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Surface modification of lithium disilicate-reinforced glass ceramic or zirconia surfaces by laser irradiation to increase the adhesion to resin cements:
an integrative review

Angelo Raffaele ESPOSITO

Dissertation leading to the degree of Master of Dental Medicine (integrated

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Work performed under the supervision of Júlio Souza

INTEGRITY DECLARATION:

I, as identified above, declare to have acted with absolute integrity in the preparation of this work, confirming that in all the work leading to its preparation I have not resorted to any form of falsification of results or the practice of plagiarism (act by which an individual, even by omission, assumes authorship of the intellectual work belonging to another, in its entirety or in parts of it). I also declare that all the sentences that I have taken from previous works belonging to other authors have been referenced or written with new words, having in this case placed the citation of the bibliographic source.

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ABSTRACT:

Purpose: The purpose of this study was to perform an integrative review on laser-texturing the inner surface of lithium disilicate-reinforced glass ceramic or zirconia to increase their bond strength to resin-matrix cements.

Method: A bibliographic review was performed on PubMed using the following search terms: “zirconia” OR “lithium disilicate” AND “laser” AND “surface” OR “roughness” AND “resin cement”. Studies published in English language until June 30th, 2022 were selected regarding the purpose of this study.

Results: A total of thirty seven studies were identified although ten studies were selected. Zirconia surfaces were significantly modified after laser irradiation resulting in macro-scale aligned retentive regions with depth values ranging from 50 up to 120 µm. Average roughness values of laser-treated zirconia with Er,Cr:YSGG laser (~ 0.83 µm) were quite similar when compared to grit-blasted zirconia surfaces (~ 0.9 µm) although roughness increased up to 2.4 µm depending on the laser type and parameters. Lithium disilicate-reinforced glass ceramics treated with Er:YAG revealed an average roughness of around 3.5 µm while surfaces treated with Nd:YAG revealed an average roughness of 2.69 µm that was quite similar to the roughness values recorded for etched surfaces (2.64 µm). The SBS values of zirconia surfaces treated on Nd:YVO_4 laser were slightly higher (~ 33.5 MPa) than those recorded for grit-blasted zirconia surfaces (28 MPa). Laser-treated zirconia surfaces on CO_2 laser revealed higher SBS values (18.1 ±0.8 MPa) than those (9.1 ±0.56 MPa) recorded for untreated zirconia surfaces. On lithium disilicate-reinforced glass ceramics, higher SBS values to resin-matrix cements were recorded for specimens treated with a combination of fractional CO_2 laser irradiation and HF acid etching (~ 22-24 MPa) when compared with grit-blasted specimens (12.2 MPa). Another study revealed SBS values at around 27.5 MPa for Er:YAG-treated lithium disilicate-reinforced glass ceramics to resin-matrix cements.

Conclusions: The laser irradiation at high power increase the roughness of the inner surface of lithium disilicate-reinforced glass ceramic or zirconia veneers and crowns leading to an enhanced bond strength to resin-matrix cements. Thus, the laser type and irradiation parameters can be adjusted to enhance the macro- and micro-scale retention of zirconia and glass-ceramics surfaces.

Keywords: lithium disilicate; zirconia; laser; bond strength; resin cement

RESUMO:

Objectivo: O objetivo deste estudo foi realizar uma revisão integrativa sobre texturização a laser da superfície interna de zircónia e vitrocerâmicas reforçada com dissilicato de lítio para aumentar a adesão a cimentos de matriz resinosa.

Método: Uma revisão bibliográfica foi realizada no PubMed usando os seguintes termos de pesquisa: *"zirconia" OR "lithium disilicate" AND "laser" AND "surface" OR "roughness" AND "resin cement"*. Estudos publicados em língua inglesa até 30 de junho de 2022 foram selecionados tendo em vista objetivo deste estudo.

Resultados: Um total de 37 estudos foram identificados embora 10 estudos foram selecionados. Superfícies de zircônia foram significativamente modificadas após a irradiação a laser, resultando em regiões retentivas alinhadas com valores de profundidade variando de 50 a 120 µm. Os valores médios de rugosidade da zircônia tratada com laser a Er,Cr:YSGG (~0,83 µm) foram bastante semelhantes quando comparados às superfícies de zircônia jateadas (~0,9 µm), embora a rugosidade foi registada em até 2,4 µm, dependendo do tipo dos parâmetros de laser. Vitrocerâmicas reforçadas com dissilicato de lítio tratadas com Er:YAG revelaram uma rugosidade média em torno de 3,5 µm, enquanto as superfícies tratadas com Nd:YAG revelaram uma rugosidade média de 2,69 µm, bastante semelhante aos valores de rugosidade registrados para superfícies condicionadas com HF (2,64 µm). Os valores de SBS de superfícies de zircônia tratadas com laser Nd:YVO$_4$ foram ligeiramente maiores (~ 33,5 MPa) do que aqueles registrados para superfícies de zircônia jateadas (28 MPa). Superfícies de zircônia tratadas com laser CO$_2$ revelaram valores de SBS mais altos (18,1 ±0,8 MPa) do que aqueles (9,1 ±0,56 MPa) registrados para superfícies de zircônia não tratadas. Em vitrocerâmicas reforçadas com dissilicato de lítio, valores mais altos de SBS para cimentos de matriz de resina foram registrados para espécimes tratadas com uma combinação de irradiação de laser de CO$_2$ e condicionamento com HF (~ 22-24 MPa) quando comparados a espécimes jateadas (12,2 MPa). Outro estudo revelou valores de SBS em torno de 27,5 MPa para vitrocerâmicas reforçadas com dissilicato de lítio tratadas com Er:YAG para cimentos de matriz resinosa.

Conclusões: A irradiação do laser em alta potência aumenta a rugosidade da superfície interna de restraurações indiretas de zircónia ou vitrocerâmicas reforçadas com dissilicato de lítio, o que resulta em uma maior adesão aos cimentos de matriz resinosa. O tipo de laser e os parâmetros de irradiação podem ser ajustados para melhorar a retenção em macro- e micro-escala de superfícies de zircônia e vitrocerâmica aos materiais de cimentação.

Palavras-chave: disilicato de lítio; zircónia; laser; adesão; cimento de resina

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LISTS OF ABBREVIATIONS:

Er:YAG laser – Erbium-doped Yttrium Aluminium Garnet laser

Er,Cr:YSGG laser – Erbium, Chromium-doped Yttrium, Scandium, Gallium and Garnet laser

Nd:YAG laser – Neodymium-doped Yttrium Aluminium Garnet laser

Laser CO_2 – Dioxide carbon laser

Nd:YVO_4 laser – Neodymium-doped Yttrium Orthovanadate Crystal and Substrates

MPa – Megapascal

mJ – Millijoule

W – Watts

Hz – Hertz

1. Introduction

Nowadays, the use of ceramics has been increasingly preferred by clinicians and patients considering aesthetic outcomes. Ceramics and glass-ceramics are the first choice for manufacturing veneers, crowns, inlay, and onlays restorations over teeth or dental implant abutments (1,2). The long term clinical success of ceramic-based restorations is strongly dependent on their retention to teeth or abutment substrates by using resin-matrix cements (1–6). Polycrystalline ceramics such as zirconia have enhanced mechanical properties although the surface modification for further adhesion to resin-matrix cements is the major disadvantage (3,7,8). Traditional methods of surface modification such as grit-blasting and acid etching have limited capability to achieve optimum morphological aspects and roughness over zirconia for mechanical interlocking of adhesive systems and resin-matrix cements (3,7,8).

The surface modification of dentin or enamel is carried out by acid etching with 37% H_3PO_4 acid following by conditioning with methacrylate-based adhesives. In the same way, titanium abutment base can be modified by grit-blasting with alumina particles (Al_2O_3) followed by acid etching with (5-10%) HF acid and then conditioning with silane and methacrylate-based adhesives (1,9). Surfaces of lithium disilicate-reinforced glass ceramics can also be modified by acid etching with (5-10%) HF acid (1). Thus, the roughness of enamel, dentin, glass-ceramics, and titanium surfaces can be increased by acid etching that increase the adhesion area to adhesives and resin-matrix cements. However, acid etching with HF or H_3PO_4 acids cannot alter the zirconia surfaces since zirconia has a highly chemical stability (10,11). Also, grit-blasting with Al_2O_3 or SiO_2

particles show limitations considering limited morphological aspects, contamination with remnant abrasive particles, and risks of cracks' propagation (10). The combination of different traditional surface modification techniques has been studied and associated with novel methods such as laser-assisted approach (10,11).

The laser-assisted approaches already have many applications in oral pathology, endodontics, operative dentistry, and prosthodontics (10,12). The surface modification of implants and prosthetic structures has gathering attention to improve roughness and wettability for adhesion to resin-matrix cements (12–17). Currently, different morphological features (i.e., micro-grooves, pits, valleys, and peaks) can be produced by using different laser intensity, type, time, and frequency (13,14,16). Previous studies have reported the surface modification of zirconia in short (mili- to nano-seconds) or ultra-short (pico- to femto-seconds) periods of time (pulses) using different types of lasers such as: Nd:YAG, Er:YAG, CO_2, Er,Cr:YSGG, and Nd:YVO_4 (13,16–18). However, zirconia is susceptible to defects such as cracks depending on the mode and intensity of the laser irradiation. Minimal surrounding defects and contaminants have been reported after surface modification of zirconia by using ultra-short pulsed lasers (pico- and femtosecond lasers) (10,12). Thus, further studies are required to validate adequate parameters for surface modification of zirconia and glass-ceramics by laser-assisted approaches to improve the bond strength to resin-matrix cements.

2. Objective and hypotheses

The main aim of the present study was to carry out an integrative review on laser-texturing the inner surface of lithium disilicate-reinforced glass ceramic or zirconia veneer and crowns to increase their bond strength to resin-matrix cements. It was hypothesized that the laser irradiation at high power increase the roughness of the inner surface of lithium disilicate-reinforced glass ceramic or zirconia veneers

3. Methods

3.1. Information sources and search strategy

A bibliographic review was performed on PubMed (via National Library of Medicine) taking into account such database includes the major articles in the field of dentistry and biomaterials. The present method was performed in accordance with the search strategy applied in previous studies on integrative or systematic reviews (9–11,19–21). The following search terms were applied: “zirconia” OR “lithium disilicate” AND “laser” AND “surface” OR “roughness” AND “bon strength” AND “resin cement”.

Also, a hand-search was performed on the reference lists of all primary sources and eligible studies of this integrative review for further relevant publications. The inclusion criteria encompassed articles published in the English language, from January 2012 until June 30th, 2022, reporting the combined effect of the laser irradiation on the surface modification of lithium disilicate-reinforced glass ceramic or zirconia veneers and their adhesion to resin-matrix cements. The eligibility inclusion criteria used for article searches also involved: *in vitro* studies; meta-analyses; randomized controlled trials; animal assays; and prospective cohort studies. The exclusion criteria were the following: papers without abstract; case report with short follow-up period; articles assessing only traditional methods of surface modification. Studies based on publication date were not restricted during the search process.

3.2. Study selection and data collection process

At first, studies were examined for relevance by title, and the abstracts were assessed for those that were not excluded at this stage. Two of the authors (JCMS, AE) individually analyzed the titles and abstracts of the retrieved potentially relevant articles meeting the inclusion criteria. The total of articles was compiled for each combination of key terms and therefore the duplicates were removed using Mendeley citation manager. The second step comprised the evaluation of the abstracts and non-excluded articles following the eligibility criteria on the abstract review. Selected articles were independently read and analyzed concerning the purpose of this study. At last, the eligible articles received a study nomenclature label, combining first author names and year of publication. The following variables were collected for this review: authors' names, journal, publication year, aims, materials, laser parameters, roughness, and adhesion. PICO question was adjusted to the issue where "P" was related to the patients or specimens while "I" referred to the methods of analyses while "C" was related to comparison of findings and "O" to the main outcomes. Data of the reports were harvested directly into a specific data-collection form to avoid multiple data recording considering multiple reports within the same study (e.g., reports with different set-ups). This evaluation was individually carried out by two researchers, followed by a joint discussion to select the relevant studies.

4. RESULTS

The search of articles on PubMed identified a total of 37 articles, as seen in Figure 1. After excluding duplicates, 35 articles were evaluated by title and abstract although 28 were excluded considering they did not meet the inclusion criteria. The remnant 7 articles were full read and selected. Three studies were added by hand-search since they were considered as relevant regarding information on laser parameters, methods, and main outcomes.

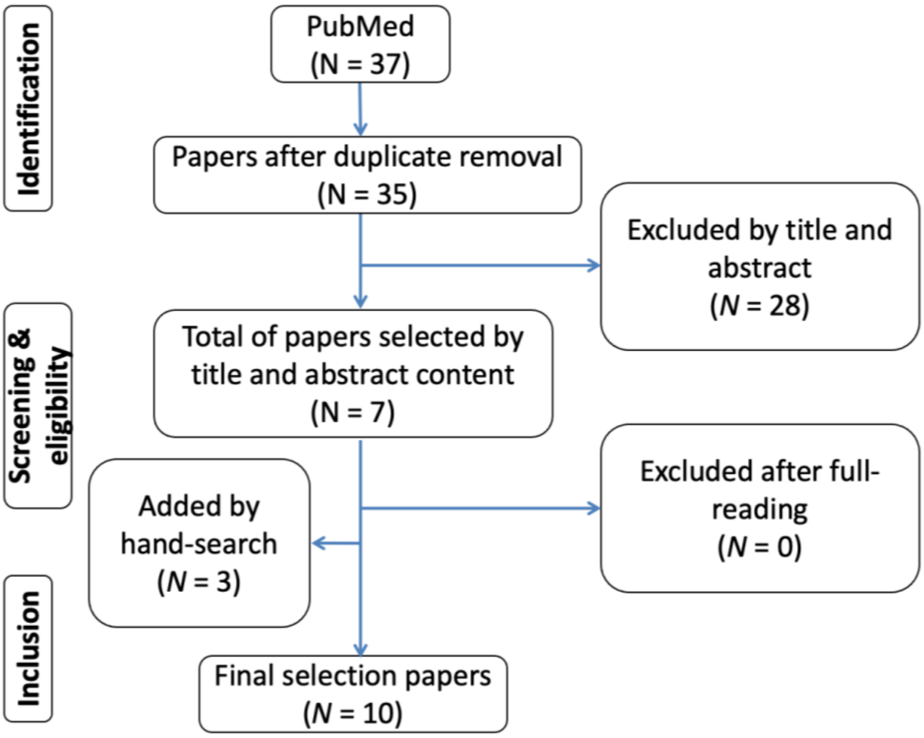


Figure 1. Study selection flowchart.

Of the 10 selected studies, yttria stabilized tetragonal zirconia polycrystals (Y-TZP) was assessed by size studies (7,8,22–25) although ceria stabilized tetragonal zirconia polycrystals (Ce-TZP) was also assessed by one study (23). The effects of laser irradiation on lithium disilicate-reinforced glass ceramic were investigated by three studies (26–28). The following types of laser were assessed by the selected studies: Er,Cr:YSGG (8,25) , Er:YAG (27,28), Nd:YAG (27), CO_2 (7,26), and Nd:YVO_4 (23). The laser irradiation parameters varied among the studies as seen in Table 1. For instance, the power intensity of the Er,Cr:YSGG laser irradiation ranged from 1 up to 6 W (8,25) while Er:YAG laser was assessed at power intensity range between 4 and 5 W (27,28). The power intensity assessed for CO_2 laser ranged from 3 up to 20 W while the power intensity of Nd:YAG laser was assessed at 2.5 W (27). After laser irradiation, roughness values were only recorded by three studies (22,25,27) although the shear bond strength of laser-treated zirconia to resin-matrix cements was recorded by each of one of the selected studies.

The main findings of the selected studies can be drawn as follow:

- The surfaces of the zirconia were significantly modified after laser irradiation with Yb-doped fiber or Nd:YVO_4 laser resulting in depression aligned retentive regions with macro-scale depth values ranging from 50 up to 120 µm (23,24);
- The average roughness of laser-treated surfaces using Yb-doped fiber laser system was recorded at around 2.4 µm that was significantly higher when compared to the untreated zirconia surfaces (~0.2 µm) (22). Nevertheless, the average roughness recorded for laser-treated surfaces using Er,Cr:YSGG (~ 0.83 µm) was quite similar to those recorded for grit-blasted zirconia surfaces (~ 0.9 µm) (25);
- Surfaces of lithium disilicate-reinforced glass ceramics were also modified by laser irradiation although the etching with HF acid resulted in high values of roughness (27).

Lithium disilicate-reinforced glass ceramics treated with Er:YAG revealed an average roughness of around 3.5 µm while surfaces treated with Nd:YAG revealed an average roughness of 2.69 µm that was quite similar to the roughness values recorded for etched surfaces (2.64 µm) (27);

- Laser-treated zirconia surfaces showed high values of shear bond strength (SBS) to resin-matrix cements (7,23). The SBS values of zirconia surfaces treated on Nd:YVO$_4$ laser were slightly higher (~ 33.5 MPa) than those recorded for grit-blasted zirconia surfaces (28 MPa) (23). Laser-treated zirconia surfaces on CO$_2$ laser revealed the highest SBS values (18.1 ±0.8 MPa) while lowest values (9.1 ±0.56 MPa) were recorded for untreated zirconia surfaces (7);
- On lithium disilicate-reinforced glass ceramics, higher SBS values to resin-matrix cements were recorded for specimens treated with a combination of fractional CO$_2$ laser irradiation and HF acid etching (~ 22-24 MPa) when compared with grit-blasted specimens (12.2 MPa) (26). Another study revealed SBS values at around 27.5 MPa for Er:YAG-treated lithium disilicate-reinforced glass ceramics to resin-matrix cements (27,28). Surfaces grit-blasted with Al$_2$O$_3$ particles showed the lowest mean bond strength to the resin composite (15.62 MPa) (28).

Table 1. Relevant data retrieved from the selected studies.

Authors (year), country	**Study design and follow-up**	**Ceramic**	**Resin-matrix cement**	**Laser type**	**Laser parameters**	**Roughness (µm)**	**Main outcomes**
Toyoda *et al.* (2022), Japan	*In vitro* - Shear bond test at 0.5 mm/min using a universal machine (Autograph, AGS-J, Shimadzu, Japan) - Thermal-cycling consisted at 5°C for 1 min and 55°C for 1 min - Scanning electron microscopy (SEM; JSM-6330F, JEOL, Tokyo, Japan) - Profilometry as the arithmetic mean height of the surface (Sa) and developed interfacial area ratio (Sdr)	ZrO_2 (97wt%), Y_2O_3 (3wt%), (Daiichi Kigenso, Japan)	1) Powder: PMMA, TiO_2; Liquid: 4-META, MMA, Catalyst: TBB (Super bond C&B^{TM}, Sun Medical, Japan) 2) Bis-GMA, TEGDMA, Silanated barium glass filler, Silanated fluoroalminosilicate glass filler, Colloidal silica, Surface treated aluminum oxide filler, Hydrophobic aromatic dimethacrylate, Hydrophilic aliphatic dimethacrylate, dl-Camphorquinone, Initiators, Accelerators, Pigments (Panavia V5^{TM}, Kuraray Nortitake, Japan) Priming agent	Ytterbium fiber laser system (MD-F3000, Keyence, Osaka, Japan)	Power output of 24 W and pulse frequency of 60 kHz for 6.6 s of laser irradiation time.	Arithmetic mean height (Sa): Untreated: 0.19 ±0.06 Grit-blasted with (Al_2O_3): 0.55 ±0.05 Laser-textured: 2.39 ±0.02	Shear bond strength mean values (MPa): 1) Super bond C&B^{TM}: Untreated before thermal cycling: 10 Untreated after thermal cycling: 10 Grit-blasted before thermal cycling: 13 Grit-blasted after cycling: 23 Laser-textured before thermal cycling: 14.5 Laser-textured after thermal cycling: 26 2) Panavia V5^{TM}: Untreated before thermal cycling: 11 Untreated after thermal cycling: 0 Grit-blasted before thermal cycling: 14.5

							Grit-blasted after thermal cycling: 2 Laser-textured before thermal cycling: 12 Laser-textured after cycling: 10 → No significant difference between grit-blasted and laser-textured
Murthy *et al.* (2014), India	*In vitro* - The shear bond strength testing to resin-matrix cement. Laser-treated surfaces compared to grit-blasted with alumina (110 or 250 µm)	Zirconia, CEREC (ZrO_2) (Cortis-YZ, Sirona Dental GmbH Bensheim, Germany)	Resin cement block of 0.5 mm (unkown)	Surgical CO_2 laser radiation (Smart US 20D, CO_2 laser, Deka Florence, Italy)	Laser energy in a pulse mode with wavelength of 10.6 µm, a pulse repetition rate of 1000 Hz and pulse duration of 160 ms at an average power setting of 3 w at 1mm away from the surface.	-	- Laser-treated surfaces revealed the highest shear bond strength values (18.1 ±0.8 MPa) while lowest values were recorded for control group (9.1 ±0.56 MPa) - There were no significant differences between the control and grit-blasted groups.

Iwaguro *et al.* (2019) Japan and Taiwan	*In vitro* - SEM (SE-8000, Keyence Corp., Osaka, Japan) at ×500 magnification. - Shear bond test at a crosshead speed of 0.5 mm/min using a universal testing machine (AGS-5kNJ, Shimadzu, Kyoto, Japan) - Groups were submitted on thermocycling (Thermal Cycler, Nissin Seiki Co. Ltd., Hiroshima, Japan) at 4°C and 60°C in water (dwell time per water bath for 1 min) for 20,000 cycles.	Zirconia : 1) Y-TZP; ZrO_2 (97wt%), Y_2O_3 (3wt%), Tosoh Corp., Japan) 2) Ce-TZP/A (ZrO_2, Al_2O_3, CeO_2 ,Yamakin Co., Ltd., Japan) Porcelain : Vintage ZR, Opaque liner A3O and Body A3B = Aluminosilicate glass, Glycerin, Propylene glycol (Shofu Inc., Japan)	Gradia^{TM} (GC Corp., Tokyo, Japan) : - Foundation opaque: UDMA, SiO_2 - Opaque A3: UDMA, SiO_2 - Dentin A3: UDMA, SiO_2, Filler, Grass powder Primer: Clearfil Ceramic Primer Plus^{TM} with MDP, ethyl alcohol (Kuraray Noritake Dental Inc., Tokyo, Japan)	$Nd:YVO_4$, CNC laser machine (LASER-TEC 40, DMG MORI, Japan)	Frequency of 70 kHz, wavelength of 1,065 nm, distance from the surface of 60 mm, and angle of incidence of 90°.	Shear bond strength mean values (MPa): 1) Y-TZP: Alumina-blasted: 28.9 Alumina-blasted after thermal cycling: 15.5 Laser-textured with microslits at 50 µm: 28.6 Laser-textured after cycling with microslits at 50 µm: 33.1 Laser-textured with microslits at 75 µm: 33.5 Laser-textured after cycling com microslits at 75 µm: 31.5 Laser-textured with microslits at 100 µm: 29.2 Laser-textured after cycling com microslits at 100 µm: 33.5 2) Ce-TZP/A: Alumina-blasted: 25.6

Alumina-blasted after thermal cycling: 16.6
Laser-textured with microslits at 50 µm: 27.1
Laser-textured after cycling with microslits at 50 µm: 34.5
Laser-textured with microslits at 75 µm: 26.6
Laser-textured after cycling with microslits at 75 µm: 32.9
Laser-textured with microslits at 100 µm: 27.6
Laser-textured with microslits at 100 µm after thermal cycling: 32

The predominant failure on laser-textured surfaces was a cohesive fracture.

Turker *et al.* (2020), Turkey	*In vitro* - The pull-out testing at 0.5 mm/min crosshead speed (Model AG-50 kNG, Shimadzu) - Surfaces were examined under a stereo-microscope (SZH10, Olympus)	Zirconia : Y-TZP ; ZrO_2 (97wt%), Y_2O_3 (3wt%)	A dual-cure self-adhesive resin cement (RelyX U200^{TM}, 3M ESPE)	ER,CR:YSGG 1.5 or 3 W	1) Power of 1.5 W at 20 Hz frequency and 80% air and 25% water at a distance of 1 mm for 30s 2) Power of 3 W at 20 Hz frequency and 80% air and 25% water at a distance of 1 mm for 30s	-	- The mean bond strength values of titanium were higher than those of the zirconia. - For zirconia, all four treatment groups (two lasers, grit-blasting and tribochemical silica coating) significantly differed from the control group, although the treatment groups were not statistically different from each other.

Fornaini *et al.* (2021), France and Italy	*In vitro* - Optical profilometry (Talysurf CCI green light, Taylor-Hobson, , UK) - Shear bond strength testing (Erischen, Wupper-tal, Germany) at a 0.05 mm/s cross-head speed.	Zirconia (DDBioZ, Dental Direkt GmbH, Spenge, Germany); ZrO_2 + HfO_2 + Y_2O_3 (≥ 99wt%), Al_2O_3 (0.25wt%) and others oxides (< 0.1wt%)	Primer (Zirconia Prime, DenMat, US) Flowable resin-matrix composite (Tetric EvoFlow^{TM}, Ivoclar Vivadent, Germany)	1070 nm Yb-doped pulsed fiber laser (AREX 20, Datalogic, Italy)	1070 nm Yb-doped pulsed fiber laser with a maximum average output power of 20 W, a fixed pulse duration of 100 ns and a repetition rate in the range 20 kHz–100 kHz.	-	- The highest forces were recorded for laser-treated surfaces (132.5 ±61.35 N) than those for non-treated ones (105.7 ±56.1 N). However, the difference was not considered statistically significant (p = 0.2155) Lines depth: 10 µm Depth at 10 W: 100 µm Depth at 20 W: 120 µm
Kirmali *et al.* (2015), Turkey	*In vitro* - All specimens were mounted on metallic stubs, gold- sputter coated (Polaron Range SC 7620; Quorum Technology, Newhaven, UK) - Shear bond testing (Lloyd LF Plus; Ametek Inc., UK)	Pre-sintered Y-TZP zirconia cylinders (Noritake, Japan) ZrO_2 (97wt%), Y_2O_3 (3wt%) Sintering at 1500°C for 8 h in a Zyrcomat (VITA Zahnfabrik,	Resin-matrix cement (unknown)	Er,Cr:YSGG laser irradiation	Irradiation at 2.78 µm wavelength. Optical fiber of the laser (600 µm diameter, 6 mm length) was placed at a distance of 10 mm. Pulse duration from 140 to 200 µs with a repetition rate of 20 Hz (pulses/sec) and pulsed laser-powered hydrokinetics, the	Control: 0.75 Grit-blasted: 0.90 1 W Laser: 0.79 2 W Laser: 0.82 3 W Laser: 0.83 µm 4 W Laser: 0.84 µm 5 W Laser: 0.84 µm 6 W Laser: 0.83 µm	- Surfaces treated by grit-blasting became rough and irregular and showed depression areas. - 43.75% fracture occurred at the veneer ceramic/ zirconia interface (adhesive failure) Shear bond strength (MPa) to resin cement:

	- Roughness (Ra, lm) was determined with a profilometer (Mitutoyo Surftest SJ-301, Japan)	Germany) sintering furnace.			output power from 0.25 to 6.0 W. The energy parameters at 1, 2, 3, 4, 5, and 6 W and water/air flow of 55% and 65% were used continuously during the irradiation for 20 s.		- Control: 11.31 - Air abrasion: 23.31 - 1W laser: 13.2 - 2W laser: 13.65 - 3W laser: 16.83 - 4W laser: 18.50 - 5W laser: 21. 69 - 6W laser: 22.99
Feitosa *et al.* (2017), Brazil	*In vitro* - Bond strength testing (model DI-1000; EMIC, Brazil) - Optical profilometry were for the arithmetic mean value of surface roughness (Ra) - SEM analyses (Inspect S50, FEI Company, USA) at different magnifications.	Lithium disilicate reinforced glass ceramic: IPS e.max Press–LTD3^{TM} (Ivoclar-Vivadent, Liechtenstein); SiO_2, Li_2O, K_2O, MgO, ZnO, Al_2O_3, P_2O_5 and other oxides	Dual-cure resin cement; = Bis-GMA, urethane dimethacrylate, triethylene glycol dimethacrylate. barium glass, ytterbium trifluoride, Ba-Al-fluorosilicate glass, spheroid mixed, oxide, catalysts, stabilizers, pigment (Variolink II^{TM} (base & catalyst, Ivoclar-Vivadent, Liechtenstein) Silane: Alcohol solution of silane methacrylate, phosphoric acidmethacrylate and sulphide methacrylate (Monobond Plus^{TM} (Ivoclar-Vivadent, Liechtenstein)	1) Er:YAG laser (Key Laser 3; KaVo Kerr, USA) 2) Nd:YAG laser (PulseMaster 600 IQ; American Dental Technologies Inc., USA)	1) Er:YAG laser: 200 mJ energy, using a pulse repetition rate set at 10 pps, 2.94 µm wavelength and at 12 mm away from the s surface with water spray cooling (5 s) 2) Nd:YAG laser: 120 mJ energy. The pulse repetition rate was set at 15 pps and a 320 µm diameter laser optical fiber was placed in contact with the surface for 1 min without water spray	(R_a roughness): Control (only HF): 2.64 (center) & 1.39 (periphery) Er:YAG: 3.48 (center) & 2.14 (periphery) Er:YAG + graphite: 1.29 (center) & 1.16 (periphery) Nd:YAG: 2.69 (center) & 1.46 (periphery) Nd:YAG + graphite: 0.91 (center) & 0.86 (periphery)	- Er:YAG laser group showed the highest bond strength (27.5 ±7.1). - Both the factors “laser” ($p = 0.00$) and “graphite coating” ($p = 0.00$) significantly affected the bond strength of the resin-matrix cement to the

					Each irradiated area was etched with HF for 60 s		lithium disilicate ceramic. The interaction of those two factors was not statistically significant (p = 0.059).
Ergun-Kunt *et al.* (2021), Turkey	*In vitro* - Shear bond testing (Micro Tensile Tester; BISCO Dental Products, USA) - Otical microscopy (Kaps ENT SOM Microscope, Germany) - SEM analyses (JSM-7001F, JEOL, Japan)	Lithium disilicate reinforced glass-ceramic: IPS e.max Press™ (Ivoclar-Vivadent, Liechtenstein)	Resin-matrix composite: Tetric N-Ceram™ (Ivoclar-Vivadent, Liechtenstein) Silane coupling agent: 3-glycidoxypropyltrimethoxysilane (Ivoclar-Vivadent, Liechtenstein)	Er:YAG laser	Frequency of 20 Hz, within a long pulse of 5 W, and a energy of 250 mJ for 30 s	-	- Surfaces treated with silane followed by laser irradiation had the highest mean bond strength values to resin composites (27.84). - Surfaces grit-blasted with Al_2O_3 particles showed the lowest mean bond strength to the resin composite (15.62 MPa). - A silane heat treatment by Er:YAG laser

							resulted inl deterioration and contamination on the ceramic.
Ahrari *et al.* (2017), Iran	*In vitro* - Optical microscopy (Dino Lite Pro, AnMo Electronics Corp., Taiwan, ROC) at ×20 magnification for fracture inspection. - Shear bond strength testing (Santam, Model STM-20, Iran).	Lithium disilicate reinforced glass-ceramic: IPS e.max CAD^{TM} (Ivoclar-Vivadent, Liechtenstein)	A dual-cured self-adhesive resin luting cement: (Clearfil SA Luting^{TM}, Kuraray Noritake Dental Inc., Japan) Silane coupling agent: (Silane Bond Enhancer, Pulpdent Corp., USA)	Fractional CO_2 laser (a wavelength of 10.6 µm; Lutronic Inc., Princeton Junction, NJ, USA)	Two powers: 1) The frequency of 200 Hz (pulse per second) and irradiation time of 10 s. The power and pulse energy were 10 W and 14 mJ, respectively. The pulse duration was 1.75 ms, and the energy delivered was approximately 28 J. 2) The power of 20 W and pulse energy of 10 mJ. The pulse duration was 0.58 ms, and the energy delivered was approximately 24 J.	-	- The highest bond strength values were recorded for specimens treated with a combination of fractional CO_2 laser irradiation and HF acid etching (22.4 and 24.3 MPa for groups 5 and 6, respectively). Grit-blasted specimens exhibited the lowest shear bond strength (12.2 MPa). - The adhesive failure was the main type of fracture followed by mixed fracture. Shear bond strength (MPa) of resin cement to lithium disilicate specimens

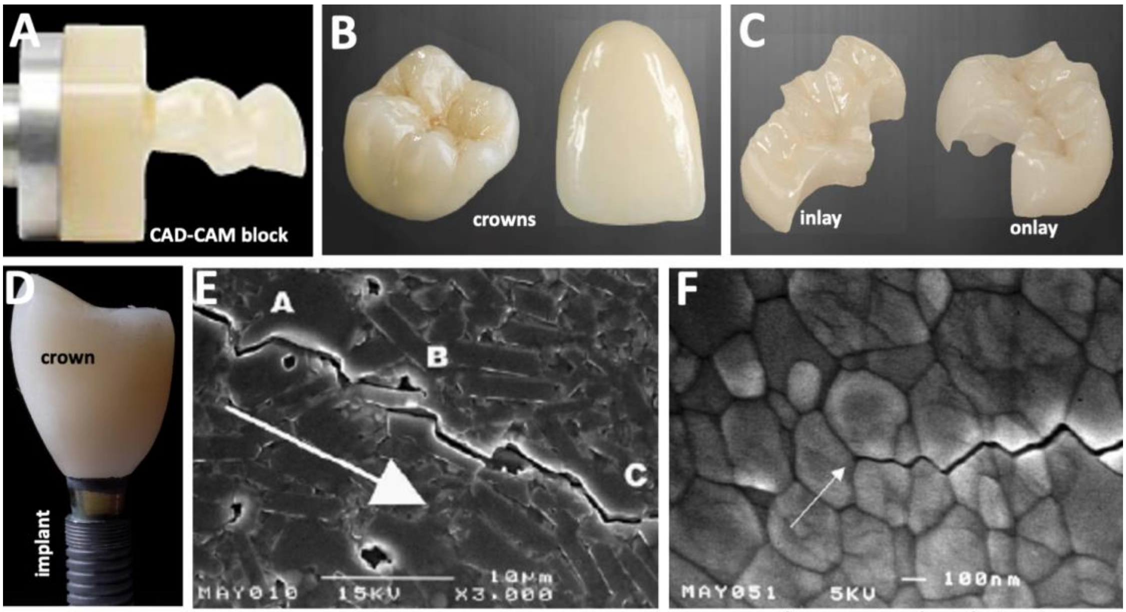
CO_2 laser (20 W/10 mJ) + acid etching : 24.3 ± 7.2 CO_2 laser (10 W/14 mJ) + acid etching : 22.4 ± 4.6 CO_2 laser (20 W/10 mJ) : 13.8 ± 2.3 CO_2 laser (10 W/14 mJ) : 13.8 ± 3.0

5. DISCUSSION

This review reported relevant findings on laser-textured lithium disilicate-reinforced glass ceramic or zirconia surfaces and their adhesion to resin-matrix cements. Results showed an increased roughness of the glass-ceramics and zirconia when compared to untreated surfaces. Thus, high values of roughness values reveal an increase in the retentive area to silane agents, adhesive systems, and resin-matrix cements. Indeed, those findings validate the hypothesis of the present review. Nevertheless, different type of laser and irradiation parameters are reported in literature. A detailed discussion on laser parameters as well as on zirconia and glass-ceramics and their adhesion to resin-matrix cements is given as follow.

5.1. Glass-ceramics and zirconia in dentistry

Nowadays, ceramics and glass-ceramics are used to synthesize metal-free (e.g. zirconia or zirconia-to-porcelain systems) and metal-ceramic (e.g. feldspar-based ceramic fused on metallic materials) for implant- or teeth-supported prostheses (Figure 2A-D). Thus, ceramics and glass-ceramics show have shown significantly improved esthetic appearances, yet higher failure rates are associated with fractures, crack propagation, and poor cement and/or bonded retention (1,29–31). Thus, the brittle mechanical behavior of glass-ceramics and zirconia remains a concern regarding catastrophic fracture (Figure 2E and F) or abrupt stress distribution across the structural materials and interfaces. High concentration of stresses at prosthetic structural materials can increase the risks of brittle fractures at the zirconia or glass-ceramics to adhesive and resin-matrix interfaces (1,13).



crack propagation through glass-ceramic

crack propagation through zirconia

Figure 2. (A) CAD-CAM blocks composed of lithium disilicate-reinforced glass ceramic. (B,C,D) All-ceramic restorations. Crack propagation through (E) lithium disilicate-reinforced glass-ceramic and (F) zirconia microstructure (Adaptated from Guazzato et al (32,33)).

Zirconium silicate and lithium disilicate-reinforced glass-ceramics are popular choices for anterior crowns because of their excellent esthetics and mechanical properties (1,34–38). Lithium silicate glass-ceramic contains approximately 65% volume fraction of lithium disilicate crystals, 34% volume fraction of residual glass and 1% volume fraction of porosity after heat treatment (33). The glass matrix is derived from a multi-component system, formulated from SiO_2-Li_2O-K_2O-ZnO-Al_2O_3-La_2O_3-P_2O_5 glass system (39,40). Lithium disilicate glass-ceramics have shown elastic modulus of around 60-105 GPa, fracture toughness at 2-3 MPa.$m^{1/2}$, bend strength values around 320 ± 30 MPa, and hardness at 5.5 ±0.3 GPa (33,38,39,41). Previous studies have reported the performance of glass-ceramic materials belonging to Li_2O-ZrO_2-SiO_2 (LZS) glass-ceramic systems for different applications (1,34,35,38) . $Li_2Si_2O_5$ and $ZrSiO_4$ were the resulting main crystalline phases within the LZS microstructure after sintering. LZS glass ceramics revealed elastic modulus of 70-110 GPa, fracture toughness at 2.3-3.3 MPa.m$^{1/2}$, bend strength values at 440 ±40 MPa and hardness at 6.5 ±0.3 GPa (38).

Zirconium dioxide (ZrO_2) known as zirconia is a polymorphic ceramic, which has three different crystallographic phases: tetragonal (t), monoclinic (m), and cubic (c) (42). Zirconium dioxide has a monoclinic structure at room temperature that remains stable up to 1170 °C (42,43). The monoclinic structure turns to the tetragonal phase when ZrO_2 is sintered at temperature between 1170 and 2370 °C while the cubic phase is achieved between 2370 and 2680 °C (42,43). On cooling down, the zirconia tetragonal phase turns monoclinic at a temperature around 970 °C (42). The transformation pathway of tetragonal to the monoclinic phase is linked to about 3 to 4 vol% expansion that can results in cracks among the crystals (42). Mechanical properties of zirconia are improved when the tetragonal phase is stabilized by the incorporation of small contents of oxides such as yttrium oxide (yttria, Y_2O_3), cerium oxide (ceria, CeO_2), magnesium oxide (magnesia, MgO), and calcium oxide (calcia, CaO) (42,43). Yttria-stabilized tetragonal zirconia polycrystals (Y-TZP) is produced by introducing 2–5 mol% Y_2O_3 into ZrO_2 formulations (42,43). The tetragonal phase stabilization results in Y-TZP with a significant increase in the elastic modulus at 230–270 GPa, fracture toughness of approximately 9–10 MPa.m$^{1/2}$, flexural strength values at around 1200 MPa, and hardness at 1.1 GPa (31,32). Those values are significantly higher when compared with those recorded for glass ceramics. Additionally, oxide-stabilized zirconia has an inherent and remarkable pathway to inhibit the propagation of cracks when the material is submitted to high stresses. It results from a transformation from tetragonal to the monoclinic phase with an increase in the surrounding volume leading to compressive stresses over the crack. Nevertheless, Y-TZP is susceptible to degradation at low temperature on performance in a humid environment as found in the oral cavity (31,44). Tetragonal-to-monoclinic phase conversion can take place under fatigue caused by cyclic stresses from thermal fluctuations or mastication loading (42,43,45,46).

5.2. Laser-modified surfaces and adhesion to resin cements

On teeth, crowns or multi-unit prostheses are retained by using resin-matrix cements. Screw or cement-retained crowns consists of two ways of retaining the implant-abutment prosthetic (1,47,48). Considering the glass matrix of both zirconium silicate and lithium disilicate-reinforced glass-ceramics, roughness of surfaces can be increased by etching with 5-10% hydrofluoric acid for further adhesion to resin-matrix cements. As seen in Table 1, lithium disilicate-reinforced glass ceramics etched with HF acid resulted in surfaces with roughness values higher than those for untreated surfaces (27). However, roughness of zirconia surfaces cannot be increased by using the commercially available acidic solutions and therefore other methods are used for zirconia surface modification such as grit-blasting and laser-assisted methods. Currently, most commercially available zirconia-based restorations are submitted to surface treatment by grit-blasting, that produce non-homogeneous and random morphological features and tendency to faster degradation (10,13). Thus, zirconia surface modification is still a contemporary challenge considering a balance among chemical stability, physical properties, and degradation behavior. It should be emphasized that the integrity of the zirconia or glass-ceramic prosthetic structures can be readily compromised by improper treatment of inner surfaces for cementation and/or failures in the cementation procedures.

Previous studies revealed the zirconia surfaces modification of zirconia and glass-ceramics by using different laser types (Er,Cr:YSGG, Er:YAG, Nd:YAG, CO_2, and Nd:YVO_4) and irradiation parameters (Table 1). In a previous selected study, Y-TZP or Ce-TZP surfaces were modified on Nd:YVO_4 laser irradiation (wavelength of 1,065 nm) at 70 kHz from 60 mm away to the surface. Morphological aspects of surfaces showed depression aligned retentive regions with macro-scale depth values ranging from 50 up to 120 µm (23). Surfaces were conditioned with a primer adhesive (Clearfil Ceramic Primer Plus^{TM}, Kuraray, Japan) and bonded to resin-matrix cements (Gradia^{TM}, GC, Corp, Japan). Half of specimens were submitted to thermal cycling and then all of specimens mechanically tested by shear bond strength (SBS) tests. After thermal cycling, SBS values of laser-treated Y-TZP or Ce-TZP surfaces to the resin-matrix cement were slightly higher (33.5 and 24.5 MPa, respectively) than those recorded for grit-blasted zirconia ones (15.5 and 16.5 MPa, respectively) (23). There were no significant differences in SBS values when comparing laser-treated Y-TZP or Ce-TZP (28.6 and 27.6 MPa, respectively) and grit-blasted surfaces (28.9 and 25.6 MPa, respectively) without the effect of the thermal cycling (23). Another study also assessed the effects of thermal cycling on the SBS values of laser-treated zirconia surfaces to resin-matrix cements. Y-TZP were treated on Yb-doped laser at a pulse repetition rate of 60 Hz, pulse duration of 6.6 s at an average power setting of 24 W (22). Laser-treated surfaces were conditioned with a primer adhesive and then bonded to a resin-matrix cement (Panavia V5^{TM}, Juraray, Japan) (22).

Half of specimens were submitted to thermal cycling and then all of specimens were assessed by SBS testing. After thermal cycling, laser treated Y-TZP surfaces to the resin-matrix cement were slightly higher (10 MPa, respectively) than those recorded for grit-blasted zirconia ones (2 MPa) (22). There were no significant differences in SBS values when comparing laser-treated (12 MPa) and grit-blasted (14.5 MPa) surfaces without the effect of the thermal cycling (22). Even though SBS values were not statistically different without thermal cycling, the adhesion of the laser-treated zirconia surfaces reached noticeable high adhesion to resin-matrix cements.

A previous study reported adhesive effects of Y-TZP treated on CO_2 laser irradiation (wavelength of 10.6 mm) at a pulse repetition rate of 1000 Hz, pulse duration of 160 ms at an average power setting of 3 W and at 1mm away from the surface (7). Specimens were bonded to a resin-matrix cement and submitted to SBS testing. The highest SBS values (18.1 ±0.8 MPa) were recorded for laser-treated zirconia surfaces while lowest values (9.1 ±0.56 MPa) were recorded for untreated zirconia (control group) surfaces (7). In another study, zirconia surfaces treated on Yb-doped pulsed fiber laser irradiation (wavelength of 1070 nm) with a maximum average output power of 20 W, a fixed pulse duration of 100 ns and a repetition rate in the range 20 kHz–100 kHz (24). Surfaces were conditioned with a primer adhesive following by bonding to a flowable resin-matrix composite (Tetric Evo Flow^{TM}, Ivoclar Vivadent, Liechtenstein) and then assessed by SBS tests (24). Laser-treated surfaces revealed high fracture forces to resin-matrix cements (132.5 ±61.35 N) when compared with non-treated ones (105.7 ±56.1 N). However, the difference was not considered statistically significant ($p = 0.2155$).

Lithium disilicate-reinforced glass ceramics were also modified by Er:YAG (200 mJ; pulse repletion at 10 pps) or Nd:YAG (120 mJ; pulse repletion at 15 pps) pulsed laser irradiation (27). Groups of specimens were also etched with HF and all of surfaces were conditioned with silane coating (Monobond Plus^{TM}, Ivoclar Vivadent, Liechtenstein) and then bonded to a dual-cure resin-matrix cement (Variolink II^{TM}, Ivoclar Vivadent, Liechtenstein). Lithium disilicate-reinforced glass ceramics treated with Er:YAG revealed an average roughness of around 3.5 µm while surfaces treated with Nd:YAG revealed an average roughness of 2.69 µm that was quite similar to the roughness values recorded for etched surfaces (2.64 µm) (27). Er:YAG-treated surfaces revealed the SBS to resin-matrix cements (27.5 MPa). In another study, lithium disilicate-reinforced glass ceramics were treated on CO_2 laser irradiation (wavelength of 10.6 µm) at two different irradiation intensity (10W and 28 J or 20 W and 28J) at a pulse repetition rate of 200 Hz, pulse duration of 1.7 ms or 0.58 ms (26). Surfaces were conditioned with a silane compound (Silane Bond Enhancer^{TM}, Pulpdent corp, USA) followed by bonding to a resin-matrix cement (Clearfill SA Luting^{TM}, Kuraray, Japan) and then the specimens were submitted to SBS tests (26). The highest SBS values to resin-matrix cement were recorded for specimens treated with a combination of fractional CO_2 laser irradiation and HF acid etching (22.4 and 24.3 MPa, respectively). Grit-blasted specimens exhibited the lowest shear bond strength (12.2 MPa) to resin-matrix cements (26).

The present review study shows some limitations considering the low number of related studies leading to a low content of information on laser-textured lithium disilicate-reinforced glass ceramic or zirconia surfaces and their adhesion to resin-matrix cements. However, showed several laser protocols have been assessed to enhance the retentive morphological aspects and increase the roughness for adhesion of ceramics and glass-ceramics to resin-matrix cements. Indeed, the variability of laser types and irradiation parameters brings an unclear overview of the efficiency of the laser-assisted method for surface modification of zirconia and glass-ceramics. Laser-assisted methods have been increasingly gathering attention in the technological field and therefore studies are performed to validate effects of different laser parameters, restorative materials, and types of resin-matrix cements.

6. CONCLUSION

The laser irradiation at high power increases the roughness of the inner surface of lithium disilicate-reinforced glass ceramic or zirconia veneers and crowns leading to an enhanced bond strength to resin-matrix cements. Laser-treated zirconia surfaces on CO_2 or $Nd:YVO_4$ laser revealed higher shear bond strength to resin-matrix than those recorded for untreated zirconia surfaces. On lithium disilicate-reinforced glass ceramics, higher SBS values to resin-matrix cements were recorded for specimens treated with a combination of fractional CO_2 laser irradiation and HF acid etching when compared with grit-blasted specimens. Thus, the laser type and irradiation parameters can be adjusted to enhance the macro- and micro-scale retention of zirconia and glass-ceramics surfaces. There are few studies reporting the effects of each type of laser on the adhesion of zirconia or glass-ceramics to resin-matrix cements and therefore further studies should consider other parameters related to the power intensity, frequency, and mode.

BIBLIOGRAPHICAL REFERENCES

1. Vahey BR, Sordi MB, Stanley K, Magini RS, Novaes de Oliveira AP, Fredel MC, et al. Mechanical integrity of cement- and screw-retained zirconium-lithium silicate glass-ceramic crowns to Morse taper implants. J Prosthet Dent. 2018 Nov 1;120(5):721–31.
2. Bansal R, Taneja S, Kumari M. Effect of ceramic type, thickness, and time of irradiation on degree of polymerization of dual - cure resin cement. J Conserv Dent. 2016;19(5):414–8.
3. Tafur-Zelada CM, Carvalho O, Silva FS, Henriques B, Özcan M, Souza JCM. The influence of zirconia veneer thickness on the degree of conversion of resin-matrix cements: an integrative review. Clin Oral Investig. 2021 Mar;
4. Samimi P, Kaveh S, Khoroushi M. Effect of Delayed Light-Curing Through a Zirconia Disc on Microhardness and Fracture Toughness of Two Types of Dual-Cure Cement. J Dent (Tehran). 2018 Nov;15(6):339–50.
5. Alovisi M, Scotti N, Comba A, Manzon E, Farina E, Pasqualini D, et al. Influence of polymerization time on properties of dual-curing cements in combination with high translucency monolithic zirconia. J Prosthodont Res. 2018 Oct;62(4):468–72.

6. Watanabe H, Kazama R, Asai T, Kanaya F, Ishizaki H, Fukushima M, et al. Efficiency of dual-cured resin cement polymerization induced by high-intensity LED curing units through ceramic material. Oper Dent. 2015;40(2):153–62.
7. Murthy V, Manoharan, Balaji, Livingstone D. Effect of four surface treatment methods on the shear bond strength of resin cement to zirconia ceramics- a comparative in vitro study. J Clin Diagn Res. 2014 Sep;8(9):ZC65-8.
8. Turker N, Özarslan MM, Buyukkaplan US, Başar EK. Effect of Different Surface Treatments Applied to Short Zirconia and Titanium Abutments. Int J Oral Maxillofac Implants. 2020;35(5):948–54.
9. Souza JCM, Sordi MB, Kanazawa M, Ravindran S, Henriques B, Silva FS, et al. Nano-scale modification of titanium implant surfaces to enhance osseointegration. Vol. 94, Acta Biomaterialia. Acta Materialia Inc; 2019. p. 112–31.
10. Schünemann FH, Galárraga-Vinueza ME, Magini R, Fredel M, Silva F, Souza JCM, et al. Zirconia surface modifications for implant dentistry. Mater Sci Eng C [Internet]. 2019;98:1294–305. Available from: http://www.sciencedirect.com/science/article/pii/S0928493118320009
11. Cunha W, Carvalho O, Henriques B, Silva FS, Özcan M, Souza JCM. Surface modification of zirconia dental implants by laser texturing. Lasers Med Sci. 2022 Feb;37(1):77–93.
12. Han J, Zhang F, Van Meerbeek B, Vleugels J, Braem A, Castagne S. Laser surface texturing of zirconia-based ceramics for dental applications: A review. Mater Sci Eng C [Internet]. 2021;123:112034. Available from: https://www.sciencedirect.com/science/article/pii/S0928493121001739
13. Henriques B, Hammes N, Souza JCM, Özcan M, Mesquita-Guimarães J, Silva FS, et

al. Influence of ns-Nd:YAG laser surface treatment on the tensile bond strength of zirconia to resin-matrix cements. Ceram Int [Internet]. 2020;46(17):27822–31. Available from: https://www.sciencedirect.com/science/article/pii/S0272884220322987

14. Kasraei S, Rezaei-Soufi L, Heidari B, Vafaee F. Bond strength of resin cement to CO2 and Er:YAG laser-treated zirconia ceramic. Restor Dent Endod. 2014 Nov;39(4):296–302.

15. Bitencourt SB, Ferreira LC, Mazza LC, Dos Santos DM, Pesqueira AA, Theodoro LH. Effect of laser irradiation on bond strength between zirconia and resin cement or veneer ceramic: A systematic review and meta-analysis. J Indian Prosthodont Soc. 2021;21(2):125–37.

16. Abu Ruja M, De Souza GM, Finer Y. Ultrashort-pulse laser as a surface treatment for bonding between zirconia and resin cement. Dent Mater. 2019 Nov;35(11):1545–56.

17. Paranhos MPG, Burnett LHJ, Magne P. Effect Of Nd:YAG laser and CO2 laser treatment on the resin bond strength to zirconia ceramic. Quintessence Int. 2011 Jan;42(1):79–89.

18. Gomes AL, Ramos JC, Santos-del Riego S, Montero J, Albaladejo A. Thermocycling effect on microshear bond strength to zirconia ceramic using Er:YAG and tribochemical silica coating as surface conditioning. Lasers Med Sci. 2015 Feb;30(2):787–95.

19. Rodrigues YL, Mathew MT, Mercuri LG, da Silva JSP, Henriques B, Souza JCM. Biomechanical simulation of temporomandibular joint replacement (TMJR) devices: a scoping review of the finite element method. International Journal of

Oral and Maxillofacial Surgery Churchill Livingstone; Aug 1, 2018 p. 1032–42.

20. Noronha Oliveira M, Schunemann WVH, Mathew MT, Henriques B, Magini RS, Teughels W, et al. Can degradation products released from dental implants affect peri-implant tissues? J Periodontal Res. 2018;53(1).

21. Souza JCM, Fernandes V, Correia A, Miller P, Carvalho O, Silva F, et al. Surface modification of glass fiber-reinforced composite posts to enhance their bond strength to resin-matrix cements: an integrative review. Clin Oral Investig. 2022 Jan;26(1):95–107.

22. Toyoda K, Taniguchi Y, Nakamura K, Isshi K, Kakura K, Ikeda H, et al. Effects of ytterbium laser surface treatment on the bonding of two resin cements to zirconia. Dent Mater J. 2022 Feb;41(1):45–53.

23. Iwaguro S, Shimoe S, Takenaka H, Wakabayashi Y, Peng T-Y, Kaku M. Effects of dimensions of laser-milled grid-like microslits on shear bond strength between porcelain or indirect composite resin and zirconia. J Prosthodont Res. 2022 Jan;66(1):151–60.

24. Fornaini C, Poli F, Merigo E, Lutey A, Cucinotta A, Chevalier M, et al. Nanosecond pulsed fiber laser irradiation for enhanced zirconia crown adhesion: Morphological, chemical, thermal and mechanical analysis. J Photochem Photobiol B. 2021 Jun;219:112189.

25. Kirmali O, Kustarci A, Kapdan A, Er K. Efficacy of surface roughness and bond strength of Y-TZP zirconia after various pre-treatments. Photomed Laser Surg. 2015 Jan;33(1):15–21.

26. Ahrari F, Boruziniat A, Alirezaei M. Surface treatment with a fractional CO2 laser enhances shear bond strength of resin cement to zirconia. Laser Ther. 2016

Mar;25(1):19–26.

27. Feitosa FA, Tribst JPM, Araújo RM, Pucci CR. Surface etching and silane heating using Er:YAG and Nd:YAG lasers in dental ceramic luted to human dentin. Int J Appl Ceram Technol. 2021;18(5):1408–16.
28. Ergun-Kunt G, Sasany R, Koca MF, Özcan M. Comparison of Silane Heat Treatment by Laser and Various Surface Treatments on Microtensile Bond Strength of Composite Resin/Lithium Disilicate. Mater (Basel, Switzerland). 2021 Dec;14(24).
29. Denry I, Kelly JR. State of the art of zirconia for dental applications. Dent Mater. 2008;24(3):299–307.
30. Yazigi C, Schneider H, Chaar MS, Ruger C, Haak R, Kern M. Effects of artificial aging and progression of cracks on thin occlusal veneers using SD-OCT. J Mech Behav Biomed Mater. 2018 Dec;88:231–7.
31. Pozzobon JL, Pereira GKR, Wandscher VF, Dorneles LS, Valandro LF. Mechanical behavior of yttria-stabilized tetragonal zirconia polycrystalline ceramic after different zirconia surface treatments. Mater Sci Eng C Mater Biol Appl. 2017 Aug;77:828–35.
32. Guazzato M, Albakry M, Ringer SP, Swain M V. Strength, fracture toughness and microstructure of a selection of all-ceramic materials. Part I. Pressable and alumina glass-infiltrated ceramics. Dent Mater. 2004;20(5):441–8.
33. Guazzato M, Albakry M, Ringer SP, Swain M V. Strength , fracture toughness and microstructure of a selection of all-ceramic materials . Part I . Pressable and alumina glass-infiltrated ceramics. Dent Mater. 2010;20(2004):441–8.
34. Souza MT, Peñarrieta-Juanito GM, Henriques B, Silva FS, Novaes de Oliveira AP, Souza JCM. Lithium-zirconium silicate glass-ceramics for restorative dentistry:

Physicochemical analysis and biological response in contact with human osteoblast. Materialia [Internet]. 2018;2:37–45. Available from: http://www.sciencedirect.com/science/article/pii/S2589152918300620

35. Fathy SM, Swain M V. In-vitro wear of natural tooth surface opposed with zirconia reinforced lithium silicate glass ceramic after accelerated ageing. Dent Mater. 2018;34(3):551–9.
36. Albero A, Pascual A, Camps I, Grau-Benitez M. Comparative characterization of a novel cad-cam polymer-infiltrated-ceramic-network. J Clin Exp Dent. 2015;
37. Sailer I, Makarov NA, Thoma DS, Zwahlen M, Pjetursson BE. All-ceramic or metal-ceramic tooth-supported fixed dental prostheses (FDPs)? A systematic review of the survival and complication rates. Part I: Single crowns (SCs). In: Dental Materials. 2015. p. 603–23.
38. Elsaka SE, Elnaghy AM. Mechanical properties of zirconia reinforced lithium silicate glass-ceramic. Dent Mater. 2016 Jul;32(7):908–14.
39. Zhang Z, Guo J, Sun Y, Tian B, Zheng X, Zhou M, et al. Effects of crystal refining on wear behaviors and mechanical properties of lithium disilicate glass-ceramics. J Mech Behav Biomed Mater. 2018 May;81:52–60.
40. Lien W, Roberts HW, Platt JA, Vandewalle KS, Hill TJ, Chu TMG. Microstructural evolution and physical behavior of a lithium disilicate glass-ceramic. Dent Mater. 2015;31(8):928–40.
41. Lawson NC, Bansal R, Burgess JO. Wear, strength, modulus and hardness of CAD/CAM restorative materials. Dent Mater. 2016;32(11):e275–83.
42. GARVIE RC, HANNINK RH, PASCOE RT. Ceramic steel? Nature [Internet]. 1975;258(5537):703–4. Available from: https://doi.org/10.1038/258703a0

43. Zhang Y, Lawn BR. Novel Zirconia Materials in Dentistry. J Dent Res. 2018 Feb;97(2):140–7.

44. Sanon C, Chevalier J, Douillard T, Kohal RJ, Coelho PG, Hjerppe J, et al. Low temperature degradation and reliability of one-piece ceramic oral implants with a porous surface. Dent Mater. 2013 Apr;29(4):389–97.

45. Zhang Y. Overview: Damage resistance of graded ceramic restorative materials. J Eur Ceram Soc. 2012 Aug;32(11):2623–32.

46. Kohorst P, Borchers L, Strempel J, Stiesch M, Hassel T, Bach F-W, et al. Low-temperature degradation of different zirconia ceramics for dental applications. Acta Biomater [Internet]. 2012;8(3):1213–20. Available from: https://www.sciencedirect.com/science/article/pii/S1742706111005034

47. Prado AM, Pereira J, Silva FS, Henriques B, Nascimento RM, Benfatti CAM, et al. Wear of Morse taper and external hexagon implant joints after abutment removal. J Mater Sci Mater Med [Internet]. 2017;28(5):65. Available from: http://link.springer.com/10.1007/s10856-017-5879-6

48. Pereira J, Morsch CS, Henriques B, Nascimento RM, Benfatti CA, Silva FS, et al. Removal Torque and Biofilm Accumulation at Two Dental Implant-Abutment Joints After Fatigue. Int J Oral Maxillofac Implants. 2016;31(4):813–9.