

ORIGINAL ARTICLE

The Correlation of Surface Roughness Parameters of Zirconia and Lithium Disilicate with Steatite Wear

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[Correction added on August 8, 2022, after first online publication: The authors' degrees have been updated.]

Abstract

Purpose: Various surface roughness parameters are utilized to describe the surface in the tooth to ceramics abrasion and to assess the resulting wear. The use of three-dimensional parameters may offer a better estimation for wear and an improved deduced clinical surface treatment. The aim of this study was to determine the influence of various surface roughness parameters of zirconia and lithium disilicate ceramics on the wear of steatite antagonists.

Material and methods: Forty zirconia specimens with a diameter of 7 mm and a thickness of 3 mm and 40 lithium disilicate specimens with the dimensions 10×10×4 mm were each divided into five subgroups. Two subgroups were treated with different clinically established diamond burs; a third subgroup was treated with a silicone polishing set. Two additional subgroups were produced by glazing the surfaces after treatment. Surface roughness parameters were determined by laser scanning microscopy. All specimens underwent 1.2 million loading cycles using steatite antagonists. After regular intervals of cycles, precision impressions were made to assess the wear. The correlation between wear and different roughness parameters was evaluated using the Spearman correlation test.

Results: For the glazed zirconia, unglazed zirconia, and glazed lithium disilicate specimens no significant correlations ($p > 0.05$) between the investigated roughness parameters and antagonist wear could be found. In the unglazed lithium disilicate groups, significant ($p \leq 0.05$) correlations with steatite substance loss could be found for several roughness parameters after 1.2 million cycles.

Conclusions: For lithium disilicate, it seems not sufficient to use only one roughness parameter to indicate the wear behavior of the surface. There was no correlation between wear and the tested roughness parameters of zirconia surfaces.

KEYWORDS

Zirconia, lithium disilicate, surface roughness parameter, wear

In the last decades all-ceramic single crowns (SCs) and all-ceramic fixed dental prostheses (FDPs) have gained widespread use, because of their high aesthetic and improved mechanical properties.¹ High-strength ceramics, combined with computer-aided design and computer-aided manufacturing (CAD-CAM) milling methods allow all-ceramic multi-span restorations, even in posterior areas, and also

produce SCs with a clinically acceptable marginal fit and survival rate.² High-strength ceramics, for example, zirconia, can be used directly as a restoration or as a substructure with subsequent veneering.³ Monolithically fabricated lithium disilicate FDPs have comparable failure load results to the metal-ceramic gold standard.⁴ In the context of the intensified usage of all-ceramic SCs and FDPs, the antagonist substance

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loss of the all-ceramic restorations in vivo has been thoroughly examined and identified as an undesirable property.⁵

The ceramic surface texture as an important factor for antagonist wear behavior has been described in various studies with varying considerations of surface textures.^{6–8} Often the treatment of the surface prior to the start of a wear experiment is described, for example, the size of the polishing diamond suspension.^{9,10} For quantifiable data surface roughness parameters such as the root-mean-square roughness R_q , or the total height of the surface profile R_t came to use.^{11,12} Various studies used the mean roughness R_a to describe the surface texture,^{3,13–15} or S_a .¹⁶ It could be stated that the higher the value of R_a , the more antagonistic wear resulted.^{14,17} The mean surface roughness R_a has been proven to play an essential role in the wear interaction of enamel and ceramics.¹⁸ Nonetheless current systematic literature reviews could not identify a dominant parameter for antagonist wear against ceramic due to a lack of standardized parameters.^{19,20}

Little research has been done on determining whether there are more suitable dental ceramic surface roughness parameters that correlate significantly with antagonist wear. A comparison of differently treated surfaces could be made possible by a greater variety of standardized surface roughness parameters. Furthermore, using up-to-date 3D measuring techniques according to DIN ISO 25178-2 is lacking; this would provide more significant and function-oriented information on surface topography.²¹

The large number of available surface parameters makes a closer selection necessary. The selected surface parameters should be function-relevant²² and manufacture-related.²³ R_a and S_a are widely used in the industry.²⁴ Unfortunately by using only R_a or S_a it is not possible to describe the surface after two processes.²³ More parameters are necessary to assess the surface texture, for example, S_p , the maximal height of the highest peak from the center plane, S_z the sum of the value of the highest peak and deepest point from a center plane, or their linear parameters further characterize the surface amplitude, while S_{ku} (areal kurtosis) or R_{ku} (linear kurtosis) describe the character of height distribution.²³ The depth of the deepest point below center line R_v is used to acknowledge a recent study, which used R_v to assess the effects of tooth brushing on the dental and restorative surfaces,²⁵ the areal version is used, too. S_{ku} or R_{ku} can be used to identify surfaces after different machining processes.²⁶ Low kurtosis also improves contact of rough surfaces and furthermore S_q/S_a strongly correlates with S_{ku} ,²³ hence these parameters are function-relevant. Other parameters of interest are S_z or R_z maximal valley depth from the center plane and depth of the deepest point below the center line. There is the opinion that the maximum roughness height S_z or R_z is related to surface damage while the averaged parameters are related to surface normal functioning.²⁷ Also S_z or R_z can be used for detecting outliers.²³ For the authors of this study it was of interest whether any sharp spikes that may be present, could affect the amount of antagonist substance loss. Therefore S_p or R_p are of interest because they define the maximum surface elevation height.²⁸ Another parameter, S_{pd} (peak density per

surface), takes into account only those significant spikes that remain on the surface after discrimination by segmentation,²⁹ similar to S_{pd} , S_{pc} (arithmetic mean of peak curvature). Or their linear parameter considers only significant spikes and describes the peak curvature.²³ A hybrid parameter should also come to use; S_{dr} is denominated as surface ratio, with specific values it correlates with S_{dq} , when the surfaces are oriented.³⁰ The treatment should take place under water irrigation to approximate the oral situation and to minimize the alteration of the system's configuration and dynamics by third particle contact.³¹

Therefore, the aim of the present laboratory study was to investigate the correlation of antagonist wear with surface roughness parameters of two dental ceramics after standardized clinically relevant surface treatments with and without subsequent glazing. Steatite balls were selected as antagonists. Although steatite may not be considered an ideal substitute for human enamel, the standardized properties seem advantageous and it has been approved for in vitro tests.^{32,33} The null hypothesis is that there are no significant correlations between roughness parameters and wear.

MATERIALS AND METHODS

Agonist and antagonist

In this laboratory study the agonist materials were 40 round discs of Y-TZP zirconia (Cercon base, Dentsply Sirona Deutschland GmbH, Germany, batch number: 20017175) with a diameter of 7 mm, a thickness of 3 mm, and a flexural strength of 1,200 MPa, and 40 rectangular discs of lithium disilicate (IPS e.max CAD, Ivoclar Vivadent, Schaan, Liechtenstein, batch number 550172) with the size of 10 mm × 10 mm, a thickness of 4 mm, and a flexural strength of 530 MPa. Four groups of the agonist material were treated with a glaze with a flexural strength of ≥ 50 MPa (Glaze Fluo, Ivoclar Vivadent, batch number WZ1008). All figures are given as provided by the manufacturers. Steatite balls (Steatit, CeramTec, Lauf, Germany) with a diameter of 6 mm, a Mohs-hardness of ≥ 7, a surface roughness $R_a = 4.21 \mu\text{m}$,³⁴ and a modulus of elasticity of >80 GPa were used as antagonists.

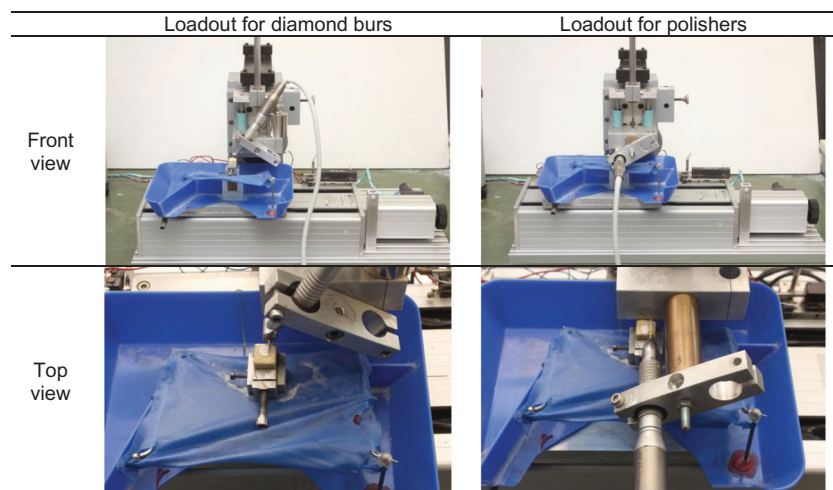
Creating equal surface conditions

All specimens were polished in a grinding machine (Ecomet 250 pro, Buehler, Esslingen am Neckar, Germany) under a load of 49 N. All specimens were surface finished with a polishing cloth and diamond emulsions. The grain sizes, 3 μm then 0.25 μm , came to use. The details of the polishing procedures are shown in Table 1.

Specimens were cleaned in an ultrasonic bath for 5 minutes in demineralized water followed by 99% isopropanol. They were dried with oil-free air. Afterwards, all specimens were scanned with a confocal laser scanning microscope (VK-X 100, Keyence, Osaka, Japan) and analyzed to verify homogenous surface conditions.

TABLE 1 Pretreatment steps for all zirconia and lithium disilicate specimens

Step	I	II	III	IV	V	VI	VII
Grinding technique	Diamond coated grinding disc	P 600 SiC	P 1 200 SiC	P 2 500 SiC	P 4 000 SiC	Diamond emulsion 3 μm	Diamond emulsion 0.25 μm

**FIGURE 1** Device used for automated surface treatment.

Degrading surface treatment

The specimens of the two ceramics were embedded into a low shrinking, cold polymerizing 3-component resin (Technovit 4000, Kulzer, Hanau, Germany, batch number R1) and then divided into 5 subgroups for each material. The surface treatment was undertaken with a self-designed machine, which applied force and at the same time moved back and forth with a speed of 5.5 mm/s (Fig 1).

Three subgroups of both ceramics were roughened with torpedo-shaped diamond burs using a load of 4.9 N and a steady movement under water cooling. For two of these subgroups red marked diamond burs (REF: 8837 314 012, batch number: 133313, FG – Friction Grip, ISO: 806 314 289 514 012, Brasseler, Lemgo, Germany) with the diamond grain size “fine” of 46 μm was used. For the remaining subgroup torpedo-shaped diamond burs with yellow marking (REF: 837EF 314 012, batch number: 128030, FG – Friction Grip, ISO: 806 314 289 504 012, Brasseler, Lemgo, Germany) diamond grain size “extra fine” of 25 μm was used. Both burs had an operation length of 8 mm and a diameter of 1.2 mm. They were used with a rotation speed of 20,000 per minute with water spray cooling. The group codes of all subgroups are shown in Table 2.

The specimens of the two remaining subgroups were polished in the grinding machine with drum-shaped silicone-polishers (Zil-Master 0640, 0646 and 0670, batch number: 071611, Shofu Dental, Ratingen, Germany) with a pressure of 1 N and 20,000 per minute, according to the recommendations of the manufacturer. The polishing set is indicated for use on lithium disilicate and zirconia ceramic and it consists of three polishers that were subse-

quently used. First the “coarse” (green marking), then the “medium” (blue marking), and finally the “fine” (yellow marking) polishers were applied. All grinding tools were used first in one direction followed by a second perpendicular direction.

The specimens were again cleaned in an ultrasonic bath for 5 minutes with demineralized water followed by 99% isopropanol and dried with oil-free air. All specimens were scanned with a confocal laser scanning microscope (VK-X 100, Keyence, Osaka, Japan) and analyzed (μsoft analysis extended version 7.4.8164, Nanofocus AG, Oberhausen, Germany). The linear roughness parameters were measured perpendicularly to the linear surface texture of the diamond burs and polishers. The following roughness parameters were evaluated: R_a , R_p , R_z , R_v , R_t , R_{ku} , R_{pc} , S_a , S_p , S_z , S_v , S_{ku} , S_{pc} , S_{pd} , and S_{dr} (Table 3).

Glazed subgroups

For each agonist material two subgroups, one finished with the red marked diamond bur and one with the silicone polishers, were glazed with the low-fusing nano-fluorapatite glass-ceramic Glaze Fluo (Ivoclar Vivadent AG, Schaan, Lichtenstein). Prior to the glaze firing, the synthetic embedding material was removed manually and the specimens were cleaned in the ultrasonic bath as aforementioned. The thickness of the glaze layer was measured with a gauge; on average it was 50 μm thick and varied between 40 μm and 70 μm . The specimens were re-embedded into the resin material. Afterwards the four groups were cleaned in the ultrasonic bath for 5 minutes with demineralized water,

TABLE 2 Treatment and group codes of all agonistic specimens

Material	Treatment	Subgroup code	Combined subgroups
Zirconia	Diamond bur red marking	Zr.R (N = 8)	ZrNG
Zirconia	Diamond bur yellow marking	Zr.Y (N = 8)	
Zirconia	Silicone polishers	Zr.S (N = 8)	
Zirconia	Diamond bur red marking, glaze firing	Zr.RG (N = 8)	ZrG
Zirconia	Silicone polishers, glaze firing	Zr.SG (N = 8)	
Lithium disilicate	Diamond bur red marking	LD.R (N = 8)	LDNG
Lithium disilicate	Diamond bur yellow marking	LD.Y (N = 8)	
Lithium disilicate	Silicone polishers	LD.S (N = 8)	
Lithium disilicate	Diamond bur red marking, glaze firing	LD.RG (N = 8)	LDG
Lithium disilicate	Silicone polishers, glaze firing	LD.SG (N = 8)	

TABLE 3 Means (standard deviations) of all included surface roughness parameters of zirconia specimens. Statistically different roughness parameters ($p \leq 0.05$) are indicated by different lowercase letters (within a row)

Zirconia	Zr.R	Zr.Y	Zr.S	Zr.RG	Zr.SG
R_a [μm]	0.622 ^a (0.107)	0.199 ^b (0.017)	0.210 ^b (0.073)	0.157 ^b (0.036)	0.202 ^b (0.062)
R_p [μm]	2.684 ^a (0.319)	1.258 ^b (0.140)	0.760 ^b (0.289)	0.472 ^b (0.101)	0.646 ^b (0.180)
R_z [μm]	5.516 ^a (0.690)	2.707 ^{ab} (0.358)	1.822 ^b (0.663)	2.192 ^b (1.086)	2.679 ^b (1.328)
R_v [μm]	2.832 ^a (0.416)	1.449 ^{ab} (0.229)	1.062 ^b (0.384)	1.721 ^{ab} (1.016)	2.034 ^{ab} (1.178)
R_t [μm]	6.554 ^a (0.865)	3.566 ^{ab} (0.388)	2.443 ^b (0.792)	4.299 ^{ab} (2.261)	5.070 ^{ab} (2.766)
R_{ku}	3.787 ^b (0.616)	7.697 ^{ab} (1.308)	5.712 ^b (1.015)	26.691 ^a (18.912)	23.342 ^a (11.153)
R_{pc} [1/cm]	204.007 ^a (16.085)	203.841 ^a (12.430)	142.048 ^{ab} (17.024)	64.124 ^b (5.993)	74.659 ^b (3.555)
S^a [μm]	0.614 ^a (0.095)	0.203 ^b (0.0155)	0.240 ^b (0.051)	0.266 ^b (0.074)	0.282 ^{ab} (0.063)
S_p [μm]	10.484 ^a (3.719)	7.730 ^a (3.335)	7.969 ^a (1.548)	6.495 ^a (1.209)	9.253 ^a (3.202)
S_z [μm]	19.336 ^{bc} (6.515)	12.872 ^c (4.853)	13.341 ^c (3.084)	45.297 ^{ab} (14.432)	56.963 ^a (8.874)
S_v [μm]	8.852 ^{ab} (2.836)	5.142 ^b (2.149)	5.372 ^b (1.862)	38.803 ^{ab} (14.009)	47.710 ^a (7.983)
S_{ku}	7.474 ^c (6.461)	17.835 ^{bc} (23.030)	10.835 ^{bc} (3.723)	1071.374 ^{ab} (1067.322)	1386.328 ^a (1009.486)
S_{pc} [1/ μm]	35.825 ^{ab} (6.501)	21.008 ^b (8.740)	23.682 ^b (13.029)	123.090 ^a (51.100)	153.720 ^a (58.693)
S_{pd} [1/ μm^2]	0.017 ^a (0.005)	0.012 ^a (0.006)	0.002 ^{ab} (0.001)	0.000 ^b (0.000)	0.000 ^b (0.000)
S_{dr} [%]	35.087 ^a (6.501)	15.395 ^{ab} (2.800)	3.849 ^b (1.968)	2.368 ^b (1.553)	3.372 ^b (2.480)

followed by 99% isopropanol and dried with oil-free air. The surfaces were measured with the confocal laser scanning microscope.

Wear evaluation

The ceramic specimens were dynamically loaded in a biaxial chewing simulator (CS 4, SD Mechatronik, Feldkirchen-Westerham, Germany) for 1,200,000 cycles using the spherical steatite balls with a nominal weight of 5 kg at a loading speed of 30 mm/s and an additional 0.3 mm sliding movement while in contact with a frequency of 1.3 Hz with water irrigation to minimize third body abrasion. Silicone impressions (Express 2 Ultra-Light Body Quick, 3M ESPE, Saint

Paul, MN) of the steatite and ceramic specimens were made before testing and after 120,000, 240,000, 480,000, 600,000, 840,000, and 1,200,000 cycles, respectively. The silicone impressions were scanned with the confocal laser scanning microscope.

The analysis of the surface roughness took place prior to the wear experiment. In order to quantify the wear behavior, the vertical substance loss of the spherical steatite and ceramic specimens after each interval was measured with software (VK-H1XP Analyzer Plus Ver. 3.4.0.1, Keyence Corporation), as shown in Figure 2. The distance from the “deepest” dent in the lithium disilicate and zirconia specimens to the normal surface level was measured. In addition, images of the specimens after 1,200,000 cycles were taken after the deposition of a 10 nm gold layer with

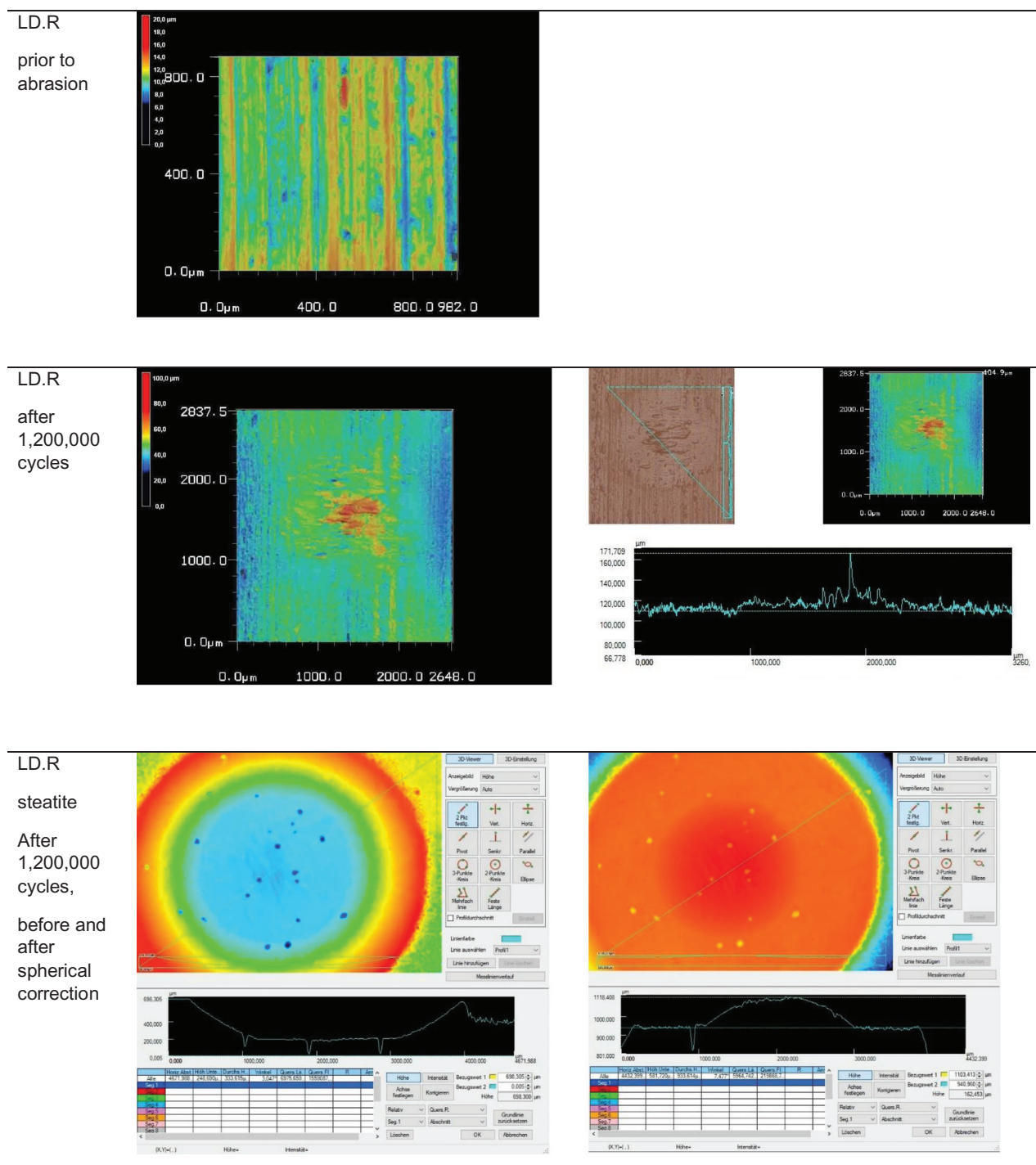


FIGURE 2 Exemplary measurement process of wear evaluation, steatite height loss measurement after spherical correction (VK-H1XP Analyzer Plus Ver. 3.4.0.1, Keyence Corporation).

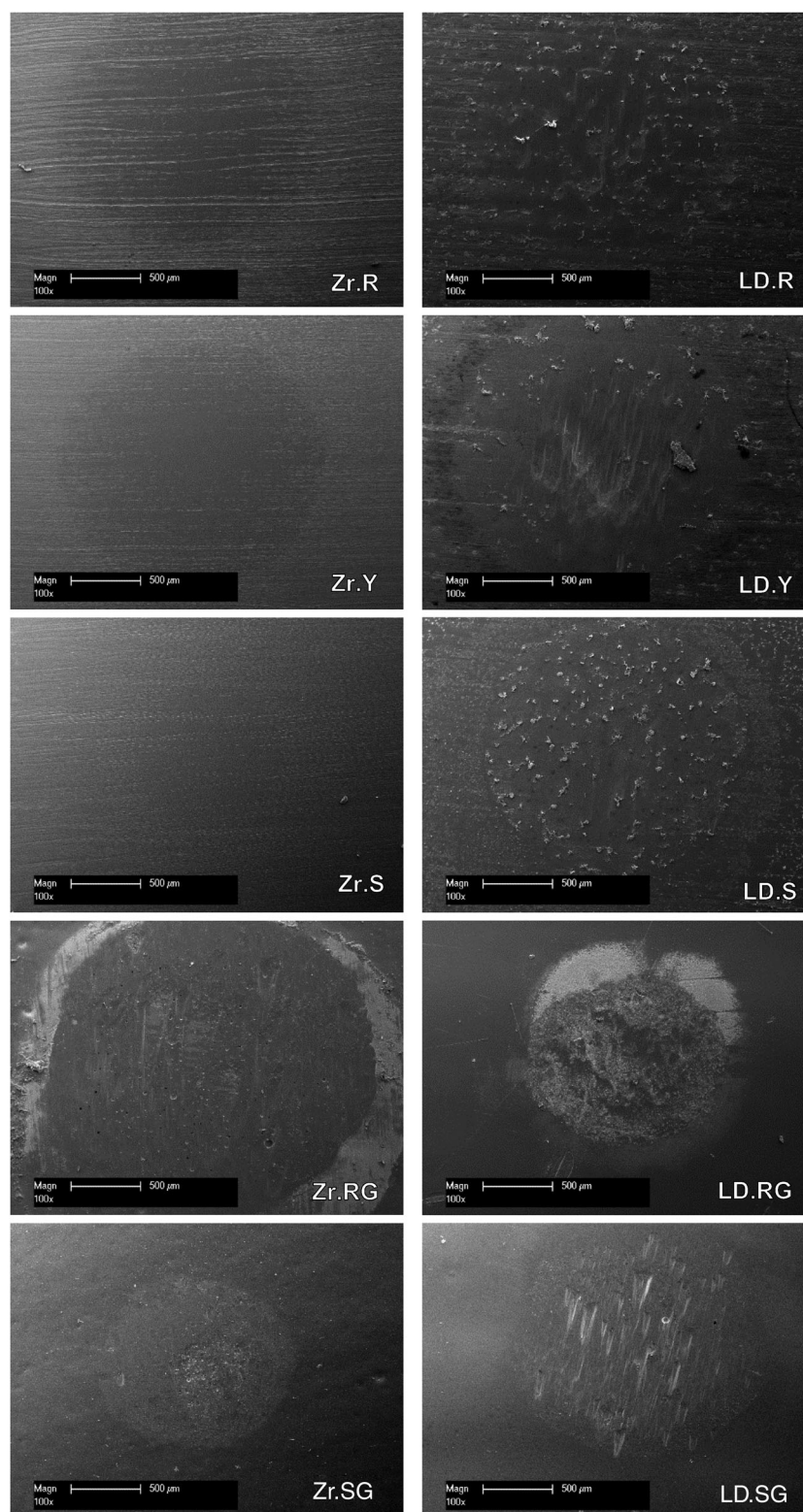
a scanning electron microscope (SEM, XL 30 CP, Philips) using an acceleration voltage of 10 kV (Fig 3).

Statistical analysis

Vertical substance loss and roughness parameters were not normally distributed in all subgroups (Shapiro-Wilk test).

Therefore, the Kruskal-Wallis test and Mann-Whitney-test with Bonferroni-Holm correction were used for statistical analysis of the significant effects of the different surface treatments on vertical substance loss. The statistical correlation between the vertical substance loss and the roughness parameters was checked with Spearman's Rho. The significance level was set at $p \leq 0.05$ for all tests (Table 4). Four combined subgroups were created according to the

FIGURE 3 SEM images of typical specimen surfaces of each subgroup after 1,200,000 loading cycles.



material, which was in contact to the antagonist during the chewing simulation. Two combined subgroups included all unglazed specimens of zirconia (ZrNG) and lithium disilicate (LDNG) ($n = 24$) and the other two combined subgroups included all glazed specimens (ZrG and LDG, respectively, $n = 16$). The combined subgroups are shown in Table 4.

The statistical analysis was carried out with the software SPSS 20.0.0 (IBM Corporation, Armonk, NY, USA). The test groups are named with abbreviations according to their material and treatment: zirconia treated with the red diamond bur (Zr.R), yellow bur (Zr.Y), Shofu-polishing (Zr.S), red bur and glazing (Zr.RG), and Shofu-polishing and glazing

TABLE 4 Means (standard deviations) of all included surface roughness parameters of lithium disilicate specimens. Statistically different roughness parameters ($p \leq 0.05$) are indicated by different lowercase letters (within a row)

Lithium disilicate	LD.R	LD.Y	LD.S	LD.RG	LD.SG
R _a [μm]	0.849 ^a (0.166)	0.196 ^{ab} (0.039)	0.152 ^b (0.072)	0.091 ^{bc} (0.042)	0.060 ^c (0.031)
R _p [μm]	4.944 ^a (1.27)	0.931 ^{ab} (0.210)	0.388 ^{bc} (0.117)	0.371 ^{bc} (0.136)	0.275 ^c (0.127)
R _z [μm]	8.608 ^a (1.818)	2.166 ^{ab} (0.488)	1.097 ^b (0.348)	0.737 ^c (0.213)	0.606 ^c (0.306)
R _v [μm]	3.663 ^a (0.636)	1.234 ^{ab} (0.288)	0.708 ^{bc} (0.257)	0.366 ^c (0.099)	0.331 ^c (0.187)
R _t [μm]	10.935 ^a (2.275)	2.889 ^{ab} (0.648)	1.501 ^{bc} (0.509)	1.173 ^{bc} (0.361)	1.037 ^c (0.528)
R _{ku}	5.616 ^{ab} (0.952)	4.515 ^b (0.452)	4.778 ^b (1.966)	17.611 ^a (13.867)	20.893 ^a (17.062)
R _{pc} [1/cm]	164.804 ^{ab} (15.799)	219.673 ^a (14.006)	157.85 ^{ab} (46.899)	63.29 ^c (6.604)	68.449 ^{bc} (12.579)
S _a [μm]	0.871 ^a (0.137)	0.206 ^b (0.037)	0.172 ^b (0.059)	0.275 ^{ab} (0.145)	0.227 ^{ab} (0.100)
S _p [μm]	19.917 ^a (3.71)	4.662 ^{bc} (.453)	3.222 ^c (0.990)	6.988 ^{ab} (4.007)	7.156 ^{abc} (3.116)
S _z [μm]	34.449 ^a (5.494)	9.588 ^{bc} (1.610)	6.717 ^c (1.482)	22.955 ^{ab} (10.166)	22.159 ^{ab} (9.110)
S _v [μm]	14.531 ^{ab} (3.23)	4.927 ^{bc} (1.238)	3.495 ^c (1.161)	15.966 ^a (7.991)	14.999 ^{ab} (7.956)
S _{ku}	18.550 ^{ab} (8.33)	8.300 ^b (2.015)	9.111 ^b (6.290)	116.598 ^a (260.761)	56.852 ^a (64.597)
S _{pc} [1/μm]	53.958 ^a (8.118)	15.974 ^{bc} (3.105)	10.105 ^c (4.530)	30.491 ^{abc} (12.570)	37.961 ^{ab} (12.551)
S _{pd} [1/μm ²]	0.021 ^a (0.008)	0.009 ^a (0.004)	0.001 ^b (0.002)	0.000 ^b (0.000)	0.000 ^b (0.000)
S _{dr} [%]	90.584 ^a (14.022)	11.0302 ^{ab} (3.791)	1.594 ^{bc} (1.354)	0.758 ^c (0.637)	0.624 ^c (0.435)

TABLE 5 Spearman correlation analysis significance (Spearman's ρ) after 1,200,000 cycles. A correlation was assumed to be significant for $p \leq 0.05$, highlighted with bold numbers

1,200,000 cycles	ZrNG	ZrG	LDNG	LDG
R _a	0.682 (−0.088)	0.542 (0.165)	0.024 (0.459)	0.862 (−0.047)
R _p	0.872 (−0.035)	0.602 (0.141)	0.049 (0.405)	0.948 (0.018)
R _z	0.716 (−0.078)	0.672 (0.115)	0.040 (0.423)	0.957 (0.015)
R _v	0.549 (−0.129)	0.656 (0.121)	0.023 (0.463)	0.867 (0.046)
R _t	0.651 (−0.097)	0.617 (0.135)	0.032 (0.438)	1.000 (0.000)
R _{ku}	0.576 (0.120)	0.787 (0.074)	0.169 (−0.290)	0.269 (0.294)
R _{pc}	0.384 (0.186)	0.418 (−0.218)	0.273 (−0.233)	0.966 (−0.012)
S _a	0.328 (−0.209)	0.542 (0.165)	0.021 (0.467)	0.259 (0.300)
S _p	0.622 (−0.106)	0.641 (−0.126)	0.019 (0.475)	0.633 (0.129)
S _z	0.460 (−0.158)	0.240 (−0.312)	0.154 (0.300)	0.762 (0.082)
S _v	0.470 (−0.155)	0.458 (−0.200)	0.198 (0.270)	0.579 (0.150)
S _{ku}	0.869 (−0.036)	0.295 (−0.279)	0.255 (0.242)	0.656 (−0.121)
S _{pc}	0.245 (−0.247)	0.721 (−0.097)	0.169 (0.290)	0.254 (0.303)
S _{pd}	0.700 (−0.083)	- (0.000)	0.030 (0.443)	0.757 (−0.084)
S _{dr}	1.000 (0.000)	0.664 (0.118)	0.047 (0.409)	0.729 (0.094)

(Zr.SG). The same naming convention was used for the lithium disilicate groups: LD.R, LD.Y, LD.S, LD.RG, and LD.SG.

RESULTS

The surface parameters prior to dynamic loading are given in Tables 5 and 6. The statistical evaluation showed that in many cases the roughness parameters of the different subgroups were not significantly different from each other. The

zirconia specimens themselves in the subgroup ZrNG did not show a measurable vertical substance loss. However, a vertical substance loss could be observed in the glazed zirconia groups. Zr.RG showed a median of 49 μm (interquartile range (IQR) = 21 μm) and Zr.SG showed a median of 43 μm (IQR = 30 μm) vertical substance loss after 1,200,000 cycles.

All groups of the lithium disilicate specimens showed a measurable vertical substance loss after 1,200,000 cycles. LD.R showed a median of 55 μm (IQR = 11 μm), LD.Y a median of 46 μm (IQR = 26), LD.S a median of 41 μm (IQR = 26 μm), LD.RG a median of 62 μm (IQR = 21 μm),

TABLE 6 Surface roughness parameters, short descriptions

	Parameter	Short explanation
Linear parameters	R_a	Arithmetic mean roughness, average deviation from center line
	R_p	Height of the biggest profile peak from center line
	R_z	Averaged mean of 5 single following roughness depths
	R_v	Depth of the deepest point below center line
	R_t	Overall height, vertical distance between top peak and lowest point along measurement line
	R_{ku}	Steepness; fourth power of square of average roughness value; no unit
	R_{pc}	Count of peaks per distance
Three-dimensional parameters	S_a	Amount of height difference of each point compared to the arithmetic mean of the surface
	S_p	Maximal height of highest peak from center plane
	S_z	Sum of value of highest peak and deepest point from center plane
	S_v	Maximal valley depth from center plane
	S_{ku}	Kurtosis, degree of sharpness of the roughness profile $S_{ku} < 3$: Height distribution is inclined above mean plane $S_{ku} = 3$: Height distribution in accordance with normal distribution $S_{ku} > 3$: Height distribution is pointy
	S_{pc}	Arithmetic mean of peak curvature, a small value means a rounder shape, a bigger value means a more pointy shape towards other objects
	S_{pd}	Peak density per surface
	S_{dr}	Percentage of additional surface originating from surface texture, compared to a perfect plane area

and LD.SG a median of 51 μm (IQR = 25) in vertical substance loss. Between groups of the same material no significant differences could be seen.

The steatite wear in the zirconia groups varied from 106 μm (IQR = 29 μm) in Zr.SG, to 145 μm (IQR = 73 μm) in Zr.Y, after 1,200,000 cycles. However, there were no statistically significant differences in the vertical substance loss between different zirconia subgroups. LD.R showed the highest steatite vertical substance loss overall with a median of 145 μm (IQR = 36 μm) after 1,200,000 cycles. Group LD.RG showed the smallest steatite wear within the lithium disilicate groups with a mean of 110 μm (IQR = 46 μm) steatite height loss after 1,200,000 cycles. The vertical substance loss of the steatite antagonist is illustrated in Figures 4 and 5.

There were only a few significant correlations between steatite vertical substance loss and surface roughness parameters until 840,000 loading cycles were completed. In the subgroup LDG after 240,000 cycles, S_a and vertical substance loss of the steatite showed significant correlations ($p = 0.044$), while in subgroup ZRG, after 480,000 cycles, S_{td} and vertical substance loss of the steatite did show a significant correlation ($p = 0.043$).

There were no significant correlations of surface roughness parameters and steatite abrasion after 1,200,000 cycles in the zirconia groups and in groups LD.RG and LD.SG. In groups LD.R, LD.Y and LD.S significant ($p \leq 0.05$) medium-strong correlations could be found in R_a , R_p , R_z , R_v , R_t , S_a , S_p , S_{pd} and S_{dr} after 1,200,000 cycles in LDNG. The results of the Spearman correlation test are shown in Table 5.

The images of the specimen surfaces after 1,200,000 loading cycles taken with the SEM are shown in Figure 3. The zirconia groups Zr.R, Zr.Y, and Zr.S apparently showed sim-

ilar surface texture after 1,200,000 loading cycles. The wear on the specimen surface is most visible in Zr.R and least in Zr.S. Groups LD.R, LD.Y, and LD.S in contrast showed a more roughened surface in addition to the loss of the applied surface texture. Groups Zr.RG, LD.RG, Zr.YG, and LD.YG, although glazed with the same material, showed great variability in the diameter of the worn surface. In addition, they exhibited a roughened surface similar to lithium disilicate surfaces.

DISCUSSION

The glazing material used had a flexural strength of 71.07 MPa and a hardness of 612 HV.^{35,36} The lithium disilicate had a flexural strength of 376.9 MPa and a hardness of 452.9 HV.³⁷ The zirconia was the most stable material with a flexural strength of 1,200 MPa and 1454 HV.³⁸ So, the three materials differed considerably in their mechanical properties and it was assumed that these differences would result in considerably different wear behaviors. More precisely less antagonistic wear was expected, when specimens are made of oxide ceramics instead of veneering ceramic³⁹ and glazed zirconia caused more antagonistic wear than polished zirconia.⁴⁰ The results showed that the glazed zirconia specimens showed less antagonistic wear than unglazed zirconia, which seems plausible due to the lower flexural strength and hardness of the glazing material, which could have preserved the steatite from degrading.

The vertical substance loss in Zr.G was in the regime of the total layer thickness of the glazing material. Thus, the surface below the glaze layer probably did not have a

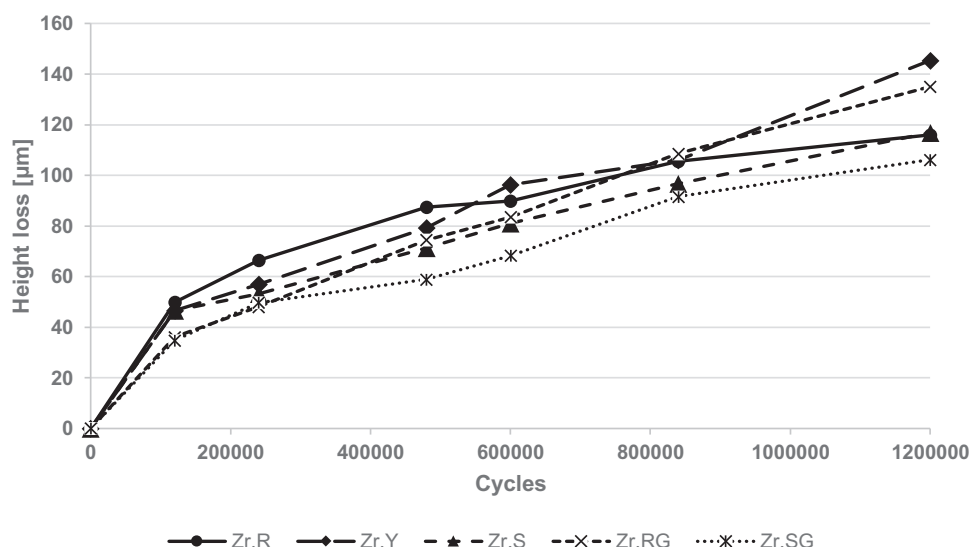


FIGURE 4 Median of vertical substance loss of steatite antagonists against zirconia

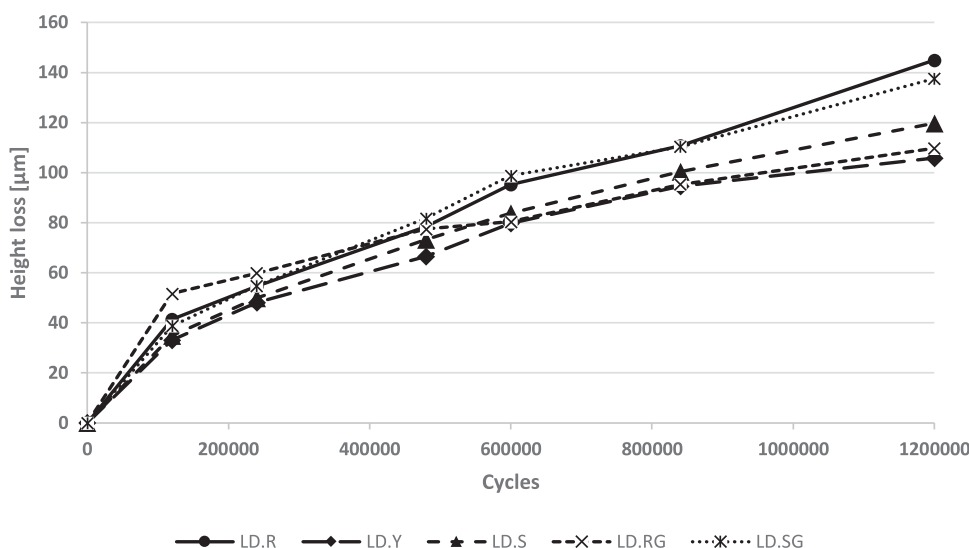


FIGURE 5 Median of vertical substance loss of steatite antagonists against lithium disilicate

relevant influence on the vertical substance loss. As could be expected, more vertical substance loss of the specimens could be observed in the lithium disilicate groups and in the glazed groups.⁴¹ A recent study reported that lithium disilicate caused more antagonist abrasion than zirconia,⁴² which could not be confirmed in the current study. Although LD.R had by far the highest R_a (Table 6), it did not cause the most antagonist wear. Although using water irrigation in this study, it was shown, that third particle contacts under a dry environment can act as a polishing agent for the lithium disilicate and cause in the long run a smoother surface and subsequently less antagonist wear.⁴³ Additionally, no significant difference of antagonistic substance loss between the glazed subgroups and the corresponding unglazed subgroups could be observed.

The different surface treatments caused very similar antagonistic vertical substance loss. It has been shown, that the antagonistic wear in zirconia treated with a diamond bur or not treated at all, was similar or higher than in the polished group.¹³ Additionally, it has been shown that polished zirconia causes less antagonist wear than glazed zirconia, polished then reglazed zirconia, veneering ceramic, and enamel.^{17,40}

These results are in contrast to the results of the present study. However, the differences in roughness between the subgroups in the present study were small. Airborne particle abrasion with 110 mm diameter alumina particles at 4 bar pressure and subsequent glazing of zirconia resulted in a higher antagonistic wear than manual polishing with a goat hair brush and diamond paste (Dia-Glaze, Yeti Dental)

for 1 minute. The differences in the abrasive behavior can be explained by the fact that the rougher surface under the glaze layer came to the surface and into contact.⁹ This could not be verified or falsified in the present study, since the vertical substance loss of the glazed specimens was still within the regime of the layer thickness of the glaze. Also, the different chewing simulator setup with a maximum occlusal load of 49 N at 1.67 Hz and simultaneous thermal cycling (5°C to 50°C every 120 s) might have caused different results.

In the present study, the zirconia surface roughness parameters showed no significant correlation with vertical antagonist substance loss. This result confirms a previous study, which showed that there was no correlation between the mean roughness and antagonist wear for zirconia and glazed zirconia.⁴⁴

In contrast to the zirconia and the glazed specimens, the lithium disilicate specimens' surface roughness parameters did show some statistically significant correlations with antagonist height loss. The mean surface roughness R_a is the base of several studies to differentiate between surface treatments and treatment quality.^{6,8,45,46} In this study, R_a correlated also with antagonist height loss in the LDNG groups. But also the surface roughness parameters R_p , R_z , R_v , R_t , S_a , S_p , S_{pd} , and S_{dr} correlate with steatite height loss. Hence, the use of R_a only does not seem to give a completely suitable surface analysis in order to predict or estimate antagonist wear and spikes might increase antagonist substance loss.

Some limitations of this study have to be addressed. In general, stronger antagonist wear against the "rougher" surfaces was expected, accordingly a larger mean roughness R_a or S_a would result in more antagonist wear, as was anticipated from preceding studies.^{14,17,18} Unfortunately, this was only the case in the lithium disilicate groups, but not in the zirconia or glazed groups. Possibly the chosen surface treatments for this experiment caused a problem. They were selected based on clinical experience and studies, which reported that coarse diamond burs and rougher surfaces should be avoided for ceramic corrections to avoid reduction of fracture resistance.^{47,48} The results of a study that clearly showed that the rougher the surface of zirconia, the more antagonist wear is to be expected cannot be accepted without reservation. The serious differences between the surface roughness parameters with this study must be addressed. For example, the mean surface roughness R_a ranged from 0.24 with a standard deviation (SD) (0.04) over 0.75 μm SD (0.25) μm , to 2.75 μm SD (0.30),¹⁸ thus differing strikingly. It seems that in this study the red and yellow marked burs and the silicone polishers produced too similar surface conditions and roughness parameters (Tables 5 and 6). Larger differences in the surface treatment, for example, using one coarser diamond grain size of the burs, would probably produce more distinguishable roughness parameters and thus more distinguishable antagonist wear results. Therefore, the differences in surface roughness parameters between groups should be magnified in future studies.

Also, the different wear behaviors of zirconia and lithium disilicate may have furthermore influenced the wear results

and represent a limitation of this study. Unlike zirconia, the contact stress produced during loading causes abrasion through micro cracking in the lithium disilicate, increasing its roughness and releasing wear particles from its surface. The lithium disilicate surface combined with the presence of the debris particles leads to dramatic increase in antagonist wear, according to a recent review.⁴⁹ In the present study the loading was performed under water, which might have altered this effect. The influence of the debris in this experimental setup should be further examined. Another limitation of this study is the use of steatite as the antagonist.⁵⁰

Not having abraded into the base layer of the glazed specimens is another topic for further investigation. One study assumed 250,000 loading cycles corresponded to one year of clinical function,⁵¹ while others considered 1,200,000 loading cycles corresponded to 5 years of clinical loading.⁵² It is possible that the application of more loading cycles could provide results on the interaction of antagonist wear with the base ceramic; however, the clinical guideline on how many loading cycles are reasonable for an in vitro study remains somewhat unclear. Studies assessing the wear rate of teeth by attrition, tooth-cleaning, corrosion, and abrasion are subject to a substantial amount of bias.⁵³ Using clinically well-proven materials and comparing the vertical substance loss of the steatite in this study with <0.16 mm (Figs 4 and 5) with other studies, it can be deemed as clinically acceptable after presumed 5 years of loading.^{54,55}

CONCLUSIONS

In the zirconia (ZrNG) and glazed groups (ZrG, LDG) no significant Spearman-correlations in vertical substance loss to surface roughness parameters could be found after 1,200,000 loading cycles. In the lithium disilicate groups (LDNG) medium strong correlations could be seen. R_p , R_z , R_v , R_t , S_a , S_p , S_{pd} , S_{dr} , and R_a correlated with antagonist wear. The differences in roughness parameters between the different tested surface-treatments were too small; more serious differences might reveal more wear influencing parameters.

ACKNOWLEDGMENTS

This study was financially supported by the DGPro (German Society of Prosthetic Dentistry and Biomaterials). This study was further supported with materials by Shofu Dental, Gebr. Brasseler, and Ivoclar Vivadent. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Open access funding enabled and organized by Projekt DEAL.

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REFERENCES

- Willard A, Gabriel Chu TM. The science and application of ips e.Max dental ceramic. *Kaohsiung J Med Sci* 2018;34:238-242
- Zarauz C, Valverde A, Martinez-Rus F, et al. Clinical evaluation comparing the fit of all-ceramic crowns obtained from silicone and digital intraoral impressions. *Clin Oral Invest* 2016;20:799-806
- Preis V, Behr M, Kolbeck C, et al. Wear performance of substructure ceramics and veneering porcelains. *Dent Mater* 2011;27:796-804
- Schultheis S, Strub JR, Gerds TA, et al. Monolithic and bi-layer cad/cam lithium-disilicate versus metal-ceramic fixed dental prostheses: comparison of fracture loads and failure modes after fatigue. *Clin Oral Invest* 2013;17:1407-1413
- Solá-Ruiz MF, Baima-Moscardó A, Selva-Otaolaurruchi E, et al. Wear in antagonist teeth produced by monolithic zirconia crowns: a systematic review and meta-analysis. *J Clin Med* 2020;9:997
- Kim MJ, Oh SH, Kim JH, et al. Wear evaluation of the human enamel opposing different y-zp dental ceramics and other porcelains. *J Dent* 2012;40:979-988
- Kern M, Strub JR, Lü X-Y. Wear of composite resin veneering materials in a dual-axis chewing simulator. *J Oral Rehabil* 1999;26:372-378
- Mörmann WH, Stawarczyk B, Ender A, et al. Wear characteristics of current aesthetic dental restorative cad/cam materials: two-body wear, gloss retention, roughness and martens hardness. *J Mech Behav Biomed Mater* 2013;20:113-125
- Stawarczyk B, Ozcan M, Schmutz F, et al. Two-body wear of monolithic, veneered and glazed zirconia and their corresponding enamel antagonists. *Acta Odontol Scand* 2013;71:102-112
- Meng M, Wang XS, Li KY, et al. Effects of surface roughness on the time-dependent wear performance of lithium disilicate glass ceramic for dental applications. *J Mech Behav Biomed Mater* 2012;121:104638
- Mehulic K, Svetlicic V, Segota S, et al. A study of the surface topography and roughness of glazed and unglazed feldspathic ceramics. *Coll Antropol* 2010;34:235-238
- Al-Shammery HA, Bubbs NL, Youngson CC, et al. The use of confocal microscopy to assess surface roughness of two milled cad-cam ceramics following two polishing techniques. *Dent Mater* 2007;23:736-741
- Sabrah AH, Cook NB, Luangruangrong P, et al. Full-contour y-zp ceramic surface roughness effect on synthetic hydroxyapatite wear. *Dent Mater* 2013;29:666-673
- Mitov G, Heintze SD, Walz S, et al. Wear behavior of dental y-zp ceramic against natural enamel after different finishing procedures. *Dent Mater* 2012;28:909-918
- Cha MS, Huh YH, Cho LR, et al. A comparative study of the wear of dental alloys against monolithic zirconia. *J Prosthet Dent* 2020;123:866-873
- Hayashi S, Homma S, Takanashi T, et al. Wear properties of esthetic dental materials against translucent zirconia. *Dent Mater J* 2019;38:250-256
- Kontos L, Schille C, Schweizer E, et al. Influence of surface treatment on the wear of solid zirconia. *Acta Odontol Scand* 2013;71:482-487
- Ghazal M, Kern M. The influence of antagonistic surface roughness on the wear of human enamel and nanofilled composite resin artificial teeth. *J Prosthet Dent* 2009;101:342-349
- Hmaidouch R, Weigl P. Tooth wear against ceramic crowns in posterior region: a systematic literature review. *Int J Oral Sci* 2013;5:183-190
- Gou M, Chen H, Kang J, et al. Antagonist enamel wear of tooth-supported monolithic zirconia posterior crowns in vivo: a systematic review. *J Prosthet Dent* 2019;121:598-603
- Keferstein M. 2015. *Fertigungsmesstechnik*. Springer Vieweg.
- Deltombe R, Kubiak KJ, Bigerelle M. How to select the most relevant 3d roughness parameters of a surface. *Scanning* 2014;36:150-160
- Pawlus P, Reizer R, Wiczeorowski M. Functional importance of surface texture parameters. *Materials* 2021;14:5326.
- Agrawal C, Wadhwa J, Pitroda A, et al. Comprehensive analysis of tool wear, tool life, surface roughness, costing and carbon emissions in turning Ti-6Al-4V titanium alloy: cryogenic versus wet machining. *Tribol Int* 2021;153
- Nima G, Lugo-Varillas JG, Soto J, et al. Effect of toothbrushing on the surface of enamel, direct and indirect CAD/CAM restorative materials. *Int J Prosthodont* 2021;34:473-481
- Krolczyk GM, Krolczyk JB, Maruda RW, et al. Metrological changes in surface morphology of high-strength steels in manufacturing processes. *Measurement* 2016;88:176-185
- David JW. Processing, Operations, and Simulations. *Handbook of Surface and Nanometrology*. USA, CRC Press 2010.
- Doluk E, Rudawska A, Kuczmazewski J, et al. Surface roughness after milling of the Al/CFRP stacks with a diamond tool. *Materials (Basel, Switzerland)* 2021;14:6835
- Senin N, Blunt L, Leah R, et al. Morphologic segmentation algorithms for extracting individual surface features from areal surface topography maps. *Surface Topography Metrology and Properties* 2013;1:015005
- Czifra Á, Barányi I. SDQ-SDR topological map of surface topographies. *Frontiers in Mechanical Engineering* 2020;6: <https://doi.org/10.3389/fmech.2020.00050>
- Milanese E, Brink T, Aghababaei R, et al. Role of interfacial adhesion on minimum wear particle size and roughness evolution. *Phys Rev E* 2020;102:043001
- Wassell RW, McCabe JF, Walls AW. A two-body frictional wear test. *J Dent Res* 1994;73:1546-1553
- Dupriez ND, von Koeckritz A-K, Kunzelmann K-H. A comparative study of sliding wear of nonmetallic dental restorative materials with emphasis on micromechanical wear mechanisms. *Journal of Biomedical Materials Research Part B: Applied Biomaterials* 2015;103:925-934
- Kewekordes T, Wille S, Kern M. Wear of polyetherketoneketones— influence of titanium dioxide content and antagonistic material. *Dent Mater* 2018;34:560-567
- Junpoom P, Kukiattrakoon B, Hengtrakool C. Flexural strength of fluorapatite-leucite and fluorapatite porcelains exposed to erosive agents in cyclic immersion. *J Appl Oral Sci revista FOB* 2011;19:95-99.
- Tang X, Nakamura T, Usami H, et al. Effects of multiple firings on the mechanical properties and microstructure of veneering ceramics for zirconia frameworks. *J Dent* 2012;40:372-380
- Lawson NC, Bansal R, Burgess JO. Wear, strength, modulus and hardness of CAD/CAM restorative materials. *Dent Mater* 2016;32:e275-e283
- Preis V, Schmalzbauer M, Bougeard D, et al. Surface properties of monolithic zirconia after dental adjustment treatments and in vitro wear simulation. *J Dent* 2015;43:133-139
- Rosentritt M, Preis V, Behr M, et al. Two-body wear of dental porcelain and substructure oxide ceramics. *Clin Oral Invest* 2012;16:935-943
- Janyavula S, Lawson N, Cakir D, et al. The wear of polished and glazed zirconia against enamel. *J Prosthet Dent* 2013;109:22-29
- Aboushabbaa M, Katamishb H, Elagroudy M. Evaluation of hardness and wear of surface treated zirconia on enamel wear. An in-vitro study. *Futur Dent J* 2018;4:76-83
- Zhang F, Spies BC, Vleugels J, et al. High-translucent yttria-stabilized zirconia ceramics are wear-resistant and antagonist-friendly. *Dent Mater* 2019;35:1776-1790
- Peng Z, Izzat Abdul Rahman M, Zhang Y, et al. Wear behavior of pressable lithium disilicate glass ceramic. *J Biomed Mater Res B Appl Biomater* 2016;104:968-978
- Stawarczyk B, Frevert K, Ender A, et al. Comparison of four monolithic zirconia materials with conventional ones: contrast ratio, grain size, four-point flexural strength and two-body wear. *J Mech Behav Biomed Mater* 2016;59:128-138
- Matzinger M, Hahnel S, Preis V, et al. Polishing effects and wear performance of chairside CAD/CAM materials. *Clin Oral Invest* 2019;23:725-737
- Abi-Rached FO, Martins SB, Campos JA, et al. Evaluation of roughness, wettability, and morphology of an yttria-stabilized tetragonal

- zirconia polycrystal ceramic after different airborne-particle abrasion protocols. *J Prosthet Dent* 2014;112:1385-1391
47. Rues S, Schwindling FS, Meyer A, et al. Fracture resistance of zirconia-based all-ceramic crowns after bur adjustment. *Eur J Oral Sci* 2017;125:310-313
 48. AMdO DP JPM T, Venturini AB, et al. Survival probability of zirconia-reinforced lithium silicate ceramic: effect of surface condition and fatigue test load profile. *Dent Mater* 2020;36:808-815
 49. Branco AC, Colaço R, Figueiredo-Pina CG, et al. A state-of-the-art review on the wear of the occlusal surfaces of natural teeth and prosthetic crowns. *Materials (Basel, Switzerland)* 2020;13:3525.
 50. Shortall AC, Hu XQ, Marquis PM. Potential counter sample materials for in vitro simulation wear testing. *Dent Mater* 2002;18:246-254
 51. DeLong R, Douglas WH. An artificial oral environment for testing dental materials. *IEEE Trans Biomed Eng* 1991;38:339-345
 52. Steiner M, Mitsias ME, Ludwig K, et al. In vitro evaluation of a mechanical testing chewing simulator. *Dent Mater* 2009;25:494-499
 53. Hmaidouch R, Weigl P. Tooth wear against ceramic crowns in posterior region: a systematic literature review. *Int J Oral Sci* 2013;5:183-190
 54. Zarone F, Di Mauro MI, Ausiello P, et al. Current status on lithium disilicate and zirconia: a narrative review. *BMC Oral Health* 2019;19:134-134
 55. Rosentritt M, Schumann F, Krifka S, et al. Influence of zirconia and lithium disilicate tooth- or implant-supported crowns on wear of antagonistic and adjacent teeth. *J Adv Prosthodont* 2020;12:1-8

How to cite this article: Krüger S, Wille S, Kern M. The Correlation of Surface Roughness Parameters of Zirconia and Lithium Disilicate with Steatite Wear. *J Prosthodont*. 2023;32:e52–e63.

<https://doi.org/10.1111/jopr.13562>