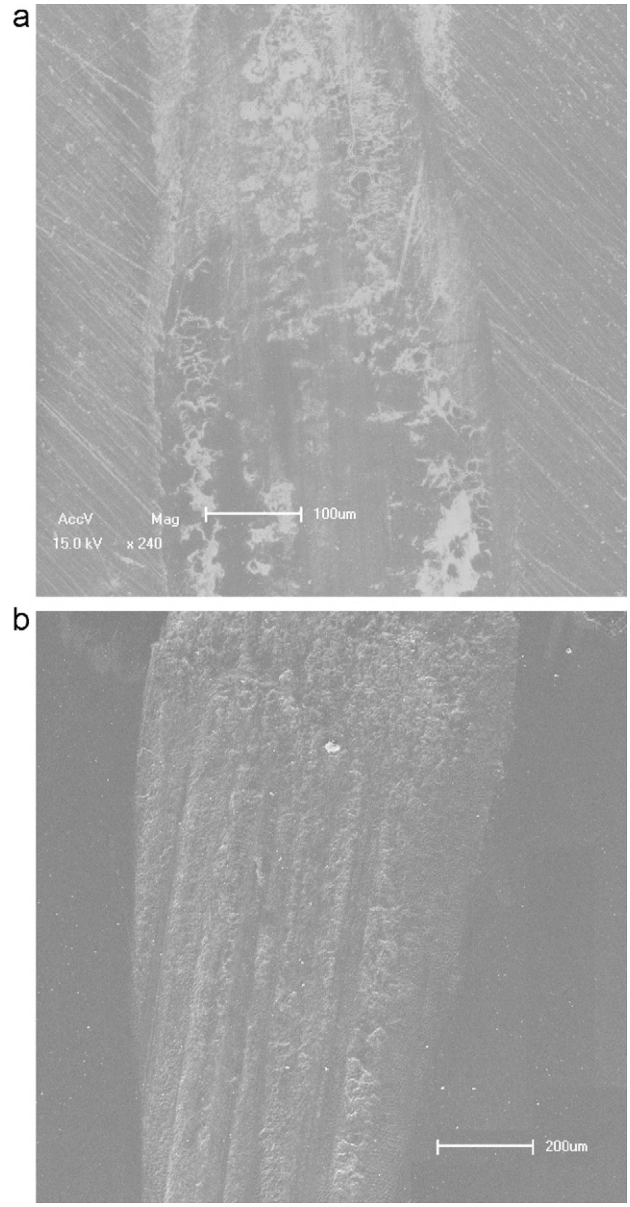

Fig. 5. SEM images of the worn surface of the natural enamel after wear test for 5400 cycles against zirconia. Small cracks and enamel flakes spreading entire wear scar were observed on the worn surface of enamel against polished zirconia (a). Deep parallel furrows were observed on the worn surface of enamel against rough zirconia (b).

wear nature owing to good ductility of Au–Pd alloy. A lot of worn furrows could be observed inside the enamel wear scar against Ni–Cr alloy antagonist. Small cracks and chipping-off were also observed; seeing Fig. 2a and b. Based on the morphology of worn damage, the wear types of enamel against Ni–Cr alloy could be described as a combination of fatigue wear and abrasive wear.

Rough parallel furrows with enamel crack granules were observed in the wear scar of enamel against Empress antagonist, see Fig. 3a and b. This observation indicates that the wear damage of enamel was dominated by abrasive wear. In addition, the extruded lithium disilicate crystalline grains and fragments

Table 2
Widths of enamel wear scars and wear types.

	Au–Pd	Ni–Cr	Polished zirconia	Rough zirconia	Glass ceramic	Porcelain
Wear scars widths (μm)	100	100	200–300	300–400	600	500
Main wear type	Adhesive	Fatigue and adhesive	Fatigue and adhesive	Abrasive and fatigue	Abrasive	Abrasive

during the fractional cycles change the abrasive style from two-body abrasion to three-body abrasion.

It appears that the paralleled furrows are the main structure features on the wear scar of enamel against veneer porcelain antagonist, seeing Fig. 4a, suggesting that wear damage of enamel in this condition was also abrasive wear.

The wear scar of enamel against rough zirconia antagonist was rough and wide. A lot of deep paralleled furrows could be observed, seeing Fig. 5b. Small granules and cracks were also observed, see Fig. 6a and b. The wear damage of enamel against rough zirconia seemed to be dominated by abrasive wear which was aggravated further by fatigue wear under large stress. Whereas, the wear scar on the wear scar of enamel against polished zirconia was much smoother, seeing Fig. 5a, with small reticular cracks spreading inside entire wear scar and a large number of small chipping flakes of enamel, accompanying with the formation of pit-like structure, seeing Fig. 7a and b. This morphology of worn surface revealed that the worn damage of enamel was dominated by fatigue wear. Obviously, the typical deep furrows found in rough zirconia case were not visible in polished zirconia case. Combined with the results of frictional coefficients, it could be described that there was lower wear loss

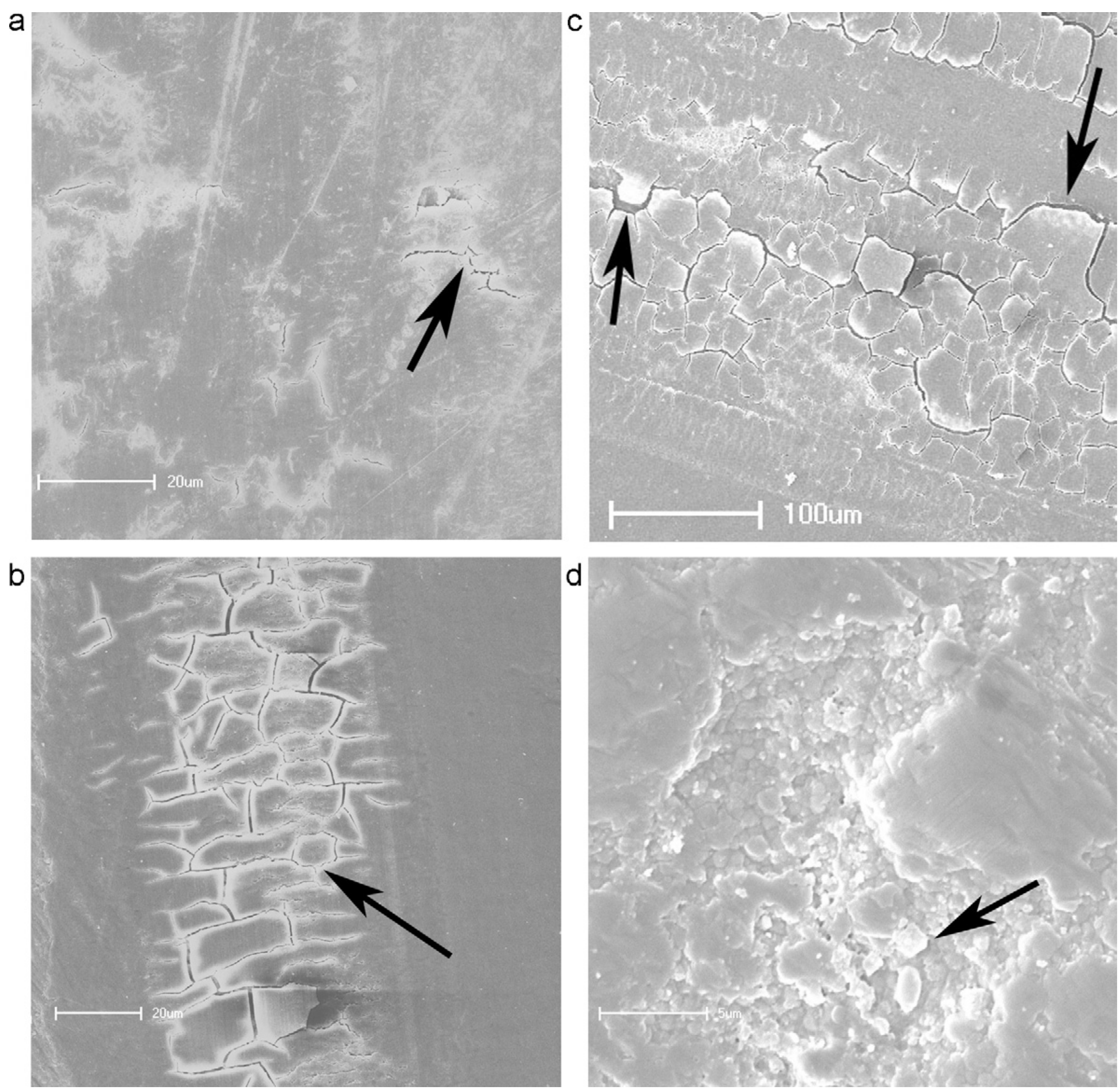

Fig. 6. High magnification SEM micrographs showing the typical damages of enamel against polished zirconia: small cracks (a, marked by arrow), reticular cracks (b) and chipping flakes (c, marked by arrow). The surface damage of zirconia was classified as grains peeling-off (d, marked by arrow).

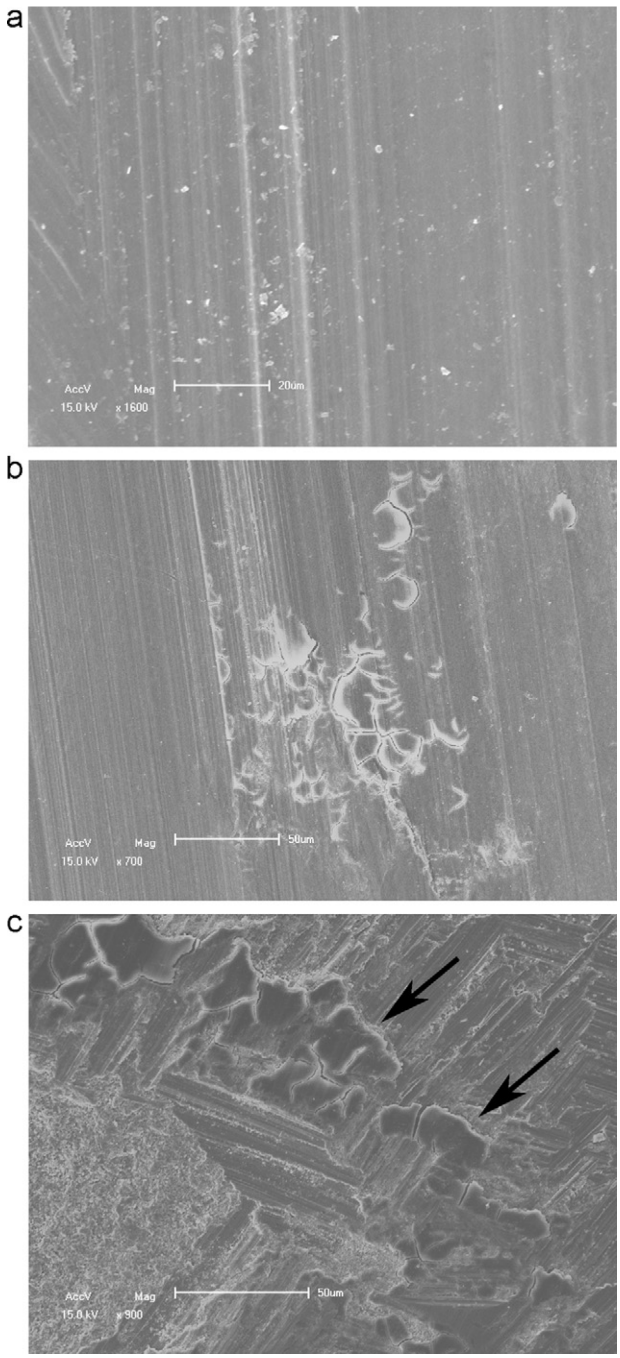

Fig. 7. High magnification SEM micrographs showing the formation of furrows with small particles (a) and small cracks (b) on the worn surface of enamel against rough zirconia. The observed small flakes (marked by arrows) on the surface of antagonist zirconia was ascribed to the accumulation of enamel chipped off (c).

of enamel against polished zirconia than against rough zirconia. It appears that fine surface polishing is necessary and is an important step towards the safe clinical use of full contour zirconia crowns.

3.2.2. Friction and wear properties matching of artificial materials to tooth enamel

After wear test a small smooth flat zone was observed on the surface of Au–Pd alloy antagonist, indicating that instead of high stress concentration on the enamel, the surface of Au–Pd alloy crowns experienced plastic deformation under stress. The worn loss of alloy is more than that of enamel because of its lower strength and hardness. This might explain the common clinical observation of worn out of Au–Pd alloy crown. In this way, it could be concluded that the friction and wear performances of Au–Pd alloy do not match with the natural enamel.

The wear scar on the worn surface of Ni–Cr alloy antagonist was small, revealing a very small mass loss. The observed deep furrows on worn surface with the adhesion of small particles suggested abrasive wear mechanism seeing Fig. 2c. These particles could be fragments of enamel wear debris under cycling sliding.

A small rough flat zone around 600 μm in diameter with furrows inside was observed on the surface of Empress glass ceramic antagonist. This indicated abrasive wear and mass losing of glass ceramics during friction test. The adhesive small particles on the surface of the Empress glass ceramic seeing Fig. 3c might be the broken fragments of Empress glass ceramic formed during cycling sliding.

The worn surface of the porcelain antagonist showed paralleled furrows on a small flat zone around 600 μm in diameter, similar to what observed on Empress glass ceramic samples, seeing Fig. 4b. It suggested that the porcelain also experienced obviously wear damage and mass loss. The main component of porcelain was a glass phase which revealed typical brittle break mode under stress. Cone cracking that leads to chipping was the immediate insight of critical damage modes.[23] Chipping fragments of porcelain were the origins of abrasive wear of enamel against porcelain.

Two same topographical performance of the worn behavior in polished and rough zirconia cases were found in this test. First, the wear damages of zirconia were very small in both cases. Peeling off individual grains on the surface of polished zirconia was observed, Fig. 6d, whereas what observed on the surface of rough zirconia are small flakes, Fig. 7c. These flakes may be the accumulation of chipped off enamel. The high strength and toughness of zirconia enabled it to resist surface damage under stress. So, the surface of polished zirconia antagonist kept its fineness during long time abrasive process, presenting a stable frictional coefficient over time. Only slight scratching was visible on the polished zirconia after 5000 cycles.

Second, the fatigue wear of enamel was the main wear style against both polished and rough zirconia antagonists. The fatigue wear was characterized by the observation of peeling slices on worn surface of enamel. When zirconia surface slid over the enamel surface there was a zone of compression in the ahead of antagonist. Plastic deformation of enamel caused a zone of tension behind the antagonist. Micro cracks nucleated in the subsurface of enamel and propagate.[22] Then, the micro cracks initiated in enamel under high stress, forming a reticular framework instead of prolonging straight in depth direction. Eventually, the cracks propagated to the surface and the structures surrounded by the cracks were lost. This fracture character was related to the unique structure of enamel layer that was composed by well-ordered enamel rod and protein-rich rod.[24] In clinic, it was found that severe tooth abrasion with evident fatigue wear features always occurred in patients with large bite force. The stress abrasion features were also found on the worn surface of enamel against Ni–Cr alloy having high elastic modulus and strength. Therefore, the large mismatch of elastic modulus and strength between enamel and antagonist materials resulted in high stress concentration on enamel under vertical load and accordingly the stress abrasion of enamel. In these cases, the stress abrasion was only observed on the enamel surface, but not on the surfaces of antagonists. This suggested that enamel was the one suffered from this stress concentration. This observation revealed an immediate implication to the clinical use of hard and strong ceramic materials that was to reduce stress concentration by proper design of occlusal surface contours. Besides vertical load, the stress abrasion is affected by the friction cycling frequencies and time. It may further be aggravated by chemical reaction, such as acid in foods. Therefore, advanced study is needed to investigate the long time surviving rate and wear mechanisms of enamel under fatigue stress and the effect of acid.

4. Conclusions

1) The frictional coefficient of tested dental materials against the enamel of freshly extracted teeth showed the following tendency, Zirconia with rough surface > Empress glass ceramics > Veneer porcelain ≈ zirconia with well polished surface » Ni-Cr alloy ≈ Au–Pd alloy.
2) Obvious abrasive wear style was seen on the worn surface of enamel against Empress glass ceramics and veneer porcelain. Whereas, the wear scars observed on the worn surface of enamel against zirconia and Ni–Cr alloy reveal fatigue wear style.
3) The friction and wear performances of zirconia ceramics can be significantly improved by improving surface smoothness. A suitable polishing surface of zirconia is very important to the clinical safe use of the full contour zirconia crowns.

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