Journal of Dentistry 83 (2019) 87–94

Contents lists available at ScienceDirect

Journal of Dentistry

journal homepage: www.elsevier.com/locate/jdent

The effect of food medium on the wear behaviour of veneering porcelain: An *in vitro* study using the three-body abrasion mode

Hongyun Zhang[a,1], Yali Sun[a,b,1], Jiawen Guo[c,1], Meng Meng[a], Lin He[d], Franklin R. Tay[a,e,*], Shaofeng Zhang[a,**]

[a] State Key Laboratory of Military Stomatology & National Clinical Research Center for Oral Diseases & Shaanxi Key Laboratory of Stomatology, School of Stomatology, The Fourth Military Medical University, Xi'an, Shaanxi, China
[b] Zhengzhou Central Hospital Affiliated to Zhengzhou University, Zhengzhou, China
[c] School of Stomatology, Jinan University, Guangzhou, Guangdong, China
[d] State Key Laboratory for Mechanical Behavior of Materials, Xi'an Jiaotong University, Xi'an, China
[e] The Dental College of Georgia, Augusta University, Augusta, GA, USA

ARTICLE INFO

Keywords:
Hardness
Medium particles
Porcelain
Three-body wear

ABSTRACT

Objectives: The present study examined the effect of food medium on the three-body wear behaviour of veneering porcelain derived from porcelain-fused-to-metal crowns.

Methods: Seventy-four rectangular metal–ceramic specimens were prepared using Ceramco III as the veneering porcelain. After storage in distilled water at 37 °C for 2 days, the specimens were tested with a custom-designed chewing machine with a stainless steel ball as antagonist (350 N loads, 2.4×10^6 cycles). Testing was performed using water, silica beads, poly(methyl) methacrylate beads, millet seed slurry, chicken slurry or celery slurry as abrasive medium. Wear analysis of the veneering porcelain was performed using a 3D profilometer after every 300,000 wear cycles and analysed with one-way analysis of variance and post-hoc pairwise comparison procedures. Worn surfaces were examined with scanning electron microscopy.

Results: The wear curves of all experimental groups demonstrated three wear stages (running-in, steady wear and severe wear) with characteristic microstructure of worn surfaces. All the three food items selected in the present study (celery, chicken and millet seeds) had lower hardness compared with the veneering porcelain and produced less abrasion of the porcelain than a two-body wear system (water only). Abrasive wear produced with silica particles was the highest for the veneering porcelain.

Conclusion: The wear process of veneering porcelain in porcelain-fused-to-metal restorations is affected by the type of food consumed during mastication.

Clinical significance: Excessive abrasion may lead to premature failure of porcelain-fused-to-metal restorations. The importance of the wear behaviour of dental ceramic materials cannot be overstated. Three-body wear is an unavoidable consequence of oral function and occurs daily during eating. Understanding the effect of food particles on the wear behaviour of dental porcelain provides insight into the clinical performance and durability of these restorations.

1. Introduction

Dental ceramics are the materials of choice for prosthetic rehabilitation of lost tooth structures because of their superb mechanical properties and excellent aesthetics. A bi-layer restoration consists of an underlying ceramic framework that is capable of withstanding occlusal stress, and a porcelain veneering layer that improves the translucency of the final restoration. Although a zirconia framework possesses high strength and toughness, it has relatively low coefficient of thermal expansion and thermal diffusivity compared to traditional metal coping. These undesirable properties are often responsible for chipping of the veneering porcelain [1,2]. In contrast, porcelain-fused-to-metal (PFM) crowns have less interfacial complications and demonstrate long-term clinical reliability [3], which is the main reason for their widespread

* Corresponding author at: The Dental College of Georgia, Augusta University, Augusta, GA, USA.
** Corresponding author at: Department of Prosthodontics, School of Stomatology, The Fourth Military Medical University, Xi'an, Shaanxi, China.
E-mail addresses: ftay@augusta.edu (F.R. Tay), sfzhang@fmmu.edu.cn (S. Zhang).
[1] These authors contributed equally.

https://doi.org/10.1016/j.jdent.2019.02.010
Received 27 January 2019; Received in revised form 18 February 2019; Accepted 21 February 2019
0300-5712/ Published by Elsevier Ltd.

use in prosthetic dentistry. A recent clinical trial reported that the annual failure rate of metal-ceramic crowns was only 0.26% after 50 months of service [4]. The structural stability of all-ceramic fixed prostheses, irrespective of whether they are fabricated from glass-ceramics or polycrystalline ceramics, is less reliable than that PFM systems [5]. Compare with metal-free restorations, PFM restorations are less costly, which accounts for their popularity with consumers.

The veneering porcelain serves as a stress-bearing component in a PFM structure [6]. Accordingly, the wear behaviour of the porcelain veneering layer is an important property in the characterisation of a PFM restoration [7,8]. After years of prolific clinical research, a consensus has been reached that the porcelain veneering layer should demonstrate wear resistance that is comparable with natural enamel for long-term clinical success [9–11]. Excessive wear of the material may lead to premature failure of the restoration [12] because cracks that cause chipping or fracture of the veneering porcelain usually originate from wear facets [13].

In contrast with other mechanical properties, wear is a tribological property [14], which is dependent on the forces of mastication, the size of the food bolus, intraoral temperature and pH value, as well as the texture of the lubricant [15,16]. Three-body abrasion refers to the interposing of food particles between the teeth and their opposing restorations during mastication. The process occurs in every human subject during eating. *in vitro* results of three-body wear are different from those derived from two-body systems [17]. This implies that the wear behaviour of a dental restoration and its antagonist is significantly affected by the presence of food particles. The hardness of particles in food-simulating media has been reported to be positively-correlated with substance loss in resin composite filling materials [18]. Other properties of food-simulating particles, such as size and shape, also affect the relative wear ranking of restorative materials [19,20].

A previous study reported a non-liner relationship existed between the loading cycle and the wear of veneering porcelain in PFM crowns [21]. Wear was divided into three stages: running-in, steady wear and severe wear. A high wear rate and extensive surface wear were observed during the running-in wear stage. Ceramics showed propagation of subsurface cracks in the steady wear phase. Extensive wear damage occurred during the severe wear stage because of the penetration of cracks and separation of porcelain pieces. It is anticipated that different types of dental ceramics will have different wear resistance, even if the same overall wear loss is detected after the same number of wear cycles. This is because the tested materials may be undergoing different stages of wear [22]. Hence, it is more appropriate to estimate the wear resistance of dental ceramics based on a wear curve, instead of relying on a simple wear loss ranking that is routinely used in dental research studies.

People from different parts of the world have variable dietary preferences, with dietary components consisting predominantly of meat, vegetables or carbohydrates (such as cooked rice). It is speculated that the wear behaviour of PFM crowns is affected by the variability in dietary components. Information on the contribution of third-body food medium to the wear of ceramic restorations is scanty. Based on a three-body wear system, the objective of the present *in vitro* study was to determine the effect of food medium on the wear of PFM veneering porcelain. Vegetable, meat and millet seeds were chosen as representatives to discriminate the dietary composition. Poly(methyl) methacrylate beads and silicon carbide particles were used as references. Two-body wear using water as medium, usually considered as bruxism, was also investigated. The null hypothesis tested was that the food or food-simulating medium has no effect on the wear behaviour of the veneering porcelain in PFM restorations.

2. Material and methods

2.1. Preparation of medium particles

The medium particles used to simulate food bolus consisted of suspensions or slurries. Millet seed slurry was prepared by grinding 50 g of seeds in a rotating blade grinder for 5 s and mixing the paste with 75 mL of distilled water. Celery and chicken suspensions were prepared respectively in the same manner. Poly(methyl) methacrylate beads (20–100 μm diameter, Mitsubishi Rayon, Tokyo, Japan) and reagent grade silica particles (~75 μm diameter, Kelon Corp., Chengdu, China) were obtained from their respective manufacturers. Fresh suspensions were used after every 150,000 wear cycles.

2.2. Specimen preparation

A poly(methyl) methacrylate block was cut with laser into 74 rectangular specimens. Each specimen was 10 mm long, 10 mm wide and 1 mm thick. Cobalt-chromium frameworks (Co 60%, Cr 24%, Heraeus Kulzer GmbH, Hanau, Germany) were produced by the lost-wax casting technique in the same dimensions, according to the manufacturer's protocol. Following sandblasting with 50 μm diameter aluminum oxide particles, the frameworks were cleaned for 5 min in an ultrasonic bath containing distilled water. The metal frameworks were then veneered with porcelain (CeramcoIII; Dentsply, Burlington, NJ, USA) by the same experienced technician using the hand-layering technique. Porcelain veneering was sintered according to the manufacturer's recommendations. The final thickness of the porcelain was 1.7 mm. After sintering, the porcelain surface was successively polished with silicon carbon papers (240, 320, 400, 600, 800, 1000, 1200, 1500 and 2000 grit) with copious running water to obtain a smooth surface. The thickness of each PFM specimen was reduced to 2.5 mm. All specimens were stored in 37°C distilled water for at least 48 h for future use.

2.3. Three-body wear testing

The specimens were randomly divided into six experimental groups ($n = 6$): distilled water (control), silica, poly(methyl) methacrylate, celery, chicken and millet seed. A custom-designed chewing machine was employed to simulate the wear that occurs during occlusal contact (Fig. 1). Each specimen was affixed to the jig at a 30-degree angle. A test chamber was fabricated using a piece of polyethylene plastic to contain the suspension or slurry. The jig with attached specimen was placed inside the test chamber. A 10-mm diameter stainless steel ball (ASTM 403) served as a simulated antagonist cusp, which had a Vickers hardness value of 350 HV after quenching and tempering treatment. The hardness is close to that of natural enamel. Wear testing was conducted after injection of the suspension or slurry into the test chamber. The metal ball contacted the PFM specimen with a loading force of 350 N followed by a slide path on the surface of the porcelain. At the end of each sliding motion, the ball was lifted and returned to its starting position for the next wear cycle. In the present study, 2.4×10^6 loading cycles were performed to simulate 10 years of clinical service, assuming an annual masticatory performance of 240,000–250,000 occlusal contacts in adults [23]. The suspension was replaced every 150,000 wear cycles.

2.4. Wear quantification

The mean height loss during wearing of the veneering porcelain was determined every 30×10^4 cycles, using a non-contact 3D white light profilometer (PS50, Nanovea, Irvine, CA, USA) with a resolution of 3 μm in both the x and y directions. Data was acquired using the profilometer's designated software. The impression technique was employed to avoid inaccurate measurement caused by dismounting of the specimen between checkpoints. At each checkpoint, an impression of

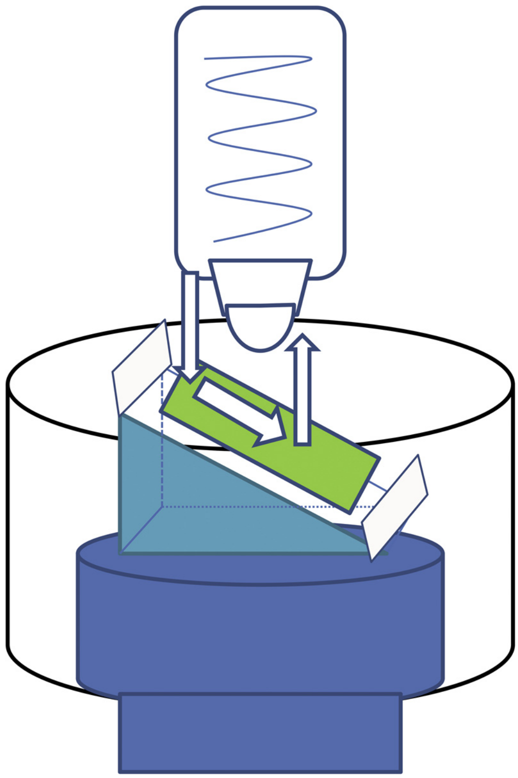

Fig. 1. Schematic of the simulated occlusal wear test.

Table 1
Summary of checkpoints in each experimental group for SEM examination.

Groups	Wear cycle (1 × 10^4 times)		
	Running-in wear stage	Steady wear stage	Severe wear stage
Water	15	180	240
Silica	15	90	240
Poly(methyl methacrylate)	15	120	240
Celery	15	120	240
Chicken	15	120	240
Millet seed	15	120	240

each specimen was taken using a polyether impression material (Permadyne, 3 M ESPE, Seefeld, Germany). The scanning area of the impression surface was 8 mm × 8 mm, which was large enough to cover the entire porcelain wear surface. All scans were obtained at a 30 Hz frequency using 20 µm step sizes in both the x and y directions, which was reported to be appropriate for ceramic materials [24]. A wear curve was generated after data collection at different checkpoints, which reflected the dynamic wear behaviour of the veneering porcelain. The wear rate at each checkpoint was calculated using the formula: $v = \triangle H / \triangle N$, where v is the wear rate, $\triangle H$ is the height loss between two adjacent checkpoints and $\triangle N$ is the wear cycle difference between two adjacent checkpoints.

2.5. Scanning electron microscopy

Two PFM specimens were examined before wear testing. Based on the wear curve obtained, three observation points from different wear stages, namely running-in, steady wear and severe wear, were selected in each experimental group to observe the worn surface. Details of the checkpoints are listed in Table 1. Two PFM specimens were examined for each checkpoint. Thirty-six specimens were examined. At the corresponding wear cycle, each specimen was cleaned ultrasonically with

Table 2
Vertical height loss and wear rate of each experimental group in different chewing cycles.

Wear Cycle (1 × 10^4 times)	Water		Silica		PMMA		Celery		Chicken		Millet seed	
	Wear loss (µm)	Wear rate (µm/10^4cycles)	Wear loss (µm)	Wear rate (µm/10^4 cycles)	Wear loss (µm)	Wear rate (µm/10^4 cycles)	Wear loss (µm)	Wear rate (µm/10^4 cycles)	Wear loss (µm)	Wear rate (µm/10^4 cycles)	Wear loss (µm)	Wear rate (µm/10^4 cycles)
30	93.1 ± 21.2	3.10 ± 0.71 A	112.4 ± 4.6	3.75 ± 0.14 A	85.3 ± 3.8	2.84 ± 0.12 A	72.6 ± 7.9	2.42 ± 0.26A	50.8 ± 7.7	1.69 ± 0.26 A	5.0 ± 0.9	0.16 ± 0.03 A
60	121.2 ± 23.5	0.94 ± 0.17 B	141.6 ± 4.5	0.98 ± 0.09 B	104.3 ± 5.0	0.63 ± 0.12 B	98.0 ± 10.8	0.85 ± 0.12 B	65.7 ± 8.9	0.50 ± 0.09 B	7.2 ± 1.7	0.07 ± 0.04 B
90	148.5 ± 23.5	0.91 ± 0.24 B	148.8 ± 4.3	0.24 ± 0.03 C	113.3 ± 5.6	0.30 ± 0.05 C	102.9 ± 11.4	0.16 ± 0.05 C	71.4 ± 8.8	0.19 ± 0.05 C	8.1 ± 1.9	0.03 ± 0.01 B
120	171.8 ± 25.3	0.78 ± 0.16 B	167.9 ± 5.5	0.64 ± 0.05 BD	122.5 ± 6.8	0.31 ± 0.05 C	109.5 ± 13.3	0.22 ± 0.11 C	75.2 ± 10.1	0.13 ± 0.06 C	8.1 ± 1.9	0.00 ± 0.00 B
150	191.6 ± 25.0	0.66 ± 0.19 B	186.4 ± 6.8	0.62 ± 0.09 D	133.3 ± 8.3	0.36 ± 0.05 C	114.9 ± 13.3	0.18 ± 0.04 C	81.9 ± 10.1	0.22 ± 0.04 C	8.2 ± 1.9	0.00 ± 0.00 B
180	198.3 ± 25.1	0.22 ± 0.06 C	208.2 ± 7.8	0.72 ± 0.05 D	144.5 ± 11.0	0.37 ± 0.11 C	139.3 ± 13.2	0.82 ± 0.25 BD	84.0 ± 10.5	0.07 ± 0.04 C	8.2 ± 1.9	0.00 ± 0.06 B
210	204.6 ± 25.9	0.21 ± 0.07 C	233.8 ± 6.8	0.85 ± 0.23 D	164.2 ± 13.8	0.66 ± 0.12 BD	162.3 ± 13.9	0.77 ± 0.08 D	102.6 ± 9.1	0.62 ± 0.14 BD	13.2 ± 2.8	0.16 ± 0.05 C
240	238.3 ± 27.9	1.12 ± 0.39 BD	261.8 ± 10.8	0.93 ± 0.16 D	185.4 ± 17.4	0.71 ± 0.11 BD	183.8 ± 21.5	0.72 ± 0.29 D	121.6 ± 7.2	0.64 ± 0.11 D	20.5 ± 2.6	0.24 ± 0.02 C
	a		a		b		b		c		d	

Abbreviation: PMMA – poly(methyl) methacrylate.
Values are means ± standard deviations (n = 6).
For analysis of final wear loss at 2.4 × 10^6 cycles, groups identified with the same low case letter are not significantly different ($p > 0.05$).
For analysis of wear rat eat each of the 8 checkpoints, groups identified with the same upper case letter are not significantly different ($p > 0.05$).

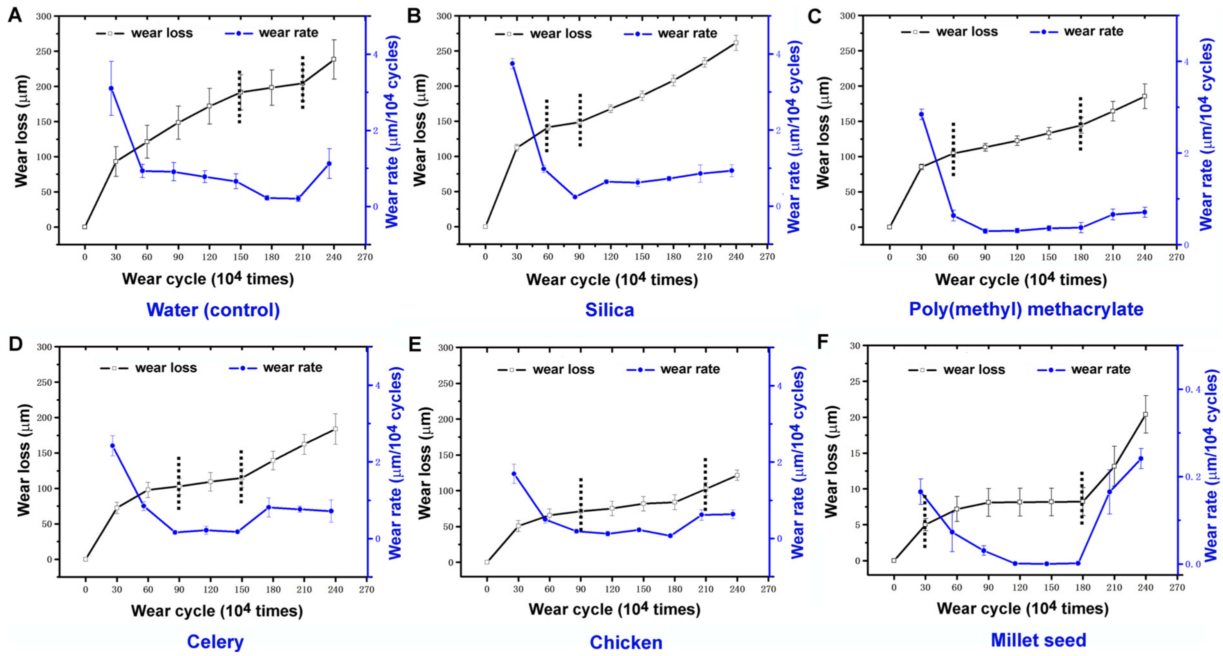

Fig. 2. The wear curve of veneering porcelain in each group over the entire wear process: A. water (control). B. silica. C. poly(methyl) methacrylate. D. celery. E. chicken. F. millet seed.

distilled water and sputter-coated with gold/palladium. The worn surfaces were examined using scanning electron microscopy (SEM; S-4800, Hitachi High Technologies Corp., Tokyo, Japan). Food medium particles were also examined using SEM after desiccation in air and sputter-coated with gold/palladium.

2.6. Statistical analysis

Data on wear loss and the wear rate were expressed as means and standard deviations. One-way analysis of variance was used to determine whether differences existed in the final wear loss of the six experimental groups, as well as the wear rates at each of the 8 checkpoints. The use of parametric statistical methods was performed after ascertaining the normality and homoscedasticity assumptions of the corresponding data sets. Post-hoc pairwise comparisons of the final wear loss, as well as the wear rates at each pair of neighbouring checkpoints, were performed using the Tukey procedure. For all analyses, statistical significance was pre-set at $\alpha = 0.05$.

3. Results

3.1. Wear of specimens

Wear loss and wear rate at each checkpoint are summarized in Table 2. Statistical analysis of the final wear loss of the six experimental groups after 2.4×10^6 simulated chewing cycles identified a significant difference among the different abrasive environments ($p = 0.021$). The PFM specimens in the silica group showed the most severe wear loss. The millet seed slurry produced the least wear. Wear loss was in the order: silica = water > poly(methyl) methacrylate = celery > chicken > millet seed ($p < 0.05$).

For each experimental group, wear curves displaying distinctive wear stages were produced by setting the wear loss and wear rate as the y-axis simultaneously (Fig. 2). Different wear stages were manifested in these wear curves. For the control group, the boundary between the running-in wear stage and the steady wear stage was situated at approximately 1.5×10^6 cycles (first dotted line on the wear loss curve). This is because the wear rate at 1.5×10^6 cycles ($0.66 \pm 0.19\,\mu m/1 \times 10^4$ cycles) was significantly higher than that at 1.8×10^6 cycles ($0.22 \pm 0.06\,\mu m/1 \times 10^4$ cycles) ($p < 0.05$), and there were no statistical differences from 0.3×10^6 cycles to 1.5×10^6 cycles ($p > 0.05$). From 1.5×10^6 cycles to 2.1×10^6 cycles, the PFM specimens in the control group underwent a steady wear stage, with the wear rate sustained at a relatively low value. After that, the ceramic layer experienced the severe wear stage commencing from 2.1×10^6 cycles (second dotted line on the wear loss curve). During this last wear stage, both the wear loss and the wear rate increased sharply. The silica, poly(methyl) methacrylate, celery, chicken and millet seed groups also showed similar wear stage characteristics as in the control group. The boundary of different wear stages was marked with dotted lines in Fig. 2. The wear behaviour of silica group was similar to the water control group, while the celery, chicken and millet seed groups exhibited a milder wear process.

3.2. Wear morphology

Scanning electron microscopy of specimens that had not been subjected to dynamic loading showed intact and smooth surfaces without visible flaws or cracks (not shown). A series of SEM images of worn specimens selected from each wear stage showed deterioration of microstructure in different abrasive environments. During the running-in wear stage (Fig. 3), widespread irregular wear traces were observed in the worn area. Wear traces in each experimental group did not increase substantially during the steady wear stage (not shown). On reaching the severe wear stage, the size of the wear traces increased markedly in each experimental group, producing relatively rough surfaces. (Fig. 4).

During the running-in wear stage, specimens in water control group showed relatively large wear traces, both in size and depth (Fig. 3A). Wear traces in the silica group were shallower but more widespread (Fig. 3B). Only shallow, discrete cracks were observed in the other four groups (Fig. 3C-F). On reaching the severe wear stage, extensively roughened surfaces could be identified in the control and silica groups (Fig. 4A, B), that resulted from the exfoliation of the fractured porcelain material. In contrast, a small amount of relatively smooth, unworn areas could be observed in the celery (Fig. 4D), chicken (Fig. 4E) and millet seed (Fig. 4F) groups.

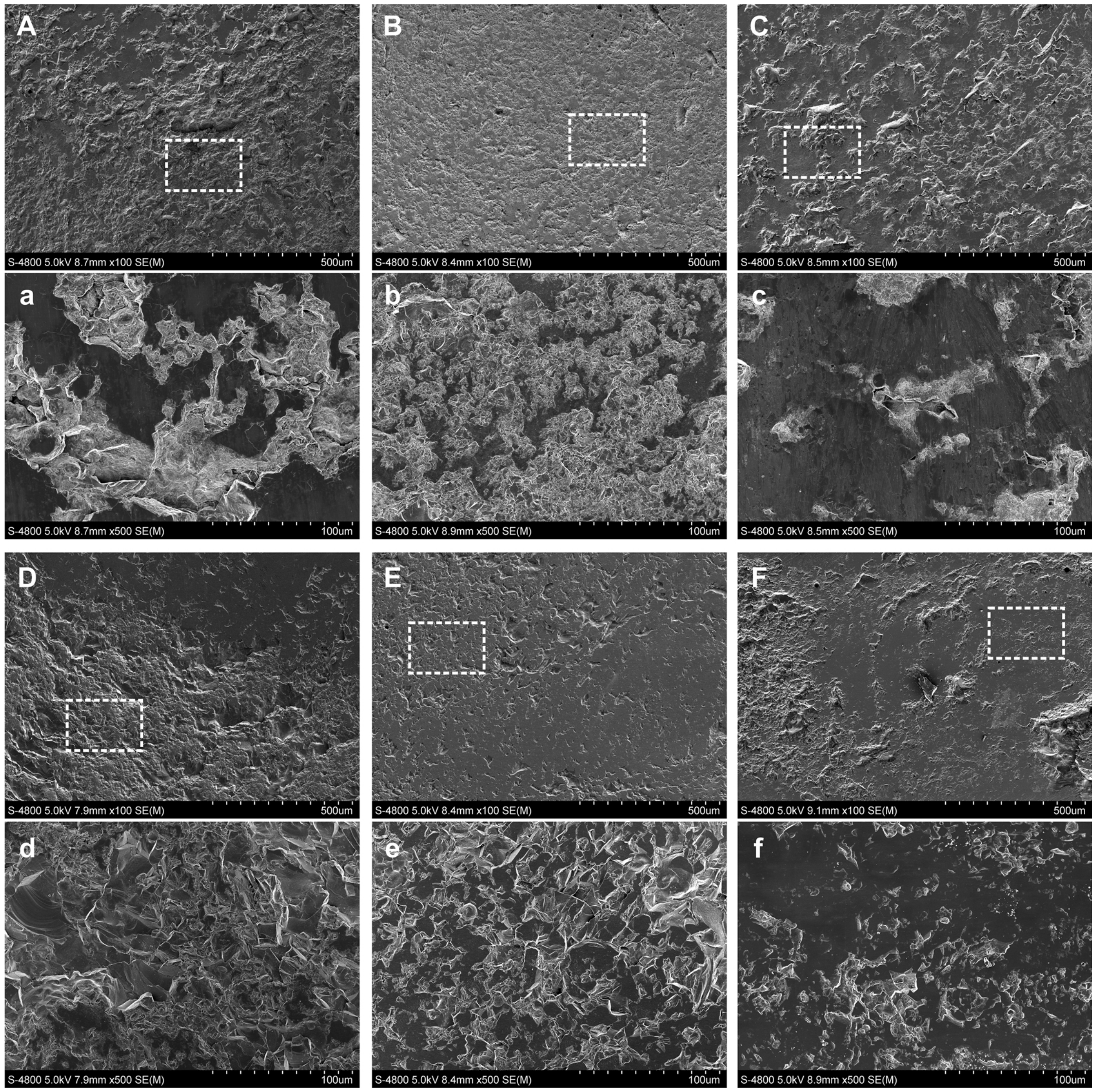

Fig. 3. SEM images of running-in wear stage in each experimental group. A. Water; (a) dotted box on (A) at high magnification. B. Silica; (b) dotted box on (B) at high magnification. C. Poly(methyl) methacrylate; (c) dotted box on (C) at high magnification. D. Celery; (d) dotted box on (D) at high magnification. E. Chicken; (e) dotted box on (E) at high magnification. F. Millet seed; (f) dotted box on (F) at high magnification.

3.3. Morphology of medium particles

Scanning electron microscopy of the five medium particles are shown in Fig. 5. The size of the silica particles was relatively uniform but the shapes were irregular with sharp edges (Fig. 5A). The poly (methyl) methacrylate beads were spherical with inhomogeneous particle sizes (Fig. 5B). The celery fibres (Fig. 5C) were larger than the chicken fibres (Fig. 5D). The size of millet seed grains was the smallest among all the food abrasives (Fig. 5E); at high magnification (Fig. 5F), a film-like structure was formed by the crushed millet seed grain aggregates.

4. Discussion

Wear behaviour of dental porcelains is an important attribute that is responsible for the longevity of PFM restorations [25]. Intraoral three-body abrasion is an inevitable process because of daily food intake. This complex phenomenon, defined by wear tribology and bio-tribocorrosion, simulates human mastication with abrasive foods such as grains, meats or vegetables. During the three-body wear process, food particles acting as the third body interpose between the teeth and the restorations [26]. Previous investigations reported a weak correlation between two-body and three-body wear systems, which was attributed to the different mechanisms of wear involved in each condition [15]. Accordingly, the present study investigated three-body wear of the veneering porcelain with different food particles. Because significant differences in wear behaviour were identified among the experimental groups, the null hypothesis that food or food-simulating medium has no effect on the wear behaviour of the veneering porcelain in PFM restorations has to be rejected.

A simulated food bolus consisting of celery fibres, chicken fibres or millet seed slurry produced wear curves of PFM veneering porcelain that were relatively mild compared to the use of water alone. In particular, a long steady wear stage could be observed for specimens abraded with chicken fibres or millet seeds, which is reminiscent of gradually-decreasing abrasiveness. Only the use of silica beads produced porcelain wear that was statistically comparable with the use of water only, with a shorter steady wear stage and a longer severe wear stage. Poly(methyl) methacrylate beads produced similar wear behaviour as celery fibres. Based on the results of the present study, the wear performance of veneering porcelain is dependent upon the abrasive medium used. The hardness and shape of the particles from each

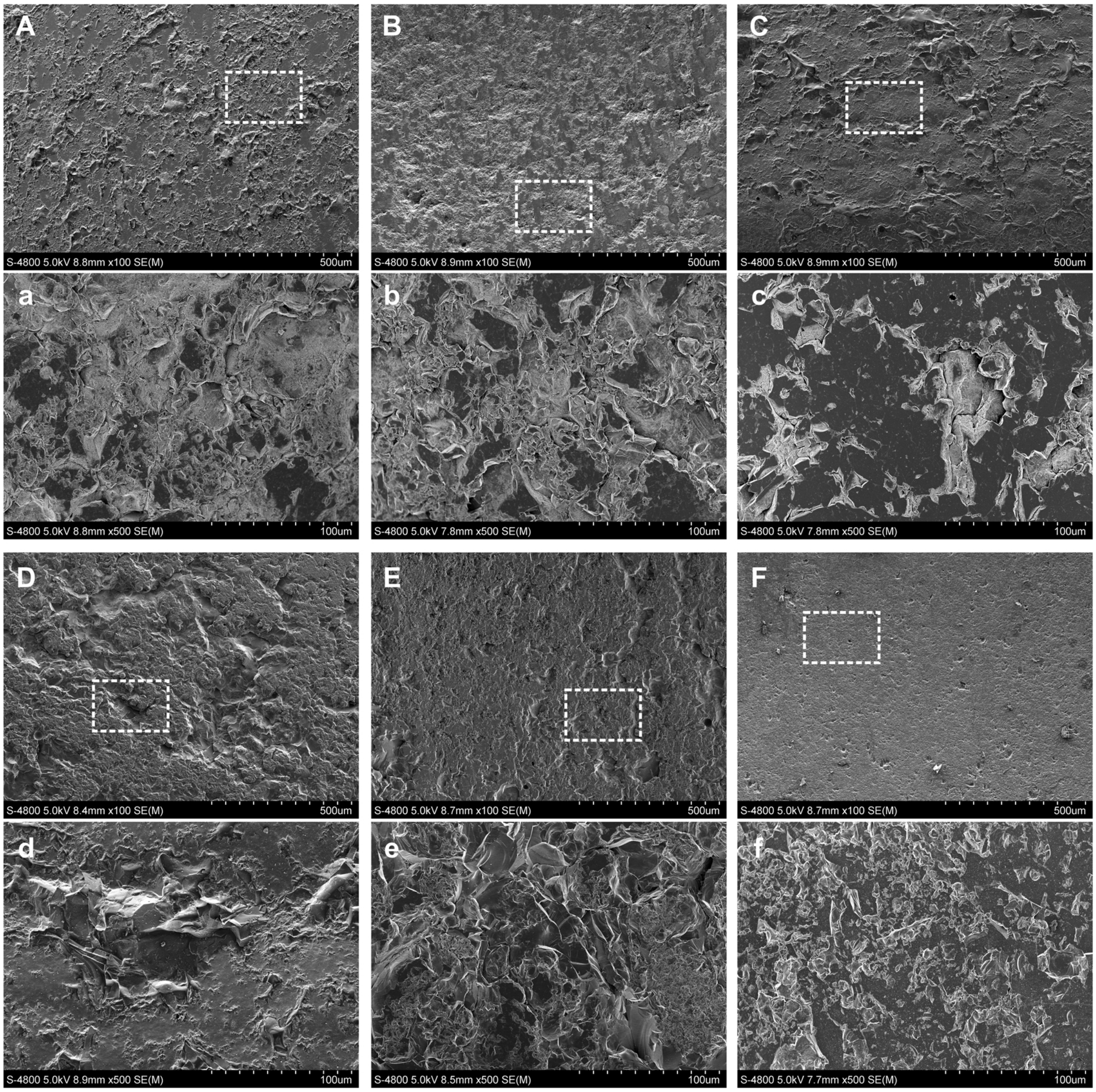

Fig. 4. SEM images of severe wear stage in each experimental group. A. Water; (a) dotted box on (A) at high magnification. B. Silica; (b) dotted box on (B) at high magnification. C. Poly(methyl) methacrylate; (c) dotted box on (C) at high magnification. D. Celery; (d) dotted box on (D) at high magnification. E. Chicken; (e) dotted box on (E) at high magnification. F. Millet seed; (f) dotted box on (F) at high magnification.

abrasive medium may have accounted for the differences in relative wear curves and degradation of the porcelain microstructure.

Hardness of the abrasive medium particles has been reported to be the most important parameter in determining the wear performance of the tooth or its opposing restoration [27]. Dietary hardness is also closely linked with human enamel wear [26]. It is not surprising to find that silica particles produced more ceramic wear than the other media. This is because silica particles are much harder than poly(methyl) methacrylate beads, celery fibres, chicken fibres or millet seeds. Pure silica has a hardness of approximately 7 GPa [28], which is slightly more than the hardness of glass ceramic (˜6.86 GPa) [29]. Hence, silica particles act as an abrasive between the antagonist and the veneering porcelain in the current system. Specimens in the silica group exhibited the highest wear loss among all the experimental groups. These specimens showed severe wear, with wide and deep wear tracks observed from the running-in stage through the severe wear stage, although their final wear loss was not significant higher than that of the water control. A similar phenomenon has been reported in the literature, in that harder medium particles expedite wear testing and produce more wear loss of materials [18]. Glass beads, selected as a medium in that study [18], produced significantly more wear on all tested resin composite materials because the glass beads were much harder than the resin matrix.

In contrast, poly(methyl) methacrylate particles, celery fibres, chicken fibres and millet seed slurry are considerably softer than the veneering porcelain. Suspensions of slurries consisting of these materials play a lubricant role during the abrasion phase when the metal sphere slides against a tooth or porcelain surface [30]. Experiment groups abraded with the aforementioned medium particles exhibited mild wear curves with significantly lower final wear loss values, compared to the water control group. Two-body abrasion with water as medium frequently occurs in the patients with bruxism, and is expected to produce more wear loss. For the millet seed group, the veneering porcelain experienced low three-body abrasion because the wear rates during the entire wear process did not exceed 15 μm/10^4 cycles (Table 2). Despite the observation of minor damage of the worn porcelain surface, relatively smooth areas could still be seen at the end of wear test (Fig. 4F). The results are indicative of a mild wear process of PFM specimens in the millet seed group. These results may be explained by the softer millet seed particles (˜0.28 GPa) [18] and the formation of a film-like structure of crushed millet seed aggregates (Fig. 5F). The presence of a thin film of millet seed particles may protect the

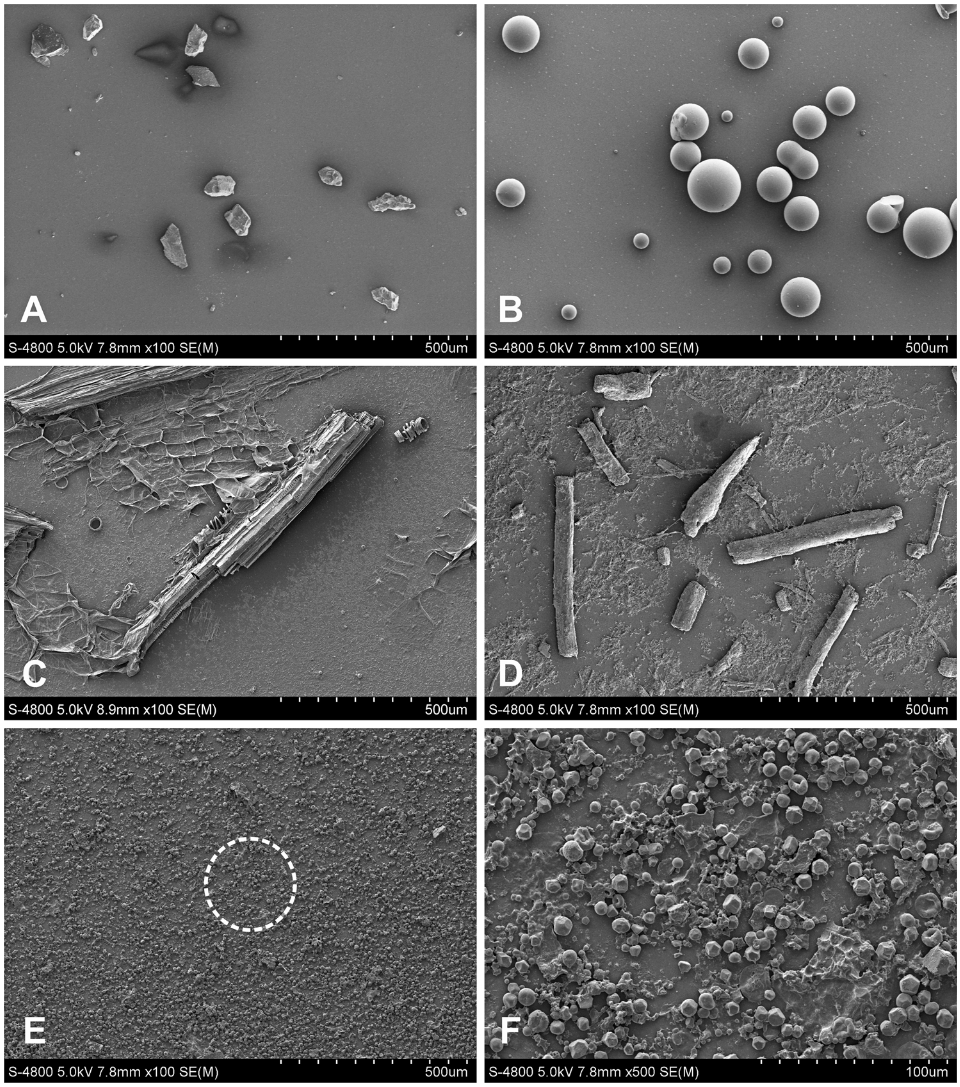

Fig. 5. SEM images of the various abrasive suspensions after preparation and desiccation. A. Silica. B. Poly(methyl) methacrylate. C. celery fibres. D. Chicken fibres. E. Millet seed grains. F. Dotted box on (E) at high magnification.

veneering porcelain from antagonist abrasion, preventing its removal during the next passage of the abrading surface. However, the protection mechanism of millet seed particles may not always work. In a study that compared the three-body wear of four resin composites, millet seeds produced as much volumetric wear as the use of water alone in a nano-filled resin composite [18]. Despite the seeds having lower hardness value than the resin matrix, the asperities on the surfaces of the millet seed particles were able to penetrate the interparticle resin matrix of the composite [31]. This feature may explain why this kind of nano-filled resin composite showed more wear with seed particles.

Reduced wear behaviour of the PFM specimens was found for abrasive media containing celery fibres or chicken fibres. The results indicate that ground meats or vegetables may act as lubricants during the masticatory cycle. A long steady wear stage could be detected in these specimens. Results from the present study are consistent with the study of Kakuta and Ogura [32], who compared the effects of the abrasive particles and fibres in the media on wear behaviour of dental materials. The worn volumes of the dental materials decreased when a fibre-containing medium was used for occlusal wear testing; the fibre components in the medium appeared to have protected the materials from wear. As shown in Fig. 5C and D, the celery fibres and chicken fibres prepared in the present study were quite large ($> 100\,\mu m$ in length); they were large enough to separate the veneering porcelain from the metal sphere. These fibres may be perceived as solid lubricants in a three-body wear system.

It is worth mentioning that poly(methyl) methacrylate beads produced more severe wear than millet seeds, although both poly(methyl) methacrylate beads and millet seeds have similar hardness (~0.28 GPa) [18]. Unlike the millet seeds that could be crushed into a thin layer, the poly(methyl) methacrylate beads did not degrade throughout the wear testing cycle [33]. Local stress concentrations could have been generated when poly(methyl) methacrylate beads were loaded between the antagonist ball and the veneering porcelain, which scratched and abraded more surface material [34]. This may help explain the pronounced abrasive wear associated with the use of poly(methyl) methacrylate beads as a wear medium.

Because of the time consuming and costly nature of clinical studies, *in vitro* wear testing is frequently used to determine the wear performance of dental materials or restorations [35]. For the evaluation of wear that occurs by three-body abrasion of interposing food particles, laboratory testing with sophisticated measuring methods, such as laser scanning and 3-dimensional imaging, are capable of controlling the wear conditions and discriminating the effects of food simulating medium on the wear properties of dental materials [36]. For three-body wear, it has been shown that the wear behaviour of natural teeth and dental materials are significantly affected by the components in an abrasive medium [27]. Our daily food comprises a diverse range of substances with different textures. Whether these food substances with varied textures act as abrasives or lubricants to the restorative materials depends on the properties of the component food particles or fibres.

5. Conclusion

Within the limitations of the present study, it may be concluded that all the three food items (celery, chicken and millet seeds) produce mild wear curves compared to the use of water alone. The results are indicative of a lubricant role of these food media in the three-body wear mode. In addition, the wear behaviour identified in two-body abrasion also explains why bruxists have a higher incidence of porcelain chipping. Softer food particles, larger sized food fibres and film-like microstructure may contribute to protection of the veneering porcelain. On the contrary, the veneering porcelain in PFM restorations exhibits more extensive surface wear when silica beads are used as the third-body medium.

Declaration of interests

None.

Acknowledgements

This study was supported by grants from the National Natural Science Foundation of China (81671018 and 81870792) and Natural Science Basic Research Plan in Shaanxi Province of China (2017ZDJC-04).

References

[1] A. Hååff, H. Löf, J. Gunne, G. Sjögren, A retrospective evaluation of zirconia-fixed partial dentures in general practices: an up to 13-year study, Dent. Mater. 31 (2015) 162–170.
[2] R.P. Christensen, B.J. Ploeger, A clinical comparison of zirconia, metal and alumina fixed-prosthesis frameworks veneered with layered or pressed ceramic: a three-year report, J. Am. Dent. Assoc. 141 (2010) 1317–1329.
[3] D. Layton, A critical appraisal of the survival and complication rates of tooth-supported all-ceramic and metal-ceramic fixed dental prostheses: the application of evidence-based dentistry, Int. J. Prosthodont. 24 (2011) 417–427.
[4] Y. Zhang, J.R. Kelly, Dental ceramics for restoration and metal veneering, Dent. Clin. North Am. 61 (2017) 797–819.
[5] C. Lopez-Suarez, R. Castillo-Oyague, V. Rodriguez-Alonso, C.D. Lynch, M.J. Suarez-Garcia, Fracture load of metal-ceramic, monolithic, and bi-layered zirconia-based posterior fixed dental prostheses after thermo-mechanical cycling, J. Dent. 73 (2018) 97–104.
[6] Y. Liu, S. Gao, Y. Han, Q. Yang, D. Arola, D. Zhang, Bearing capacity of ceramic crowns before and after cyclic loading: an in vitro study, J. Mech. Behav. Biomed. Mater. 87 (2018) 197–204.
[7] J. Sripetchdanond, C. Leevailoj, Wear of human enamel opposing monolithic zirconia, glass ceramic, and composite resin: an in vitro study, J. Prosthet. Dent. 112 (2014) 1141–1150.
[8] R. Zandparsa, H.R. El, H. Hirayama, M.I. Johnson, Effect of different dental ceramic systems on the wear of human enamel: an in vitro study, J. Prosthet. Dent. 115 (2016) 230–237.
[9] P. Lambrechts, M. Braem, M. Vuylsteke-Wauters, G. Vanherle, Quantitative in vivo wear of human enamel, J. Dent. Res. 68 (1989) 1752–1754.
[10] M.J. Kim, S.H. Oh, J.H. Kim, S.W. Ju, D.G. Seo, S.H. Jun, J.S. Ahn, J.J. Ryu, Wear evaluation of the human enamel opposing different Y-TZP dental ceramics and other porcelains, J. Dent. 40 (2012) 979–988.
[11] S.P. Passos, Y. Torrealba, P. Major, B. Linke, C. Flores-Mir, J.A. Nychka, In vitro wear behavior of zirconia opposing enamel: a systematic review, J. Prosthodont. 23 (2014) 593–601.
[12] J.J. Kruzic, J.A. Arsecularatne, C.B. Tanaka, M.J. Hoffman, P.F. Cesar, Recent advances in understanding the fatigue and wear behavior of dental composites and ceramics, J. Mech. Behav. Biomed. Mater. 88 (2018) 504–533.
[13] Z. Pang, A. Chughtai, I. Sailer, Y. Zhang, A fractographic study of clinically retrieved zirconia-ceramic and metal-ceramic fixed dental prostheses, Dent. Mater. 31 (2015) 1198–1206.
[14] P. Lambrechts, E. Debels, K. Van Landuyt, M. Peumans, B. Van Meerbeek, How to simulate wear? Overview of existing methods, Dent. Mater. 22 (2006) 693–701.
[15] J.R. Condon, J.L. Ferracane, Factors effecting dental composite wear in vitro, J. Biomed. Mater. Res. 38 (1997) 303–313.
[16] R. DeLong, W.H. Douglas, Development of an artificial oral environment for the testing of dental restoratives: bi-axial force and movement control, J. Dent. Res. 62 (1983) 32–36.
[17] N. Koottathape, H. Takahashi, N. Iwasaki, M. Kanehira, W.J. Finger, Two- and three-body wear of composite resins, Dent. Mater. 28 (2012) 1261–1270.
[18] N.C. Lawson, D. Cakir, P. Beck, M.S. Litaker, J.O. Burgess, Characterization of third-body media particles and their effect on in vitro composite wear, Dent. Mater. 28 (2012) e118–e126.
[19] S.M. Reich, A. Petschelt, M. Wichmann, R. Frankenberger, Mechanical properties and three-body wear of veneering composites and their matrices, J. Biomed. Mater. Res. A. 69 (2004) 65–69.
[20] N. Iwasaki, H. Takahashi, N. Koottathape, M. Kanehira, W.J. Finger, K. Sasaki, Texture of composite resins exposed to two- and three-body wear in vitro, J. Contemp. Dent. Pract. 15 (2014) 232–241.
[21] J. Guo, B. Tian, R. Wei, W. Wang, H. Zhang, X. Wu, L. He, S. Zhang, Investigation of the time-dependent wear behavior of veneering ceramic in porcelain fused to metal crowns during chewing simulations, J. Mech. Behav. Biomed. Mater. 40 (2014) 23–32.
[22] Z. Xu, P. Yu, D.D. Arola, J. Min, S. Gao, A comparative study on the wear behavior of a polymer infiltrated ceramic network (PICN) material and tooth enamel, Dent. Mater. 33 (2017) 1351–1361.
[23] R. DeLong, R.L. Sakaguchi, W.H. Douglas, M.R. Pintado, The wear of dental amalgam in an artificial mouth: a clinical correlation, Dent. Mater. 1 (1985) 238–242.
[24] Z. Zhang, J. Guo, Y. Sun, B. Tian, X. Zheng, M. Zhou, L. He, S. Zhang, Effects of crystal refining on wear behaviors and mechanical properties of lithium disilicate glass-ceramics, J. Mech. Behav. Biomed. Mater. 81 (2018) 52–60.
[25] S.D. Heintze, A. Cavalleri, M. Forjanic, G. Zellweger, V. Rousson, Wear of ceramic and antagonist - a systematic evaluation of influencing factors in vitro, Dent. Mater. 24 (2008) 433–449.
[26] N.C. Lawson, S. Janyavula, D. Cakir, J.O. Burgess, An analysis of the physiologic parameters of intraoral wear: a review, J. Phys. D Appl. Phys. 46 (2013) 404007.
[27] A.J. de Gee, P. Pallav, C.L. Davidson, Effect of abrasion medium on wear of stress-bearing composites and amalgam in vitro, J. Dent. Res. 65 (1986) 654–658.
[28] M. Barlet, J. Delaye, M. Gennisson, R. Caraballo, B. Boizot, D. Bonamy, C.L. Rountree, Influence of electronic irradiation on failure and hardness properties of pure silica glasses, Procedia Mater. Sci. 7 (2014) 286–293.
[29] H. Meng, H. Xie, L. Yang, B. Chen, Y. Chen, H. Zhang, C. Chen, Effects of multiple firings on mechanical properties and resin bonding of lithium disilicate glass-ceramic, J. Mech. Behav. Biomed. Mater. 88 (2018) 362–369.
[30] E. Sajewicz, Effect of saliva viscosity on tribological behaviour of tooth enamel, Tribol. Int. 42 (2009) 327–332.
[31] T. Stober, M. Henninger, M. Schmitter, M. Pritsch, P. Rammelsberg, Three-body wear of resin denture teeth with and without nanofillers, J. Prosthet. Dent. 103 (2010) 108–117.
[32] K. Kakuta, H. Ogura, Effects of abrasive and fiber components in medium on wear of composite resins, Dent. Mater. J. 27 (2008) 716–722.
[33] A.J. de Gee, P. Pallav, Occlusal wear simulation with the ACTA wear machine, J. Dent. 22 (Suppl. 1) (1994) S21–S27.
[34] A.U. Yap, S.H. Teoh, C.L. Chew, Effects of cyclic loading on occlusal contact area wear of composite restoratives, Dent. Mater. 18 (2002) 149–158.
[35] S.D. Heintze, How to qualify and validate wear simulation devices and methods, Dent. Mater. 22 (2006) 712–734.
[36] P. Pallav, A.J. de Gee, A. Werner, C.L. Davidson, Influence of shearing action of food on contact stress and subsequent wear of stress-bearing composites, J. Dent. Res. 72 (1993) 56–61.