Journal of Materials Science: Materials in Medicine (2018) 29:34
https://doi.org/10.1007/s10856-018-6031-y

BIOMATERIALS SYNTHESIS AND CHARACTERIZATION

Original Research

The effect of abrading and cutting instruments on machinability of dental ceramics

Satoshi Sakoda[1] · **Noriko Nakao**[2] · **Ikuya Watanabe**[1]

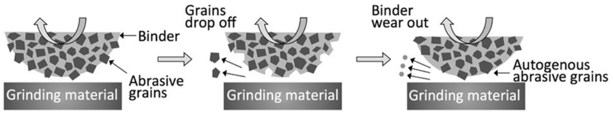
Received: 29 September 2017 / Accepted: 16 January 2018 / Published online: 16 March 2018

Abstract

The aim was to investigate the effect of machining instruments on machinability of dental ceramics. Four dental ceramics, including two zirconia ceramics were machined by three types (SiC, diamond vitrified, and diamond sintered) of wheels with a hand-piece engine and two types (diamond and carbide) of burs with a high-speed air turbine. The machining conditions used were abrading speeds of 10,000 and 15,000 r.p.m. with abrading force of 100 gf for the hand-piece engine, and a pressure of 200 kPa and a cutting force of 80 gf for the air-turbine hand-piece. The machinability efficiency was evaluated by volume losses after machining the ceramics. A high-abrading speed had high-abrading efficiency (high-volume loss) compared to low-abrading speed in all abrading instruments used. The diamond vitrified wheels demonstrated higher volume loss for two zirconia ceramics than those of SiC and diamond sintered wheels. When the high-speed air-turbine instruments were used, the diamond points showed higher volume losses compared to the carbide burs for one ceramic and two zirconia ceramics with high-mechanical properties. The results of this study indicated that the machinability of dental ceramics depends on the mechanical and physical properties of dental ceramics and machining instruments.

Graphical Abstract

The abrading wheels show autogenous action of abrasive grains, in which ground abrasive grains drop out from the binder during abrasion, then the binder follow to wear out, subsequently new abrasive grains come out onto the instrument surface (autogenous action) and increase the grinding amount (volume loss) of grinding materials.



1 Introduction

Dental ceramics are commonly used as esthetic material for conventional restorations, such as ceramic veneers, single crowns and fixed partial dentures, or implant-supported superstructures [1, 2]. Because of their outstanding esthetic demands, there has been a strong emphasis on improving ceramics to make them endurable for stressful applications, such as full-coverage posterior crowns and fixed partial denture restorations that do not have a metal substrate coping for supports. However, their mechanical and physical properties (flexural strength, fracture toughness,

---

✉ Ikuya Watanabe
ikuyaw@nagasaki-u.ac.jp

[1] Department of Dental and Biomedical Materials Science, Nagasaki University Graduate School of Biomedical Sciences, 1-7-1 Sakamoto, Nagasaki 852-8102, Japan

[2] Department Perioperative Oral Management, Nagasaki University Hospital, Nagasaki, 1-7-1 Sakamoto, Nagasaki 852-8102, Japan

hardness, thermal expansion, and so on) depend on the composition of elemental ingredients, such as feldspar, alumina, leucite, and lithium disilicate, and on the crystalline structures those are composed of glassy and crystalline phases. The restorative ceramics classified mainly into: (1) feldspar ($KAlSi_3O_8$) porcelain for porcelain-fused-to-metal (PFM) restorations, (2) leucite ($KAlSi_2O_6$)-based or lithium disilicate ($Li_2Si_2O_5$)-based ceramics for sintering and heat-pressing of ceramics, and (3) alumina (Al_2O_3) or zirconia (ZrO_2) ceramics as machinable ceramics for CAD/CAM systems [1, 3–6]. The feldspathic veneering porcelains require a minimum flexural strength of 50 MPa according to the international standard (ISO) [7, 8], and are also used to veneer the metal coping for the PFM restorations or to veneer the zirconia coping which has the highest flexural strength and fracture toughness among all currently available dental ceramics [1, 2, 4]. The leucite-based ceramics are composed of leucite ($K_2O·Al_2O_3·4SiO_2$ or $KAlSi_2O_6$) as a reinforcing phase (35–55% in amounts) and have the flexural strength (~120 MPa) which is about two times of strength compared to that of conventional feldspathic porcelains. One of the leucite-based ceramics is fluorapatite-leucite ceramic containing dispersed fluorapatite ($Ca_5(PO_4)_3F$) crystals which are known to be an important constituent of tooth enamel [1, 4]. The presence of the fluorapatite crystals imparts very special optical properties, such as translucence and opalescence in the ceramics [4, 9]. These leucite-based ceramics are commonly used as the sintering and heat-pressing ceramic material. The lithium disilicate-based ceramics contain disilicate ($Li_2Si_2O_5$) as a major crystalline phase. The main advantage of the lithium disilicate-based ceramics is their good flexural strength (>350 MPa), and fracture toughness, which extend their range of applications (can be applied for both heat-pressing and CAD/CAM), and are theoretically possible to apply for fabrication of three-unit fixed partial dentures [10]. The zirconia based machinable ceramics was introduced in dental market in a past decade [11, 12]. It consists of tetragonal zirconia polycrystals stabilized by addition of yttrium. Partially sintered blanks are machined by CAD/CAM and later completely sintered to form densely packed tetragonal zirconia crystal, which yield the highest flexural strength (>900 MPa) and highest fracture toughness ($>5\ MPa·m^{0.5}$) in all dental ceramics [1, 13]. Although they were favorably used as core material due to their high-mechanical strengths and colorimetric property (low translucency) [14–16], highly translucent zirconia was recently developed and is currently available to fabricate full contoured restorations [17].

The ceramic materials are well known to have difficulties of grinding (include abrading, polishing, and finishing) and cutting during fabrication and clinical applications. Machining efficiency of dental ceramics depends on the mechanical and physical properties of each ceramics and on the properties of abrading and cutting instruments. Although there is a few literature [18–20] regarding the machinability of dental ceramics for laboratory and clinical applications, there is a little information about the machinability of dental ceramic for zirconia ceramics. Therefore, the objective of this study was to investigate the effect of abrading and cutting instruments on the machinability of dental ceramic materials mentioned above. The hypothesis examined was the machinability of dental ceramics is affected by mechanical and physical properties of machining instruments and dental ceramics.

2 Materials and methods

2.1 Specimen preparation

Ten rectangular block specimens (5 × 3 × 30 mm) were prepared from each type of restorative ceramic listed in Table 1. Lithium disilicate-based and fluorapatite leucite-based ceramic blocks were prepared by heat pressing. Wax blocks with the specimen dimensions were embedded in the molds with a refractory material (IPS PressVEST Powder and Liquid, Ivoclar Vivadent, Schaan, Leichtenstein). After the invested molds were burned out in a furnace set at 850 °C, the heat pressing was conducted using a press furnace (EP 600, Ivoclar Vivadent) according to the manufacturer's instruction. The pressed ceramic blocks were retrieved by divesting the refractory material, and were ultrasonically cleaned in an invex liquid (IPS e.max Press Invex Liquid, Ivoclar Vivadent) for 10 min, followed by air-abrasion (50 µm Al_2O_3, 20 psi). Zirconia blocks, which sizes are 20% larger than the stipulated setting size, were machined from pre-sintered zirconia and then completely sintered in a sintering furnace (Zenotec Fire P1, WIELAND Dental + Technik GmbH & KG, Pforzheim, Germany) set at 1450 °C for 2 h. Feldspathic porcelain blocks were prepared by using rubber-based molds and conventional vibration-condensation technique and sintered in a porcelain furnace (Austromat 3001, Dekema Dental-Keramiköfen GmbH, Freilassing, Germany). The firing schedule followed the manufacturer's instruction. All surfaces of each block specimens were polished with a silicon carbide paper (No.600-grit).

3 Machinability test

Machinability testing was conducted on the 3.0-mm-width surface of each specimen with the use of an electric hand-piece engine (UP 500, Brasseler USA, Savannah, GA) and an air-turbine hand-piece (Tradition L, Midwest, Des

Table 1 Dental restorative ceramics used in this study

Type	Ceramic	Composition (wt. %)	Manufacturer
Lithium disilicate-based ceramic	IPS e-max	Component: SiO_2 (57 ~ 80)	Ivoclar Vivadent, Schaan, Leichtenstein
		Additional components: Li_2O (11 ~ 19), K_2O (0 ~ 13), P_2O_5 (0 ~ 11), ZrO_2 (0 ~ 8), ZnO (0 ~ 8), other oxides (0 ~ 10), and coloring oxides (0 ~ 8)	
Fluorapatite leucite-based glass-ceramic	IPS e-max ZirPress	Component: SiO_2 (57 ~ 62)	Ivoclar Vivadent
		Additional components: Al_2O_3 (12 ~ 16), Na_2O (7 ~ 10), K_2O (6 ~ 8), CaO (2 ~ 4), ZrO_2 (1.5 ~ 2.5), P_2O_5 (1 ~ 2), F (0.5 ~ 1), other oxides (0 ~ 6), and pigments (0.2 ~ 0.9)	
Zirconia (Yttria-stabilized)	Zenostar	Zirconia ($ZrO_2 + HfO_2 + Y_2O_3$) >99 Y_2O_3 (4.5 ~ 6), HfO_2 (< 5), $Al_2O_3 < 0.5$, other oxides <0.5	WIELAND Dental + Technik GmbH and Co. KG, Pforzheim, Germany.
Zirconia (Ceria-stabilized)	P-nano ZR	ZrO_2, Al_2O_3, CeO_2, TiO_2 (0.05 mol% TiO_2 doped 10Ce-TZP/30 vol% Al_2O_3)	Panasonic Healthcare Co., Ltd. Tokyo, Japan
Feldspar-based porcelain	Vintage MP	SiO_2 (55 ~ 60), Al_2O_3 (10 ~ 16), K_2O (5 ~ 11), Na_2O (2 ~ 16), CaO (1 ~ 2), B_2O_3 (0 ~ 5), Sb_2O_3 (0.1 ~ 0.2), Others (0 ~ 5)	Shofu Inc., Kyoto, Japan

Plaines, IL) mounted on an apparatus used in a previous studies [21–23]. Three abrading wheels with similar diameter (13 mm) and thickness (1.8 mm) employed for the electric hand-piece were (1) SiC wheel (No.11, Shofu, Tokyo, Japan), (2) Diamond vitrified wheel (Vitrified Dia. HP11, Shofu), and (3) Diamond sintered wheel (Sintered Dia. 110 W, Shofu). The two air-turbine burs with similar head length (6 mm) and diameter (1.4 mm) employed for the air-turbine hand-piece were carbide fissure burs (Mani 559, Morita, Osaka, Japan) and diamond points (FG regular 211, Shofu). The 3.0-mm wide surface of each specimen was abraded using two abrading speeds (10,000 and 15,000 r.p.m.) and an abrading force of 100 gf with for the electrical hand-piece engine, and a cutting speed ($\sim 4.2 \times 10^5$ r.p.m. measure by the manufacturer) with a pressure of 200 kPa and a cutting force of 80 gf for the air-turbine hand-piece. The cutting with the air-turbine hand-piece was conducted under water spray. Before the machinability test, the weight of each specimen was measured on an electrical balance (TW223N, Shimadzu, Kyoto, Japan). Machinability efficiency was evaluated as volume loss calculated from the weight loss abraded for 30 s for the electrical hand-piece engine and the weight loss cut for 10 s for the air-turbine hand-piece using the density (calculated based on Archimedes' principle) of each ceramic specimen. The results of machining efficiency ($n = 10$) were statistically analyzed using a three-way (factors: wheel, speed, and ceramics) analysis of variance (ANOVA) for low-speed abrading and one-way ANOVA for each high-speed cutting instrument, followed by post hoc Tukey's test at a p-value of 0.05. Student's T-test was also conducted to compare between burs for each ceramic in high-speed cutting.

4 Results

Figures 1, 2 and 3 demonstrate the volume loss-of-dental ceramics abraded with SiC, diamond vitrified, and diamond sintered wheels, respectively. Table 2 shows the result of a 3-way ANOVA for low-speed abrading through Figs. 1–3. There were significances in each factor for speed, wheel and ceramic, and their interactions. A high-abrading speed (15,000 r.p.m.) had a significantly high-abrading efficiency (high-volume loss) compared to low-abrading speed (10,000 r.p.m.) in all abrading instruments used (Figs. 1–3). The SiC wheels (Fig. 1) indicated more effectiveness in abrasion for conventional feldspar-based porcelain (Vintage MP), lithium disilicate-based ceramic (IPS e-max), fluorapatite leucite-based glass-ceramic (IPS e-max ZirPress) than for zirconia ceramics (Zenostar and P-nano Zr): significant at $P < 0.05$. On the other hand, the diamond vitrified wheels tend to demonstrate high-volume loss for zirconia ceramics (Zenostar and P-nano Zr) when compared

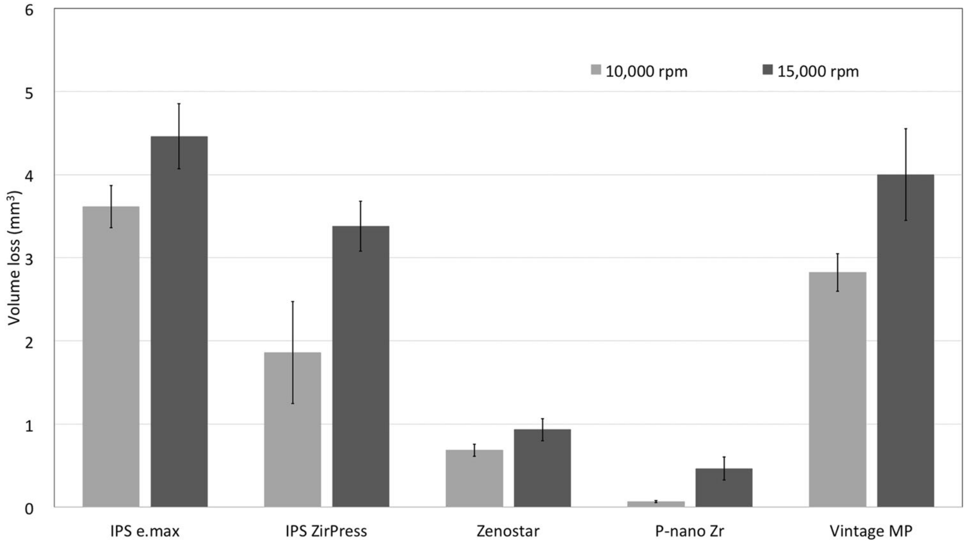


Fig. 1 Volume loss-of-dental ceramics abraded with SiC wheel

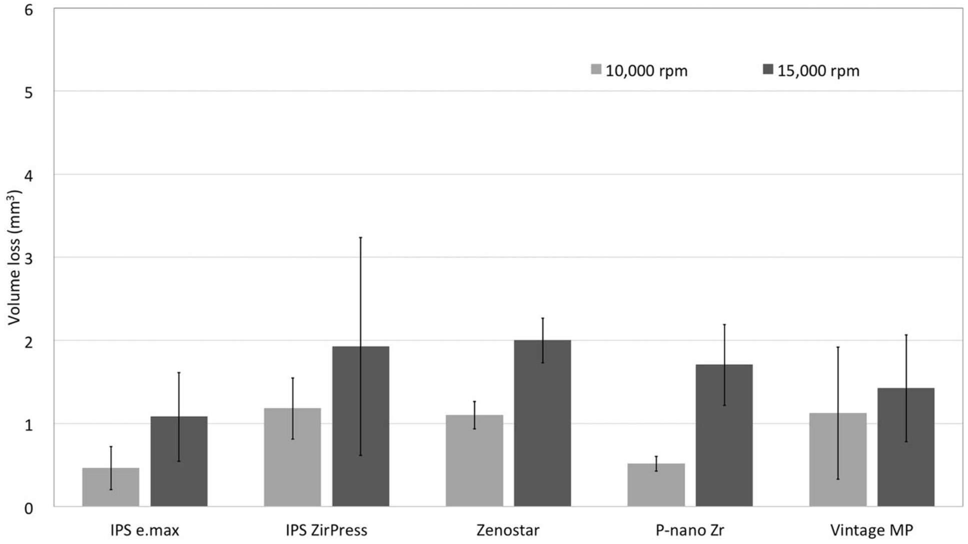


Fig. 2 Volume loss-of-dental ceramics abraded with Diamond vitrified wheel

to SiC wheels (Fig. 1). Note that the volume losses of feldspar-based porcelain (Vintage MP), lithium disilicate-based ceramic (IPS e-max), fluorapatite leucite-based glass-ceramic (IPS e-max ZirPress) abraded with SiC wheels (Fig. 1) dramatically decreased when the diamond vitrified wheels were used (Fig. 2), and the volume losses of zirconia ceramics (Zenostar and P-nano Zr) abraded with diamond vitrified wheels (Fig. 2) are higher than those abraded with the SiC wheels (Fig. 1). The diamond sintered wheels (Fig. 3) showed the results of volume losses between the SiC wheels and diamond vitrified wheels. However, diamond sintered wheels demonstrated the greatest volume loss when the fluorapatite leucite-based glass-ceramic (IPS e-max ZirPress) were abraded at an abrading speed of 15,000 r.p.m. (Fig. 3).

When the high-speed air-turbine instruments were used to cut the dental ceramics (Fig. 4 and Table 3), the carbide burs had high-cutting efficiency (volume losses) to cut the fluorapatite leucite-based glass-ceramic (IPS e-max ZirPress) and the conventional feldspar-based porcelain (Vintage MP). There was no statistical difference between them and they showed significantly higher volume loss compared to other ceramics (Table 3). To cut the lithium disilicate-based ceramic (IPS e-max) and zirconia ceramics (Zenostar and P-nano Zr), the diamond points showed higher volume losses compared to the carbide burs. See that the volume losses cut with diamond points were similar between a zirconia ceramics (Zenostar) and conventional feldspar-based porcelain (Vintage MP). The P-nano Zr showed the

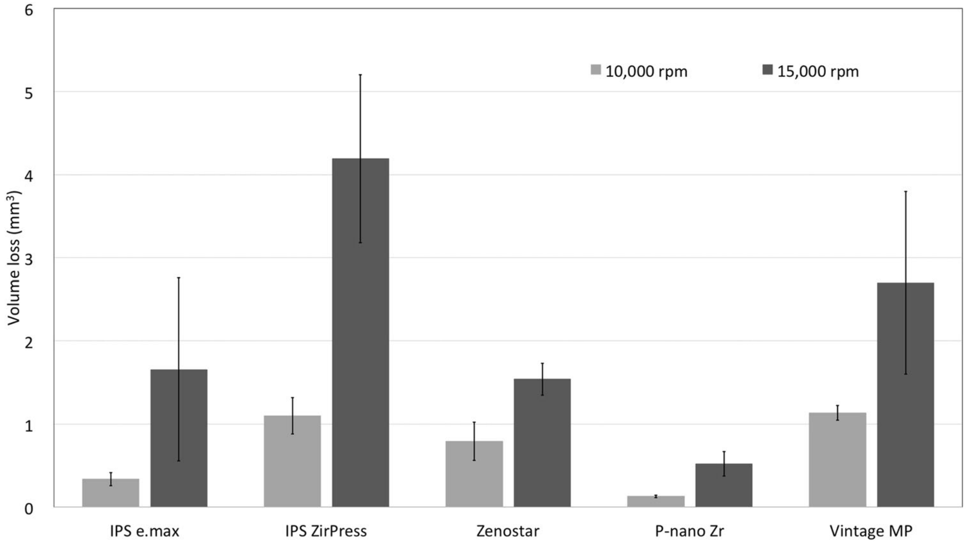


Fig. 3 Volume loss-of-dental ceramics abraded with Diamond sintered wheel

Table 2 Statistical analysis of a 3-way ANOVA for low-speed abrading

Source	Sum of square	df	*F*-value	*P*-value
Intercept	809.8	1	3233.7	<.0001
Speed	79.5	1	317.3	<.0001
Wheel	59.8	2	119.3	<.0001
Ceramics	135.2	4	135.0	<.0001
Speed × ceramics	16.4	4	16.3	<.0001
Speed × wheel	6.1	2	12.3	<.0001
Wheel × ceramics	154.5	8	77.1	<.0001
Wheel × ceramics × speed	16.4	8	8.2	<.0001

most difficulty (the lowest volume loss among ceramic materials) to cut with either diamond points or carbide burs.

5 Discussion

The factors affecting the machining (abrading and cutting) efficiencies to dental ceramics include the mechanical and physical properties of dental ceramics and machining instruments, machining force and machining speed. In fact, a high-abrading speed (15,000 r.p.m.) demonstrated higher machining efficiency (high-volume losses) compared to a low-abrading speed (10,000 r.p.m.) under a constant abrading force (100 gf) in all abrading instruments used in this study (Figs. 1–3). The mechanical and physical properties of abrading instruments are related to their elemental compositions (abrasive grains and binder) and binding methods (vitrifying or sintering), and the properties of cutting instruments depend on cutlery materials (diamond or tungsten-carbide). The compositions and binding method of the abrading instruments used for an electric hand-piece engine in this study are as follows: (1) the SiC wheel was composed of silicon carbide abrasive grains vitrified with glass binder, and (2) the diamond vitrified wheel was made of diamond abrasive grains vitrified with glass binder, whereas (3) the diamond sintered wheel was composed of diamond abrasive grains sintered with metal binder. These different abrasive grains bound with different binder and method resulted in different abrading efficiencies to dental ceramics for an electric hand-piece engine (Figs. 1–3).

The mechanical and physical properties of dental ceramics also affect the machining (abrading and cutting) efficiencies. Those properties (Table 4) include flexural strength (FS: MPa), fracture toughness (FT: MPa·$m^{0.5}$), elastic modulus (EM: GPa) and hardness (HN: Hv). When the SiC wheel and the diamond sintered wheel (Figs. 1 and 3) for an electric hand-piece engine and the carbide bur (Fig. 5) for an air-turbine hand-piece were used, the volume losses of zirconia ceramics (Zenostar and P-nano Zr) were much lower than those of conventional feldspar-based porcelain (Vintage MP), lithium disilicate-based ceramic (IPS e-max) and fluorapatite leucite-based glass-ceramic (IPS e-max ZirPress). Very low volume losses of zirconia ceramics are because of their higher mechanical and physical properties (FS: >1300 MPa; FT: >7 MPa·$m^{0.5}$; EM: >210 GPa; HN: >1290 Hv) [24] compared to those (FS = 80 ~ 400 MPa; FT = 0.9 ~ 2.75 MPa·$m^{0.5}$; EM = 70 ~ 95 GPa; HN = 460 ~ 580 Hv) [24, 25] of the other ceramics. When two zirconia ceramics were compared, volume losses of the ceria-stabilized P-nano Zr were lower than those of the yttria-stabilized Zenostar in all of the abrading and cutting instruments (Figs. 1–4). This is because that the mechanical and physical properties (FS = 1500 MPa; FT = 11 MPa·$m^{0.5}$; EM = 240 GPa; HN = 1300 Hv) [24]

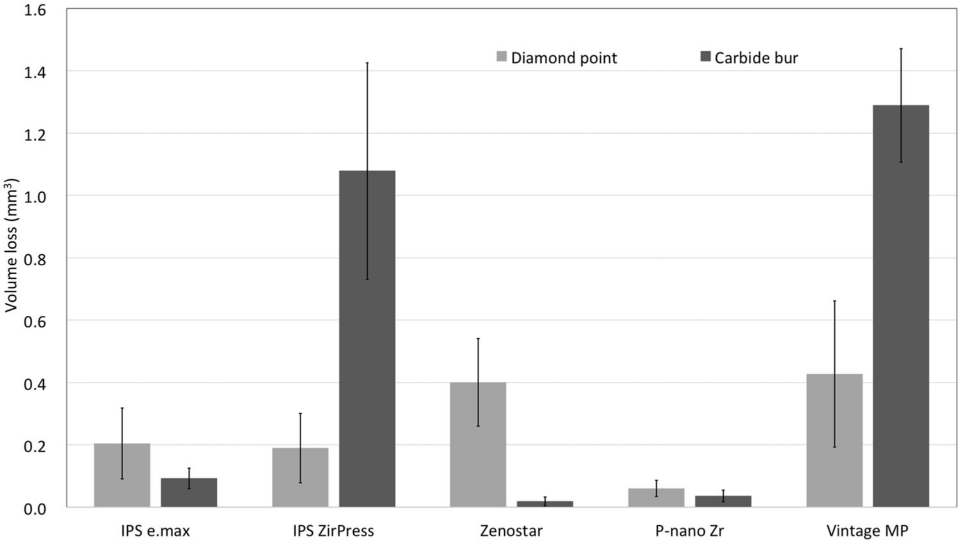


Fig. 4 Volume loss-of-dental ceramics cut with high-speed air-turbine instruments

Table 3 Volume loss (mm^3) cut with diamond point and carbide fissure bur for each ceramic

	IPS e-max	IPS ZirPress	Zenostar	P-nano Zr	Vintage MP
Diamond point	0.20 (0.11)^{a,*}	0.19 (0.11)^{a,*}	0.40 (0.14)^{b,*}	0.06 (0.03)^{a,*}	0.43 (0.23)^{b,*}
Carbide fissure bur	0.09 (0.03)^{a,*}	1.08 (0.35)^{b,*}	0.02 (0.01)^{a,*}	0.04 (0.02)^{a,*}	1.29 (0.18)^{b,*}

Identical letters ('a' and 'b') indicate no statistical differences in the same row (*p*-value: 0.05)

*indicate statistical difference between the instruments in each ceramic (Student's *T*-test)

Table 4 Mechanical and physical properties of materials used in this study (24–26)

Materials	Ceramics	Flexural strength (FS: MPa)	Fracture toughness (FT: $MPa \cdot m^{0.5}$)	Elastic modulus (EM: GPa)	Hardness (HN: Hv, Hk*)
Lithium disilicate-based ceramic	IPS e-max	400	2.75	95	580
Fluorapatite leucite-based glass-ceramic	IPS e-max ZirPress	110	1.1	80	540
Zirconia (Yttria-stabilized)	Zenostar	1300	6	210	1290
Zirconia (Ceria-stabilized)	P-nano ZR	1500	11	240	1300
Feldspar-based porcelain	Vintage MP	80	0.9	70	460
Silicon carbide	–	–	–	–	2000–2500*
Tungsten-carbide	–	–	–	–	1900–2000*
Diamond	–	–	–	–	7000–10,000*

Hv Vickers hardness, **Hk* knoop hardness

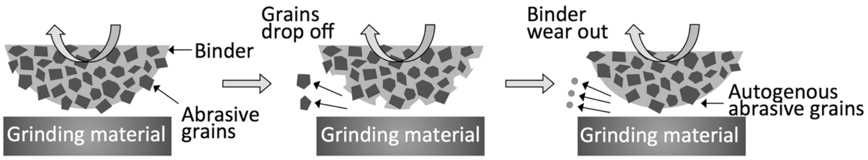


Fig. 5 Schematic drawing for autogenous action of abrasive grains for abrading wheel

of the P-nano Zr were higher than those (FS = 1300 MPa; FT = 6 MPa·m$^{0.5}$; EM = 210 GPa; HN = 1290 Hv) [24] of the Zenostar (Table 4).

When the diamond vitrified wheels were used (Fig. 2) to abrade dental ceramics, volume losses of conventional feldspar-based porcelain (Vintage MP), lithium disilicate-based ceramic (IPS e-max) and fluorapatite leucite-based glass-ceramic (IPS e-max ZirPress) dramatically decreased when compared to the volume losses abraded by the SiC wheel (Fig. 1) and the diamond sintered wheel (Fig. 3). On the other hand, the volume losses of two zirconia ceramics abraded by the diamond vitrified wheels increased when compared with the SiC wheel and the diamond sintered wheel (Fig. 2 vs. 1; Fig. 2 vs. 3). In general, the abrading wheels show autogenous action of abrasive grains (Fig. 5), in which ground abrasive grains drop out from the binder during abrasion, then the binder follow to wear out, subsequently new abrasive grains come out onto the instrument surface and increase the grinding amount (volume loss) of grinding materials. As a result, this autogenous action of abrading wheels promote abrading efficiency. Since the zirconia ceramics are tough materials (high mechanical and physical properties), the autogenous action of abrasive diamond grains might occur on the surface of diamond vitrified wheels, resulted in increase of volume loss. In regard to the other three ceramics, the autogenous action of abrasive diamond grains might not occur because of their relatively low mechanical and physical properties which could not drop off the diamond abrasive grains vitrified with glass binder. Therefore, abrasive debris of these ceramics might clog on the grinding surface of the diamond vitrified wheel during abrasion. On the contrary, the autogenous action of abrasive grains might effectively occur when these ceramics were abraded by the SiC wheel (Fig. 1) and diamond sintered wheel (Fig. 3).

When the carbide burs with a high-speed air turbine were used (Fig. 4), the conventional feldspar-based porcelain (Vintage MP) and the fluorapatite leucite-based glass-ceramic (IPS e-max ZirPress) showed great volume losses. See that the volume losses of the other ceramics are high when the diamond points are used. The diamond points are made of diamond abrasive powders (HN = 7000 ~ 10,000 Hk) [26] electrodeposited with chromium plating on the metal core rod. On the other hand, carbide bur blades are made of cutlery material of sintered tungsten-carbide (cemented carbide: HN = 1900 ~ 2000 Hk) [26]. Therefore, the diamond point is a type of abrasive motion with diamond particles, whereas the carbide bur is a type of cutting motion with blade. The differences in machining motion and mechanical properties of dental ceramics are closely related to the results of volume loss for the high-speed air turbine. Since two ceramics mentioned above have low-mechanical properties (Vintage MP: FS = 80 MPa, FT = 0.9 MPa·m$^{0.5}$ HN = 460 Hv; IPS e-max ZirPress: FS = 110 MPa, FT = 1.1 MPa·m$^{0.5}$ HN = 540 Hv) [24, 25], they were effectively cut by carbide-bur blades and showed high-volume losses. As for as the other ceramics, the abrasive motion of diamond points were effective because the mechanical properties of these ceramics (IPS e-max: FS = 400 MPa, FT = 2.75 MPa·m$^{0.5}$ HN = 580 Hv; Zenostar: FS = 1300 MPa, FT = 6 MPa·m$^{0.5}$ HN = 1290 Hv; P-nano Zr: FS = 1500 MPa, FT = 11 MPa·m$^{0.5}$ HN = 1300 Hv) [24] are higher than those of two ceramics mentioned above.

6 Conclusions

A high-abrading speed demonstrated higher machining efficiency compared to a low-abrading speed under a constant abrading force in all abrading instruments used in this study. For the machinability of three types of wheels with a hand-piece engine, the diamond vitrified wheels showed high-abrading efficiency for zirconia ceramics, and the SiC and diamond sintered wheels had high-abrading efficiency for conventional feldspar-based porcelain, lithium disilicate-based ceramic and fluorapatite leucite-based glass-ceramic. When the carbide burs with a high-speed air turbine were used, the conventional feldspar-based porcelain and the fluorapatite leucite-based glass-ceramic showed great volume losses (cutting efficiency), whereas the diamond points showed high-cutting efficiency for the lithium disilicate-based ceramic and two zirconia ceramics. The hypothesis that the machinability of dental ceramics is affected by mechanical and physical properties of machining instruments and dental ceramics were confirmed.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Denry I, Holloway JA. Ceramics for dental applications: a review. Materials. 2010;3:351–68.
2. Sailer I, Philippa, Zembic A, Pjetursson BE, Hämmerle CH, Zwahlen M. A systematic review of the performance of ceramic and metal implant abutments supporting fixed implant reconstructions. Clin Oral Implants Res. 2009;20:4–31. Suppl 4
3. Albakry M, Guazzato M, Swain MV. Biaxial flexural strength, elastic moduli, and x-ray diffraction characterization of three pressable all-ceramic materials. J Prosthet Dent. 2003;89:374–80.
4. Conrad HJ, Seong WJ, Pesun IJ. Current ceramic materials and systems with clinical recommendations: a systematic review. J Prosthet Dent. 2007;98:389–404.
5. Kontonasaki E, Kantiranis N, Papadopoulou L, Chatzistavrou X, Kavouras P, Zorba T, Sivropoulou A, Chrissafis K, Paraskevopoulos KM, Koidis PT. Microstructural characterization and

comarative evaluation of physical, mechanical and biological properties of three ceramics for metal-ceramic restrations. Dent Mater. 2008;24:1362–73.

6. Gonzaga CC, Cesar PF, Miranda WG Jr, Yoshimura HN. Slow crack growth and reliability of dental ceramics. Dent Mater. 2011;27:394–406.
7. International Organization for Standardization. ISO 6872: Dental ceramic. Geneva, Switzerland; 2008.
8. International Organization for Standardization. ISO 9693: Metal-ceramic dental restorative systems. Geneva, Switzerland; 1999.
9. Denry IL, Holloway JA. Elastic constants, Vickers hardness, and fracture toughness of fluorrichterite-based glass-ceramics. Dent Mater. 2004;20:213–9.
10. Kern M, Sasse M, Wolfart S. Ten-year outcome of three-unit fixed dental prostheses made from monolithic lithium disilicate ceramic. J Am Assoc. 2012;143:234–40.
11. Kosmac T, OBlak C, Jevnikar P, Funduk N, Marion L. Strength and reliability of surface treated Y-TZP dental ceramics. J Biomed Mater Res. 2000;53:304–13.
12. Sax C, Hämmerle CH, Sailer I. 10-year clinical outcomes of fixed dental prostheses with zirconia frameworks. Int J Comput Dent. 2011;14:183–202.
13. Choi JE, Waddell JN, Torr B, Swain MV. Pressed ceramics onto zirconia. Part 1: comparison of crystalline phases present, adhesion to a zirconia system and flexural strength. Dent Mater. 2011;27:1204–12.
14. White SN, Miklus VG, McLaren EA, Lang LA, Caputo AA. Flexural strength of a layered zironia and porcelain dental all-ceramic system. J Prosthet Dent. 2005;94:125–31.
15. Fischer J, Stawarczyk B, Hämmerle CH. Flexural strength of veneering ceramics for zirconia. J Dent. 2008;24:471–5.
16. Albashaireh ZS, Ghazal M, Kern M. Two-body wear of different ceramic materials opposed to zirconia ceramic. J Prosthet Dent. 2010;104:105–13.
17. Jung YS, Lee JW, Choi YJ, Ahn JS, Shin SW, Huh JB. A study on the in-vitro wear of the natural tooth structure by opposing zirconia or dental porcelain. J Adv Prosthodont. 2010;2:111–5.
18. Taira M, Wakasa K, Yamaki M, Matsui A. Dental cutting behaviour of mica-based and apatite-based machinable glass-ceramics. J Oral Rehabil. 1990;17:461–72.
19. Schmidt C, Weigl P. Machinability of IPS Empress 2 framework ceramic. J Biomed Mater Res. 2000;53:348–52.
20. Song XF, Ren HT, Yin L. Machinability of lithium disilicate glass ceramic in in vitro dental diamond bur adjusting process. J Mech Behav Biomed Mater. 2016;53:78–92.
21. Ohkubo C, Watanabe I, Ford JP, Nakajima H, Hosoi T, Okabe T. The machinability of cast titanium and Ti-6Al-4V. Biomaterials. 2000;21:421–8.
22. Watanabe I, Ohkubo C, Ford JP, Atsuta M, Okabe T. Cutting efficiency of air-turbine burs on cast titanium and dental casting alloys. Dent Mater. 2000;16:420425.
23. Ohkubo C, Hosoi T, Ford JP, Watanabe I. Effect of surface reaction layer on grindability of cast titanium alloys. Dent Mater. 2006;22:268–74.
24. Ban S. Properties of zirconia for realization of all-ceramic restoration. Shikwa Gakuho. 2007;107:670–84.
25. Tang X, Nakamura T, Usami H, Wakabayashi K, Yatani H. Effects of multiple firings on the mechanical properties and microstructure of veneering ceramics for zirconia frameworks. J Dent. 2012;40:372–80.
26. Anusavice KJ. Phillip's Science of Dental Materials. 12th ed St. Louis: Elsevier; 2013. P. 239.