Purpose: To compare wear behavior, durability during in vitro mastication simulation, and fracture force of an established and a novel lithium disilicate CAD/CAM material, as well as to examine the impact of cementation and reduced ceramic thickness on durability and fracture force. Materials and Methods: Specimens (n = 8 per group) were prepared from lithium disilicate (LS 2; IPS e.max, Ivoclar Vivadent) and advanced lithium disilicate (ALD; Cerec Tessera, Dentsply Sirona). Specimens were polished, and two-body wear test and thermocycling were performed (50 N, 120,000 cycles, 1.6 Hz, H2O dist., 5°C/55°C, 600 cycles). Maximum vertical loss, surface roughness, surface roughness depth, and antagonist wear were determined. Single crowns (n = 8 per group; thickness 1.5 mm/1.0 mm) were manufactured from LS2 and ALD and mounted on human molar teeth with adhesive resin (AB; CalibraCeram, Dentsply Sirona), glass-ionomer cement (GIC; Ketac Cem, 3M ESPE), and hybrid glass-ionomer cement (HGIC; Calibra Bio, Dentsply Sirona). Thermocycling and mechanical loading (2 × 3000 × 5°C/55°C, 2 minutes, H2O dist., 1.2 × 10^6 50 N) were performed. Fracture force was determined by a universal testing machine (1446, ZwickRoell), and one-way analysis and Bonferroni post hoc test (α = .05) were used for statistical analyses. Results: Mean (ALD: 210 ± 42.4 µm; LS2: 264.3 ± 56.1 µm) and maximum (ALD: 391.1 ± 86.3 µm; LS2: 518.3 ± 113.2 µm) wear between groups were significantly different (P ≤ .047). Fracture force varied between 1,911.4 ± 468.4 N (ALD/AB 1 mm) and 2,995.3 ± 880.6 N (LS 2/GIC), without significant differences (P ≥ .152). Conclusion: ALD showed better wear behavior than LS2, but provided similar fracture force. Cementation and reduction of ceramic thickness had only minor effects on fracture force. Int J Prosthodont 2022 February 22. doi: 10.11607/ijp.7820. Online ahead of print.
350 MPa, these materials allow for cementation when designing retentive preparations. However, the type of cementation is expected to affect the mechanical strength of ceramic restorations, and weaker glass-matrix ceramics (<200 MPa) seem to benefit from adhesive luting. An in vitro comparison of ZLS and LS$_2$ crowns on human teeth showed no differences in fracture resistance with different cementations, but the highest stability was found with adhesive bonding. However, in a study that compared the fracture force of ZLS and LS$_2$ crowns that were either bonded to implant abutments, chairside or bonded in the lab and then screw retained, significant differences between ZLS and LS$_2$ were found.

Advanced lithium disilicate (ALD) shows a structure that is similar to that of zirconia-reinforced lithium silicate (ZLS). However, for ALD, in addition to LS$_2$ crystals, the crystal phase contains virgilite (LiAlSi$_2$O$_6$) crystals, which do not occur with ZLS. For ALD, the manufacturer promises higher biaxial strength combined with processing that is easier and faster than for ZLS. Restorations made from ceramics with higher strength are expected to show better thermal cycling and mechanical loading (TCML) performance and better fracture force. The question arises whether the diverging composition of the materials also causes different long-term stabilities of the clinical restorations. Furthermore, crown thickness might play a decisive role in fracture force, even for high-strength ceramic materials. Previous studies have shown that for lithium (di)silicate materials, not reaching the minimum ceramic thickness results in significantly reduced mechanical strength of the respective restorations. Whether the investigated novel material tolerates fabrication of thinner crowns must be controlled.

To avoid occlusal interference, restorative materials should functionally resemble natural teeth. Superficial defects and wear might cause clinical fractures. In contrast to other restorative ceramic materials such as zirconia, LS$_2$ undergoes occlusal wear that is equivalent to natural enamel. However, LS$_2$ restorations seem to cause higher antagonist wear than that observed with zirconia or alloy restorations, as well as increased surface roughness. In a recently published in vivo investigation, ZLS and LS$_2$ showed no significant differences in wear behavior. Wear behavior decisively depends on the surface finishing of the restorative material, which is determined by the type and size of the crystalites. Therefore, a variation in the composition may cause an improvement in wear performance.

The aim of the present study was to investigate the wear behavior, durability during in vitro mastication simulation, and fracture force of a novel CAD/CAM ALD material in comparison to an established LS$_2$. Furthermore, the impact of cementation (adhesive resin cement, glass-ionomer cement, hybrid glass-ionomer–based cement), as well as the impact of reduced ceramic thickness on the durability and fracture force, were also examined.

The investigated hypotheses were that ALD ceramic shows improved wear behavior, durability during in vitro mastication simulation, and fracture force compared to an established LS$_2$ material. Furthermore, it was hypothesized that cementation type and a reduction in ceramic thickness affect the TCML performance and fracture force of molar crowns.

**MATERIALS AND METHODS**

Wear test specimens (n = 8 per group; diameter = 5 mm, thickness = 3 mm) were prepared from LS$_2$ (IPS e.max, Ivoclar Vivadent) and ALD (Cerec Tessera, Dentsply Sirona). The specimens were polished (Tegramin, Struers; P1200 grit, diamond paste 6 µm) and fixed on aluminum stubs (Alu Stubs, D) using a light-curing dental resin. A two-body wear test was performed in a pneumatic pin-on-block design (vertical load 50 N, 120,000 cycles, 1.6 Hz, lateral movement = 1 mm, mouth opening = 1 mm) with steatite balls (magnesium silicate, CeramTec; radius = 1.5 mm) as antagonists. Thermal cycling was applied during wear simulation ($H_2O$ dist., $5^\circC/55^\circC$; 600 cycles; 2 minutes each). The maximum vertical loss (µm) and mean roughness (Ra)/mean roughness depth (Rz) were determined with a 3D laser-scanning microscope (KJ 3D, Keyence, J). Antagonist wear was determined as the percent area of the projected antagonist area.

The roots of freshly extracted human molars were coated with a layer of polyether impression material (1-mm thickness; Impregum, 3M ESPE) to simulate the resilience of the human periodontium and then fixed in resin bases. The teeth were prepared according to the manufacturer instructions (circular reduction 1.0 to 1.5 mm with 5- to 6-degree angulation, occlusal reduction 1.5 mm, minimum cervical to occlusal height 4 mm, shoulder preparation without chamfering, all angles rounded, smooth preparation surfaces). The molar single crowns were manufactured from LS$_2$ and ALD. Based on the tooth scans, crowns (n = 8 per group) were designed with a ceramic thickness of 1.5 mm (1.0 mm for the specimen group “AB 1 mm” with reduced ceramic thickness; Fig 1) and milled out of C14 blocks (Cerec inLab MC XL, Dentsply Sirona). Crystallization and glaze firing were performed according to the manufacturer instructions. The crowns were mounted on the prepared teeth with the following cements (Table 1):

- Adhesive resin cement system with etching, conditioning, and adhesive bonding (AB; Calibra Ceram, Dentsply Sirona)
- Glass-ionomer cement (GIC; Ketac Cem, 3M ESPE)
- Hybrid glass-ionomer–based cement with calcium aluminate (HGIC; Calibra Bio, Dentsply Sirona)
Constant loading (50 N) was applied during the setting phase. TCML (2 x 3,000 x 5°C/55°C, 2 minutes each cycle, H₂O dist. 1.2 x 10⁶, force 50 N) was performed to simulate approximately 5 years of clinical use. The crowns were checked for failure (cracks, chipping, fracture; VHX-5000 digital microscope, Keyence J) or detachment from the abutment tooth. For all crowns that survived TCML, the fracture force was determined by mechanically loading the crowns to failure in a universal testing machine (1446, ZwickRoell). The force was applied on the center of the crowns using a steel ball (diameter = 12 mm, testing speed = 1 mm/minute). A tin foil (1-mm thickness) was inserted between the crown and the ball. The failure determination was set to a 10% loss of the maximum loading force or acoustic signal (crack).

Scanning electron microscopy images (SEM; Quanta FEG 400, Fei; NL, low vacuum, 12.5 KEV, working distance 41 mm, < x100 magnification) of the ceramics were made to characterize the microstructure (Fig 2). Mean and SD values were calculated. The statistical analysis was performed using one-way ANOVA and Bonferroni post hoc test (SPSS software version 26.0, IBM). The level of significance was set to α = .05.

Table 1 Specimen Groups and Cementation

<table>
<thead>
<tr>
<th>Code</th>
<th>Material</th>
<th>Cementation</th>
<th>Etching</th>
<th>Pretreatment</th>
</tr>
</thead>
</table>
| LS₂  | IPS e.max, Ivoclar Vivadent (biaxial flexural strength 648 MPa) | AB: Adhesive resin cement (Calibra Ceram, Dentsply Sirona)  
GIC: Glass-ionomer cement (Ketac Cem, 3M ESPE)  
HGIC: Hybrid glass-ionomer–based cement (Calibra Bio, Dentsply Sirona) | 5% hydrofluoric acid, 20 s | Silane (Prime & Bond, Dentsply Sirona) |
| ALD  | Cerec Tessera, Dentsply Sirona (biaxial flexural strength > 700 MPa) | AB: Adhesive resin cement (Calibra Ceram, Dentsply Sirona)  
GIC: Glass-ionomer cement (Ketac Cem, 3M ESPE)  
HGIC: Hybrid glass-ionomer–based cement (Calibra Bio, Dentsply Sirona)  
AB 1 mm: Adhesive resin cement (Calibra Ceram, Dentsply Sirona; crowns with reduced ceramic thickness of minimum 1 mm) | – | Silane (Prime & Bond, Dentsply Sirona) |

LS₂ = lithium disilicate; ALD = advanced lithium disilicate.
RESULTS

The mean wear values of the two groups (Table 2 and Fig 3) were significantly different ($P = .047$), with $210 \pm 42.4$ µm for ALD and $264.3 \pm 56.1$ µm for $LS_2$. A significant difference was also found for the maximum wear values, with $391.1 \pm 86.3$ µm for ALD and $518.3 \pm 113.2$ µm for $LS_2$ ($P = .024$). Antagonist wear values were $14.8\% \pm 5.4\%$ for ALD and $17.2\% \pm 1.7\%$ for $LS_2$. No significant difference ($P = .278$) was found. The investigated materials did not show significantly different ($P \geq .495$) roughness. The mean Ra of the materials was $4.1 \pm 1.6$ µm for ALD and $4.4 \pm 1.1$ µm for $LS_2$, and the mean Rz was $29.0 \pm 14.2$ µm for ALD and $33.2 \pm 9.5$ µm for $LS_2$.

No crowns failed during TCML. The fracture force (Table 3) of the ALD specimens varied from $2,101.4 \pm 752.6$ N (ALD/AB), to $1,911.4 \pm 468.4$ N (ALD/AB 1 mm) with reduced ceramic thickness, to $2,808.8 \pm 1,162.3$ N (ALD/GIC). The fracture force of the $LS_2$ specimens varied from $2,529.0 \pm 468.7$ N ($LS_2/AB$) to $2,995.3 \pm 880.6$ N ($LS_2/GIC$). No significant differences in fracture force were found ($P \geq .152$). The prevailing failure mode was fracture of the crowns originating from the occlusal contact points. All investigated materials and

Fig 2 SEM images at $\times 20,000$, $\times 40,000$, and $\times 60,000$ magnifications. The microstructure of ALD shows different crystal structures (lithium metasilicate, lithium disilicate, lithium orthophosphate, and virgilite) embedded in a glass matrix. $LS_2$ consists of a glass matrix filled with lithium disilicate and lithium orthophosphate crystals.
Table 2  Mean ± SD Measurement Results

<table>
<thead>
<tr>
<th></th>
<th>Wear, µm</th>
<th>Maximum wear, µm</th>
<th>Antagonist wear, %</th>
<th>Ra/Rz, µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS₂</td>
<td>264.3 ± 56.1a</td>
<td>518.3 ± 113.2b</td>
<td>17.2 ± 1.7</td>
<td>4.4 ± 1.1/33.2 ± 9.5</td>
</tr>
<tr>
<td>ALD</td>
<td>210.0 ± 42.4a</td>
<td>391.1 ± 86.3b</td>
<td>14.8 ± 5.4</td>
<td>4.1 ± 1.6/29.0 ± 14.2</td>
</tr>
</tbody>
</table>

Ra = roughness; Rz = roughness depth.
Values with the same superscript letters were significantly different (P < .05) between groups.

Table 3  Mean ± SD Fracture Force

<table>
<thead>
<tr>
<th>Material</th>
<th>Cementation</th>
<th>Fracture force, N</th>
<th>Failure mode, no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS₂</td>
<td>AB</td>
<td>2,529.0 ± 468.7</td>
<td>CF = 7; TF = 6; CH = 1</td>
</tr>
<tr>
<td></td>
<td>GIC</td>
<td>2,995.3 ± 880.6</td>
<td>CF = 7; TF = 4; CH = 1</td>
</tr>
<tr>
<td></td>
<td>HGIC</td>
<td>2,598.3 ± 614.5</td>
<td>CF = 8; TF = 2</td>
</tr>
<tr>
<td>ALD</td>
<td>AB</td>
<td>2,101.4 ± 752.6</td>
<td>CF = 8; TF = 2</td>
</tr>
<tr>
<td></td>
<td>GIC</td>
<td>2,808.8 ± 1162.3</td>
<td>CF = 6; TF = 4; CH = 1</td>
</tr>
<tr>
<td></td>
<td>HGIC</td>
<td>2,579.7 ± 783.0</td>
<td>CF = 5; TF = 6</td>
</tr>
<tr>
<td></td>
<td>AB 1mm</td>
<td>1,911.4 ± 468.4</td>
<td>CF = 8; TF = 2</td>
</tr>
</tbody>
</table>

CF = crown fracture; TF = tooth fracture; CH = cusp chipping. The differences in fracture force were not statistically significant.
cementation methods predominantly showed residual crown fragments after fracture, and only a few crowns were completely detached from the abutment teeth. The second-most frequent failure mode was fracture of the abutment teeth, and accumulation was not observed for a specific material or cementation type. Cusp chipping occurred in two LS$_2$ specimens and one ALD specimen.

**DISCUSSION**

Part of the hypothesis, that the ALD material would show improved wear behavior compared to the established LS$_2$ material, was confirmed. Mean wear values and maximum wear values indicated better wear resistance for ALD. Previous investigations indicated that, while glass-ceramics show occlusal wear of the restorative material that is similar to human enamel, they can cause high wear on antagonist teeth. In the present study, ALD showed significantly lower wear and a notable tendency toward lower antagonist wear than LS$_2$. These findings might be explained by the exposure of the hard LS$_2$ crystallites, which might be associated with surface roughening. ALD contains virgilite crystals with a size of approximately 200 nm that can fill the gaps between the larger LS$_2$ crystals (approximate size of 600 nm). Thus, virgilite might stabilize the glass matrix and smooth the profile of the worn surface. In this respect, the ALD specimens showed slightly lower roughness values than the LS$_2$ specimens. The measured values were within a magnitude that has been obtained in a previous study. In this context, adequate and repeated polishing of restoration surfaces is crucial. In the present study, the pin-on-block design and respective wear-testing parameters were chosen to investigate the wear behavior of the examined materials, as they have been successfully applied in previous investigations regarding the wear of dental ceramics. For legitimate simulation of clinical conditions and to ensure debris was rinsed from the contact surfaces during testing, specimens were subjected to thermal cycling in distilled water.

The hypothesis that the novel ALD material shows improved durability during in vitro mastication simulation and/or improved fracture force compared to the established LS$_2$ material could not be confirmed. Despite the manufacturer specifications indicating higher biaxial flexural strength for ALD, no significant differences in performance during mastication simulation or fracture force values of ALD and LS$_2$ were found. The crowns did not show different fracture patterns. Similar previous investigations obtained fracture force values within the same range for LS$_2$ crowns. During TCML, the crowns were not macroscopically damaged (eg, cracked) or detached from the abutment teeth. The results might have been influenced by the type of test, the preparation design, and/or the design of the crowns. The complex anatomical structure of natural teeth cannot be entirely simulated with artificial materials. With the application of natural abutment teeth in this study, the validity of the simulation obtained herein comes at the expense of standardization, as the shape of the prepared abutment teeth and thus the shape of the investigated restorations can vary within the range of the manufacturer specifications. It is known that the abutment affects the fracture force. Therefore, using freshly extracted human molars ensured that the simulation was highly valid and relevant to the clinical situation (eg, bonding to tooth structure). Nevertheless, polyether coating of the roots might not entirely simulate periodontal attachment, and this might be a limitation when interpreting the findings of the present study.

The hypothesis that the type of cementation affects the mechanical strength of the investigated materials must be rejected. In this study, the type of cementation did not affect the TCML performance or fracture force of the investigated crowns. Especially for glass-ceramics with low flexural strength, such as leucite or feldspar ceramics, only adhesive bonding guarantees sufficient mechanical strength of the crown for application in clinical situations. However, bond strength may vary depending on surface pretreatments. If the bond does not stabilize the crown, cracks or fractures will occur during TCML or clinical application. Several studies showed trends in the relationship between strength and bonding, at least for high-strength materials such as ZLS and LS$_2$. This trend could not be confirmed for ALD and LS$_2$ because no significant differences in TCML behavior or the fracture force of single crowns were found, regardless of the cementation. The results confirm earlier investigations that the impact of the bonding seems to be reduced with increasing strength of the ceramic material. Nevertheless, a systematic review could not clarify whether self-etching, self-adhesive, or adhesive methods should be preferred in clinical applications.

The hypothesis that a reduction in ceramic thickness affects the mechanical strength of the investigated materials must also be rejected. Reduction of the ALD ceramic thickness to a minimum of 1 mm resulted only in a tendency toward lower fracture forces. Analogous to their low sensitivity to cementation, medium-strength ceramics seem to tolerate a reduction in restoration thickness to a moderate extent. ALD with reduced ceramic thickness to 1 mm provided only a 10% force decrease in comparison to the 1.5-mm crowns, although the ceramic thickness was reduced by 30%. Crowns in both groups even showed comparable fracture patterns. The differences compared to the other test groups were not significant, and these results indicate that in cases of bruxism, the crowns should be sufficient to withstand even clinical loading of approximately 1,000 N.

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CONCLUSIONS

The novel ALD material showed better wear resistance than the established LS₂ material, and the materials showed similar fracture force values after TCML. Cementation had only minor effects on durability during in vitro mastication simulation and fracture force. A reduction in ceramic thickness led to a slightly lower but clinically sufficient fracture force.

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