Heliyon 9 (2023) e17457

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

LASER as a tool for surface modification of dental biomaterials: A review

Runki Saran[a,1], Kishore Ginjupalli[a,1], Sajan D. George[b,c], Santhosh Chidangil[b,d], Unnikrishnan V K[b,d,*]

[a] Department of Dental Materials, Manipal College of Dental Sciences, Manipal Academy of Higher Education, Manipal, 576104, India
[b] Department of Atomic and Molecular Physics, Manipal Academy of Higher Education, Manipal, 576104, India
[c] Centre for Applied Nanosciences, Department of Atomic and Molecular Physics, Manipal Academy of Higher Education, Manipal, 576104, India
[d] Centre of Excellence for Biophotonics, Department of Atomic and Molecular Physics, Manipal Academy of Higher Education, Manipal, 576104, India

A R T I C L E I N F O

Keywords:
Laser
Dental implant
Ceramics
Surface pattern
Surface topography
Osseointegration

A B S T R A C T

In recent years, the application of lasers for modifying the surface topography of dental biomaterials has received increased attention. This review paper aims to provide an overview of the current status on the utilization of lasers as a potential tool for surface modification of dental biomaterials such as implants, ceramics, and other materials used for restorative purposes. A literature search was done for articles related to the use of lasers for surface modification of dental biomaterials in English language published between October 2000 and March 2023 in Scopus, Pubmed and web of science, and relevant articles were reviewed.

Lasers have been mainly used for surface modification of implant materials (71%), especially titanium and its alloys, to promote osseointegration. In recent years, laser texturing has also emerged as a promising technique to reduce bacterial adhesion on titanium implant surfaces. Currently, lasers are being widely used for surface modifications to improve osseointegration and reduce peri-implant inflammation of ceramic implants and to enhance the retention of ceramic restorations to the tooth. The studies considered in this review seem to suggest laser texturing to be more proficient than the conventional methods of surface modification. Lasers can alter the surface characteristics of dental biomaterials by creating innovative surface patterns without significantly affecting their bulk properties. With advances in laser technology and availability of newer wavelengths and modes, laser as a tool for surface modification of dental biomaterials is a promising field, with excellent potential for future research.

1. Introduction

The invention of LASER (light amplification by stimulated emission of radiation) has made a major renaissance in the field of light-based experiments. As compared to the conventional light sources wherein the emitted photons diffuse in all directions, the lasers emit nearly single wavelength photons (monochromatic) that are in phase (coherent) and propagate along the pre-defined direction with

* Corresponding author. Department of Atomic and Molecular Physics, Manipal Academy of Higher Education, Manipal, 576104, India.
E-mail address: unnikrishnan.vk@manipal.edu (U. V K).

[1] Runki Saran and Kishore Ginjupalli had equally contributed to this work.

https://doi.org/10.1016/j.heliyon.2023.e17457
Received 28 October 2022; Received in revised form 9 June 2023; Accepted 19 June 2023
Available online 20 June 2023

minimum divergence (directionality). These unique properties make LASER as an ideal tool to deposit photon energy into a highly localized region and cause physiochemical changes to the matter [1].

The discovery of the first ruby laser in 1960 by an American physicist, Theodore Maiman [2], generated a lot of interest in the medical fraternity. In the subsequent years, research involving the study of laser interaction with biological systems, including clinical trials, led to an increase in their applications [3].

In the field of dentistry, soon after the discovery of ruby laser, researchers began exploring their potential for treating tooth decay and other oral conditions [4,5]· Initial experiments with lasers reported severe damage to teeth and dental pulp [6]. Although lasers in dentistry were widely explored in the 70s and 80s, it was not until 1990 that laser dentistry became safe and practical when Dr. Terry Myers developed the first Nd:YAG laser (neodymium-doped yttrium aluminium garnet) exclusively for dental applications [7].

In early 1990s, Ar (argon), CO_2 semiconductor diodes and Nd:YAG lasers were mostly used which were more suited for ablating soft tissues than hard tissues. In 1989, a pulsed Er:YAG laser (erbium-doped yttrium aluminium garnet) was found to be capable of cutting bone, dentine, and enamel [8]. Later in 1997, Er,Cr:YSGG laser (Erbium, chromium-doped yttrium, scandium, gallium and garnet) was developed, which was suitable for the surgical needs of dentistry.

In the last decade, lasers have gained diverse applications in dentistry including detection and removal of dental caries [9–14] as well as testing the pulp vitality [15–17]. Lasers have also proven to be an efficient tool for performing fast, high precision and minimally damaging cavity cutting of teeth [18,19]. Tooth bleaching using lasers has also gained popularity in recent years [20–22]. Apart from this, many surgical procedures are being carried out with the help of lasers, such as gingival sculpting, osseous crown lengthening, biopsies, etc. [23–26].

Of late lasers have been increasingly used as a tool for surface modification of several biomedical devices such as pacemakers, implants etc. Dental biomaterials are natural or synthetic materials used to replace or restore damaged dental tissues [27]. One of the major requirements of dental biomaterials is biocompatibility in the oral environment, which is often influenced by surface characteristics of the materials such as roughness, surface energy, wettability, etc. The ability of the lasers to precisely change the surface features of a material and hence its interaction with the surroundings generated much interest among the researchers to harness this unique feature to improve the material's behavior with biological systems. When a laser beam with sufficient energy is focused on the material surface, there is localized melting, ablation, evaporation and/or resolidification of the material, resulting in the formation of various micro or nanoscale surface features with consequent changes in the surface characteristics. By adjusting the laser's parameters, it is possible to selectively modify surface of the materials without affecting the internal structure and bulk properties. Controlled laser ablation for modifying the surface topography of dental biomaterials and thereby tuning their biological and other surface properties is being widely explored. In view of increasing application of lasers, the present review aims to provide an overview of the current status on the utilization of lasers as a potential tool for surface modification of dental biomaterials such as implants, ceramics, and other materials used for restorative purposes, as well as the effect of these surface modifications on their surface topography, wettability, osseointegration, bond strength and microbial adhesion. This review also aims to provide a comprehensive insight to the readers regarding the fundament principles of lasers, variable laser parameters which affect the surface modification and the basic experimental set-up used for the process.

2. Methods

A literature search was done for articles related to the use of lasers for surface modification of dental biomaterials by using electronic database search tools such as Scopus, Pubmed and Web of Science. The keywords used in the search were laser, dental implant, ceramics, surface pattern, surface topography, osseointegration. All the articles obtained during initial search and related articles were evaluated for relevance by reading their titles and abstracts. For articles with insufficient data, the manuscript was read in full. All the relevant articles were then read in full and their eligibility was assessed based upon the inclusion and exclusion criteria established previously (Table 1). Articles which fulfilled the inclusion criteria were included in the review.

3. Results and Discussion

Based on the studies included in the present review, it can be observed that lasers have been mainly used for surface modification of implant materials (71%), especially titanium and its alloys, to promote osseointegration (Figs. 1 and 2). Among the different types of lasers for surface modification, Nd:YAG is the most commonly used. Several *in vitro* and *in vivo* studies have been conducted to evaluate the effect of laser patterning on the adhesion, growth, and proliferation of cells, wettability, surface hardness, mechanical properties, surface finish, antibacterial properties and formation of biofilm on implant surfaces. Apart from dental implants, lasers have also been

Table 1
Inclusion and exclusion criteria used in the selection of relevant studies.

Inclusion criteria	Exclusion criteria
Online sources: PubMed, Scopus, Web of science	
Articles written in English language	Articles in languages other than English
Articles published during October 2000 to March 2023	Articles with indistinct information
Relevant articles before October 2000 included for historical reference where necessary	Published data not available
Review articles, clinical journals, e-books related to laser applications in dentistry	Case reports and Expert opinions

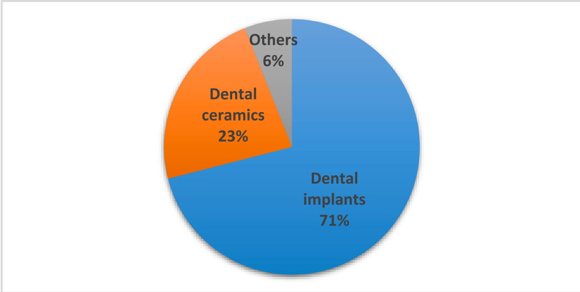

Fig. 1. Application of lasers for surface modification of materials in dentistry in the last 10 years [[43]–[172]].

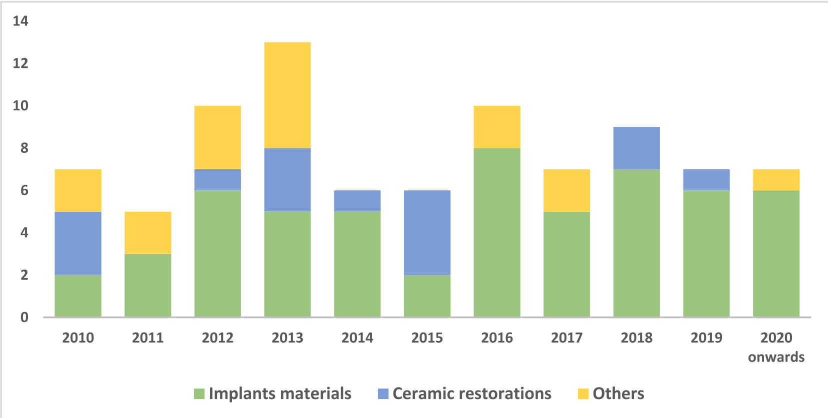

Fig. 2. Number of studies done on surface modification in various fields of dentistry in the last 10 years based upon the studies included in our review [[43]–[172]].

frequently used on ceramic restorations to improve their bonding to tooth using resin luting cement.

The results are further discussed under the following sub-sections. Sub section 1 deals with basic principles and mechanisms involved in the use of lasers for surface modifications. Sub section 2 details the use of lasers for the surface modification of dental implants. In Sub section 3, application of lasers for the surface modification of various dental restorative materials is presented.

3.1. Basic principles and mechanisms involved in the use of lasers for surface modifications

Controlled surface ablation is carried out by focusing the laser beam on the sample mounted on an X-Y-Z motion motorized translation stage. By varying the laser energy, the fluence can be controlled on the sample surface and different crater sizes can be created. Variations in the speed and direction of movement of the translation stage can generate different patterns on the surface of the sample which can be imaged using a microscope. A schematic diagram of the basic experimental set-up for nano second laser patterning process is depicted in Fig. 3.

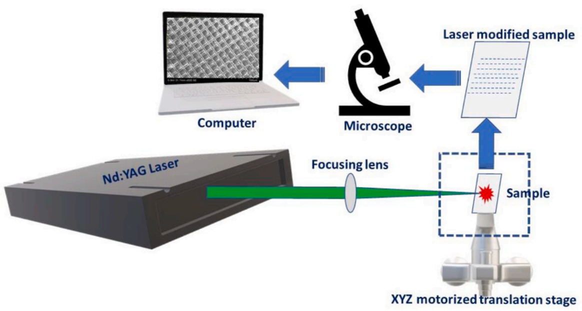

Fig. 3. Schematic representation of a conventional laser patterning facility [28,29].

3.1.1. Theoretical background

Based on the nature of the output beam from the source laser, the lasers are classified as continuous wave (CW), pulsed and ultrafast lasers. While the CW lasers provide photons continuously, the pulsed laser gives photons in the form of pulses which are typically in the duration of 0.5–500 ns. The short pulse duration of pulse lasers results in very high peak power (Peak power = pulse energy/pulse duration) of the order of megawatts and allows the release of stored energy rapidly to the substrate of interest. On the other hand, ultrafast lasers with pulse widths of 5 fs to 100 ps result in a considerable increase in peak power of the laser at a time scale comparable to or even lower than electron-phonon interaction time in the matter and thus cause little thermal damage to the sample [30].

Of late, the high peak power of the pulsed lasers is successfully exploited for surface texturing/patterning of various kinds of materials via laser ablation. In laser ablation, the absorption of the deposited laser energy for a short duration and in a spatially confined region causes the removal of the material from the substrate at the irradiated zone. The localized removal of the materials via laser ablation facilitates localized surface texturing and the tailoring of the laser parameters and focusing optical conditions provide control over the extent of texturing [31]. Typically, in the laser ablation process, the material starts with photon absorption, followed by heating and photo-ionization of the material at the target area by the laser beam. Subsequently, the ablated materials are eliminated/removed from the target surface as solid fragments, vapours, liquid drops, or as an expanding plasma plume.

The amount of ablated material thus depends on the laser parameters as well as the substrate material (Table 2). As the laser exposure time scale of nanosecond laser pulses is larger than the interaction time scale of electrons and phonons in the ablated sample, the nanosecond laser often causes undesirable thermal effects and thus limits the resolution of the ablation zone. In nanosecond laser beam interaction with the material, the surface of the target material gets heated to melting point and then to vaporization temperature. The melted material resolidifies on the material surface itself and thus results in a non-uniform ablated zone (larger heat-affected zone, HAZ) as compared to the ablation using a femtosecond laser, as depicted in Fig. 4.

As shown in Fig. 4, the ultrafast laser pulses (~fs) and short laser pulses (~ps) cause a little effect beyond the irradiation zone due to the fact that for the time scale employed the energy transfer between the lattice and the free electrons does not occur. Therefore, very high temperatures and pressures are produced at a very shallow depth in the range of microns. Herein, contrary to the irradiation with a pulsed laser, the material ablation happens without producing a recast layer on the ablated area and thus results in a smooth ablated region as compared to the irradiation with a pulsed laser [Fig. 5(a-d)] [33].

3.2. Use of lasers for the surface modification of dental implant

A dental implant is a biomaterial inserted in the jawbone or skull to support a dental prosthesis. There are three basic components of an implant: i) fixture or implant body, inserted directly into the bone. It can be threaded, perforated, grooved, coated etc. ii) Prosthesis such as crown, bridge or denture etc. iii) Abutment - the piece that connects the implant fixture to the overlying prosthesis [39]. Macro-features of implant fixture such as shape, design, neck and apex, number and pitch of the threads contribute to achieving the implant's immediate fit and initial stability [40,41]. The microscopic features such as surface roughness influence bone-to-implant contact and the host tissue's cellular response, help in achieving osseointegration, and thus long-term stability of the implant. Such surface features enhance the expression of biological markers and stimulate the proliferation of osteoblasts, thereby facilitating faster healing and better osseointegration.

Numerous methods have been reported for modifying the surface of implants, of which grit blasting or sandblasting and acid etching or their combination (Sand-blasted, large grit and acid etched [SLA]) are widely used. In grit blasting, an abrasive media like Al_2O_3 and TiO_2 is accelerated through a blasting nozzle by means of compressed air to create microscopic features on to the surface of the implant fixture. Alternatively, strong acids like HCl, H_2SO_4, and HNO_3 above 100 °C are used for etching the implant surface. SLA technique involves sandblasting the implant fixture followed by etching with HCl and H_2SO_4 [42].

Though these methods are well known with proven clinical success and have been in practice for several years, the following are

Table 2
Variables that affect surface modification on biomaterials[34–38].

Variable	Effect on surface modification
Laser factors	
Type of laser	Pulsed lasers are generally preferred in order to achieve high fluence for material ablation and thus surface patterning
Pulse width	Nanosecond, Picosecond and femtosecond lasers are generally preferred because of their high peak power
Laser Wavelength	532, 800 and 1030 and 1064 nm are generally used
Fluence	It varies depending on the type of material to be ablated. However, it is generally in the range of 10^8 W/cm^2 to 10^{10} W/cm^2
Speed of translation	This factor determines the inter-pattern spacing. A high speed of translation will result in greater inter-pattern spacing vice versa
Repetition rate	Higher repetition rate results in more number of spots per unit area. 1–10 Hz for nanosecond lasers, 1–40 MHz for picosecond lasers and kHz and MHz for femtosecond lasers are generally used
Focusing conditions	Large beam diameter results in bigger spot size for a given focusing scheme
Material factors	
Nature of Material	Ablation threshold of metals is generally higher compared to polymers and hence require higher fluence
Thermal characteristics	Thermal conductivity and diffusivity determine the crater or ablated spot size on the material
Optical property	Better absorption by the material reduces the ablation threshold
Environmental factors	
Atmosphere	Ambient, inert or vacuum atmospheres can be used depending on the reactivity of the material

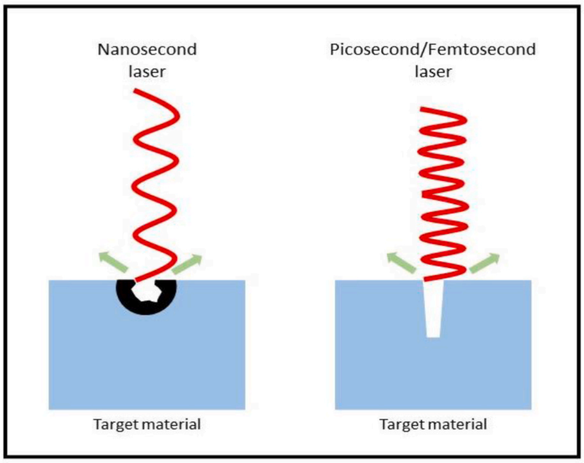

Fig. 4. Heat affected zone (in black) created by nano and pico or femtosecond laser [32].

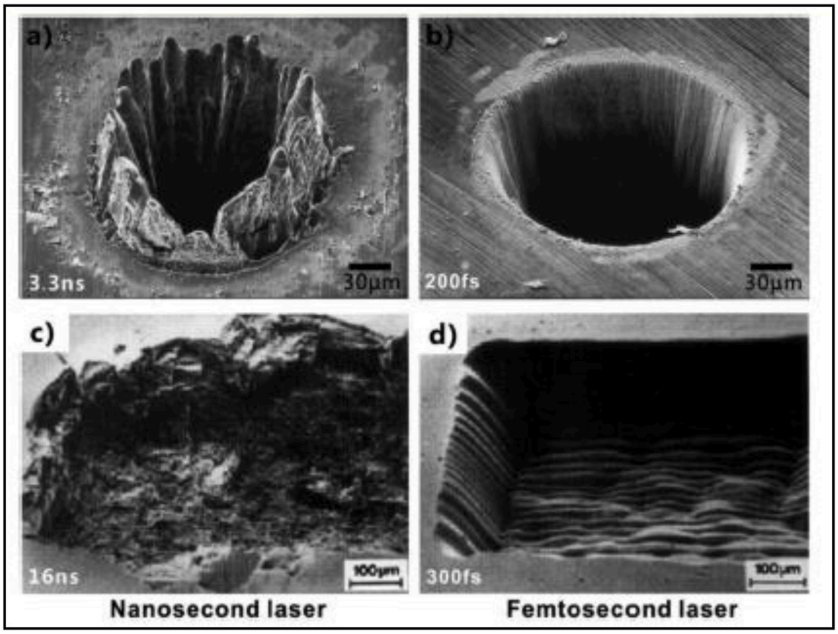

Fig. 5. SEM image of the substrates after nanosecond and femtosecond laser ablation respectively. Reproduced from Ref. [33] with permission from the Royal Society of Chemistry.

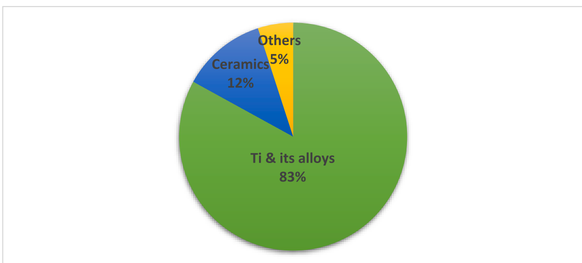

Fig. 6. Different types of implants materials used for surface modification using lasers based upon the studies included in our review [[43]–[145]].

Table 3
Important studies on laser modification of Ti/Ti alloy implant materials.

Author, Year	Type of study	Type of Laser Used	Observations
Radnai et al., 2002 [54]	*In vitro*	ArF nanosecond excimer laser	Cleaner surface with a thicker oxide layer formed which promoted osseointegration
Hallgren C et al., 2003 [55]	*In vivo*	Nd:YAG laser	More bone-to-implant contact and peak removal torque
Braga et al., 2007 [56]	*In vitro*	Nd:YVO_4 laser (Neodymium-doped yttrium orthovanadate)	Variation in the repetition rate, pulse energy, scanning speed and fluency could be used to control the formation of oxides and other compounds on the surface of Ti dental implants
Marticorena M et al., 2007 [57]	*In vivo*	Nd:YAG laser	Better peri-implant reparative process response/bone response to implant
Heinrich A et al., 2008 [58]	*In vitro*	KrF (krypton fluoride) excimer laser	Preferential attachment of fibroblast to the laser created holey structure that is an effective biological barrier against bacteria
Faeda RS et al., 2009 [59]	*In vivo*	Nd: YAG laser	Higher removal torque, faster osseointegration
Mutlu Erdoğan et al., 2011 [60]	*In vitro*	MHz-repetition-rate femtosecond and picosecond Yb-doped fiber lasers	Micron-and nanoscale textures can be created with femtosecond laser whereas only micron scale textures can be created with picosecond laser. Different patterns can be created to facilitate or hinder cell attachment/proliferation as required.
Palmquist A et al., 2011 [61]	*In vivo*	Q-switched Nd:YAG laser	Higher removal torque value and greater bone-implant interface
Cunha A et al., 2013 [62]	*In vitro*	Femtosecond laser	Induced hydrophilic property on implant surface
Baltriukiene D et al., 2014 [63]	*In vitro*	Impulse laser (NL640, Expla, Lithuania)	Greater expression of focal adhesion kinase and surface adhesion of human gingival fibroblasts
Kang SH et al., 2014 [64]	*In vivo*	Nd:YAG laser	Higher removal torques
Chu *S*–F et al., 2016 [65]	*In vitro*	Q-switched DPSS Nd:YVO_4 laser system	Hydrophilic Ti surface with greater adhesion, proliferation, differentiation of MG63 osteoblast-like cells and prostaglandin E production
Gnilitskyi I et al., 2016 [66]	*In vitro*	Femtosecond laser	Periodic nanostructures promoted Fibroblast adhesion and proliferation on the implant surface
Kazutoshi Katahira et al., 2016 [67]	*In vitro*	Yb fiber pulse laser	Improved the biocompatibility oftitanium alloys
Yang F et al., 2017 [68]	*In vivo*	Laser beam melting	Better stress distribution in the surrounding bone tissue, biocompatibility and developed osteoinduction property
Z. Yu et al., 2018 [69]	*In vitro*	Picosecond laser	Correlation between picosecond laser parameters and its corresponding microstructure feature was established. Laser textured surfaces can promote cell adhesion and provide cell contact guidance
Ionescu AC et al., 2018 [70]	*In vitro*	KrF excimer laser, or Nd:YAG laser	Reduction in formation of biofilm
L. Orazi et al., 2019 [71]	*In vitro*	Pico and femtosecond lasers	Improved biocompatibility, increased tissue ingrowth and decreased bacterial adhesion and inflammatory response
Shaikh S et al., 2019 [72]	*In vitro*	Femtosecond Laser	Exhibited antibacterial property
Arifagaoglu et al. O, 2019 [73]	*In vitro*	Laser beam melting	Promoted HGF-1 proliferation
Laura Tiainen et al., 2019 [74]	*In vitro*	Nd:YAG laser	Surface topography obtained using different patterning plans influenced the wetting behavior and the coefficient of friction against bone
Yansheng DUAN et al., 2020 [75]	*In vivo*	Selective laser melting	Better surface characteristics, greater yield strength, higher bone–implant contact rate and removal torque
Gheisarifar, M et al., 2021 [76]	*In vitro*	Ytteria laser	Greater proliferation and guided gingival fibroblast attachment
Eghbali N et al., 2021 [77]	*In vitro*	Pulsed fiber laser	Enhanced adhesion of human osteoblast-like osteosarcoma cells on its surface as well as improved antibacterial properties
M. Filiberto et al., 2021 [78]	*In vivo*	Ytterbium laser active fiber	Enhanced vital bone formation, bone-to-implant contact and Dynamic Osseointegration index
Florian F et al., 2021 [79]	*In vitro*	Yb:YAG laser	Positive interaction of bone cells with surfaces irradiated with laser followed by phosphate deposition
Singh et al., 2021 [80]	*In vitro*	Ytterbium fiber laser	Laser induced microtexturing with different patterns increased the surface roughness, surface energy and base wettability characteristics
Meinshausen A et al., 2021 [81]	*In vitro*	Nd:YAG laser	Aspect ratio of nano/microstructures determines *Staphylococcus aureus* adhesion on; minimal bacterial adhesion was identified for an aspect ratio of about 0·02.
Libin Lu et al., 2022 [82]	*In vitro*	Femtosecond laser	Antibacterial and osteointegration-promoting properties induced by micro/nano surface structures
Du C et al., 2022 [83]	*In vitro*	Femtosecond laser	A laser-induced periodic surface structure (LIPSS) demonstrated reduced bacterial adhesion
Godoy et al., 2023 [84]	*In vitro*	CO_2 laser	Laser treatment altered the surface morphology of the titanium alloy which inhibited candida biofilm formation

some of their drawbacks: i) they may leave behind contaminants on the implant surface, which may adversely affect the biological response at the bone-implant interface; ii) an entire implant fixture is subjected to surface modification with little scope for variations at different parts of the fixture; iii) occupational hazards associated with long term exposure to the materials used in such processes to the personnel involved [43,44]. In a recent study, physicochemical modifications to enhance hydrophilicity of Titanium created a rougher surface that was more susceptible to surface alterations, resulting in more Ti particle release into the bone bed during surgical insertion. The higher Ti intensities detected in the cervical region of bone beds could lead to *peri*-implantitis and marginal bone resorption [45]. In this context, lasers offer a contaminant-free alternative to produce a cleaner surface. Lasers can be used to create different textures on specific parts of the implant surface to modify the cell response and no other techniques can provide such spatial selectivity [46], For these reasons, lasers have been increasingly used for surface modification of dental implants in the recent past, especially Ti and its alloys [47,48]. (Fig. 6).

3.2.1. Ti and Ti alloy implant materials

Ever since the discovery of suitability of Titanium as an implant material by Per-Ingvar Brånemark, its use as medical and dental implant material increased significantly. Titanium is a transition element with an atomic number of 22 and atomic weight of 47.86. It exhibits a silver metallic color and exists in alpha phase with hexagonal close-packed (HCP) lattice structure below 882 °C and as a beta phase with body-centered cubic (BCC) lattice structure above 882 °C [50]. It exhibits a high strength to weight ratio, less density, low modulus of elasticity, superior surface oxide produced by passivation that makes it highly resistant to corrosion, and excellent biocompatibility [51]. With the longest clinically proven record of being a successful implant, most commercial dental implants available today are made of Titanium or its alloys [52].

Despite their excellent clinical success, research in the area of surface modification of these materials to further enhance the tissue response to achieve more predictable osseointegration is intense. In this regard, several studies have been conducted to evaluate the effect of laser patterning on the adhesion, growth, and proliferation of cells, wettability, surface hardness, mechanical properties, surface roughness, antibacterial properties and formation of biofilm [53]. A summary of these studies and their significant observations are presented in Table 3.

Several studies have reported increase in surface roughness of titanium and its alloys using varying laser parameters [69,74]. In general, slower scanning speed and increased frequency produces greater overlapping of laser pulses in an area which result in deeper grooves causing higher surface roughness [85]. Increased surface roughness provides greater contact area between bone and implant and may thus favor adhesion and proliferation of bone forming cells, leading to better osseointegration. An optimal roughness ranging between 1 and 2 μm for the Ra parameter has been reported by Lecka et al., 2019 [86].

Treatment of titanium alloys with Nd:YAG laser at higher frequency demonstrated increased surface roughness with better cell viability and spreading of osteoblast-like cells [87]. Laser irradiation of titanium surfaces with either a CO_2 or an Er,Cr:YSGG laser was suggested to promote osteoblastic attachment [88]. Controlled surface texturing of Ti surfaces using fiber lasers created microstructures with 10–20 μm size features using picosecond pulses whereas femtosecond pulses created similar microstructure as well as surface roughness in 50–100 nm range. Initial cell attachment to these laser textured surfaces was shown to be equivalent to surfaces treated with non-laser techniques [89]. Erdoğan et al., 2011 reported that picosecond and femtosecond lasers could be used to create distinct surface patterns to promote or hinder attachment of cells [60]. Femtosecond laser produced nanoscopic surface roughness at low fluences and micron-scale surface texture at high fluences whereas only micron-scale surface textures was possible with picosecond laser (Fig. 7). Surface modification of Ti6Al4V alloy using femtosecond laser-induced periodic surface structure (LIPSS) was reported to improve the cell adhesion and proliferation of Human Dermal Fibroblasts (HDFa) [66].

Laser treated titanium implant surfaces demonstrated higher adhesion of human gingival fibroblasts and higher focal adhesion kinase values than polished and sandblasted Titanium [63]. Similar findings were reported by Gheisarifar, M et al., 2021, where laser treated and PEEK surfaces exhibited more proliferation and guided gingival fibroblast attachment compared to machined titanium [76].

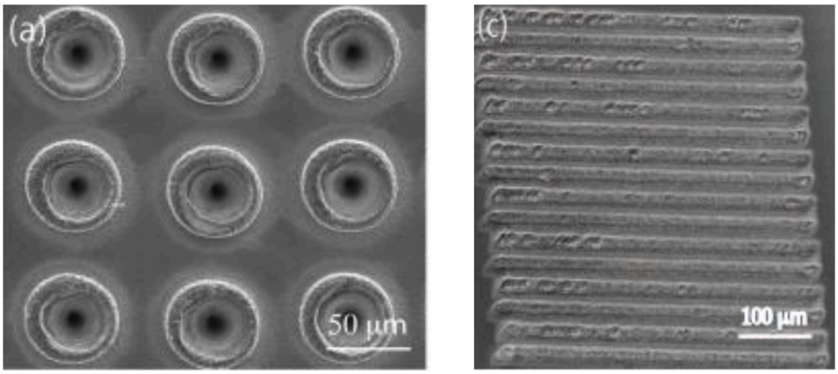

Fig. 7. Scanning electron microscopic images of titanium surface modified with picosecond laser and femtosecond lasers. Reprinted with permission from Ref. [60] © The Optical Society.

Several studies have reported formation of oxides on the laser treated titanium surfaces [67,90]. Presence of these oxide films on the surface of implant materials have been shown to have a positive influence on osseointegration as they facilitate adsorption of blood plasma proteins which are involved in osseointegration [91].

Titanium implants subjected to surface ablation with pulsed argon fluoride (ArF) nanosecond excimer laser exhibited better osseointegration due to thicker surface oxide layer [54]. Neodymium doped yttrium orthovanadate ($Nd:YVO_4$) laser irradiation with varying laser parameters on the formation of oxides and other compounds on the surface of Ti dental implants has been investigated. It was observed that for the same pulse energy and repetition rate, a decrease in the scanning speed was associated with higher surface roughness whereas fluency together with the scanning speed was reported to influence the resulting phase distribution. For the same fluency, scanning speed was found to be inversely related to the formation of Titanium with higher oxidation states [56].

Comparative analysis of polished and laser dimpled titanium (Ti) surfaces revealed that epithelial cells and fibroblasts around the laser dimples appeared larger and showed increased expression of adhesion proteins. Moreover, greater adhesion of epithelial cells on Ti surfaces with 5 μm laser dimples was reported compared to polished Ti surfaces. In contrast, adhesion of fibroblasts to polished and laser-treated implant surfaces showed no significant difference [92].

Laser modified micro-/nanoporous titanium surfaces with hydrophilic properties exhibited greater adhesion, proliferation, differentiation of MG63 osteoblast-like cells, and prostaglandin E production compared to polished surfaces and SLA surfaces [65]. Surface treatment of titanium implants using femtosecond laser in simulated body fluids showed a unique surface texture that facilitated deposition of calcium and phosphate along with enhanced osteoblast adhesion [93]. However, no difference was reported in the adhesion and proliferation of MG63 osteoblast-like cells between SLA treated titanium disks and those irradiated with a Nd:YAG or krypton fluoride (KrF) excimer laser [94]. KrF excimer laser was used to create a holey structure on the polished area of titanium implant surface. Preferential attachment of fibroblasts to the laser induced structure resulted in the formation of bridges inside, covering the hole completely, indicating that laser-treated surfaces can form an effective biological barrier against bacteria [58]. Laser peening of titanium significantly changed its surface nanoarchitecture and improved the adhesion, differentiation of osteoblast cells and fracture strength of titanium-bone cement interface [95].

Anti-microbial potential of laser treated titanium has also been investigated [71,81,96–99]. Femtosecond laser treated Ti6Al4V alloy exhibited antibacterial property, wherein the adhesion and growth of both gram positive (*Staphylococcus aureus* and *Streptococcus mutans*) and gram negative (*Pseudomonas aeruginosa*) bacteria was found to be inhibited [72]. Similarly, a laser-induced periodic surface structure [LIPSS] made with femtosecond laser significantly lowered the bacterial adhesion on the titanium alloy [83]. Antibacterial and osseointegration promoting properties induced by micro/nano surface structures created on titanium alloy using femtosecond laser has also been reported by Libin Lu et al., 2022 [82]. Reduced biofilm formation was reported on laser micro-textured titanium implant surfaces compared to machined and grit-blasted surfaces [70]. Similarly, creation of LIPSS on titanium alloy surface by picosecond laser reduced the biofilm formation by decreasing the number of adhesive bacteria on the material surface [100]. Singh et al., 2021 demonstrated that laser induced microtexturing of titanium alloys, ceramics and polymers with different patterns increase the surface roughness, surface energy and wettability characteristics of the material which in turn affects the microbial adhesion [80]. Laser texturing of titanium alloys using CO_2 lasers under active nitride conditions, altered the surface morphology which reduced the biofilm formation potential of *Candida albicans* [84].

Micro-nano scale surface modification of Ti6Al4V through the modern fiber engraving laser method enhanced the adhesion of human osteoblast-like osteosarcoma cells on its surface as well as improved its antibacterial properties [77]. Based on the result of their study, Porrelli et al., 2021 proposed that a rough surface is optimal for cell adhesion whereas a smooth surface with lower wettability is the best choice to limit bacterial adhesion and biofilm formation on dental implant materials [101].

Recently, suitability of γ-TiAl, which possesses slower corrosion rate in biological media than Ti–6Al–4V, as an implant material has been investigated. Laser surface treatment affected the surface roughness, surface topography, wettability, and chemical composition of the surface. Similarly, Ti–15Mo alloy surface modified by laser-beam irradiation followed by calcium phosphate deposition was shown to positively interact with bone cells, which may improve and accelerate the osseointegration process of dental implants [79].

Laser treatment on cast titanium surfaces showed significant microstructural changes in the material and an improvement in the mechanical properties [102]. Surface peening of titanium alloy using a Q-switched Nd:YAG lasers improved their surface hardness and resistance to wear [103].

Wettability is a crucial surface characteristic feature for dental implants. Good wettability of an implant surface enhances the adhesion, proliferation, and differentiation of cells in the early stages of bone formation. Femtosecond lasers have been reported to successfully modify the surface of Ti6Al4V implants, making them more hydrophilic which reduced the formation of biofilm and bacterial growth [62,104]. On the contrary, higher bacterial adhesion was reported for laser treated surfaces in few studies [105,106]. The laser irradiation of Ti alloy by femtosecond laser pulses at fluence above the ablation threshold resulted in the formation of sharp conical spikes, covered by sub-wavelength laser-induced periodic surface structures. These areas with laser-induced spikes and additional electrochemical oxidation exhibited hydrophilic characteristics and behaved as a cell repelling surface exhibiting reduced fibroblast cell adhesion [107].

The removal torque test, which measures the force required to remove the implant from the bone, is widely used in *in vivo* studies to assess osseointegration. A higher force required to remove the implant is interpreted as superior stability of dental implant in the bone, indicating enhanced osseointegration. Several studies have reported that laser-treated implants possess higher removal torque values compared to machined surfaces [44,108–110]. Creation of nano-scale surface topographical features in laser-modified implants were found to promote a strong and long-term bone anchorage [61,111].

Bone-to-implant contact is another parameter frequently used to measure the extent of osseointegration. A significantly higher bone-to-implant contact and greater torque values were reported in pulsed Nd:YAG laser modified implants than machined implants

[55,57,112].

Vital bone formation, bone-to-implant contact and Dynamic Osseointegration index were reported to be higher in titanium surfaces ablated with ytterbium laser active fiber compared to sandblasted acid-etched surfaces [78]. In contrast, no significant difference was found in the bone-implant interface between Q-switched Nd:YAG laser modified Ti6Al4V alloy and pure Ti or Ti6Al4V surfaces [113].

Clinical performance of implants in which the collar was textured with laser (Laser-Lok (LL)-modified titanium implants) was reported to be better with lesser pocket depth compared to machined collar implants. These results indicate the benefits of using lasers to texture the implant collar to produce an effective mucosal seal vital for the implant's long-term clinical success [114]. Texturing of titanium using pulsed laser technology produced the same range of roughness as grid blasted or acid etched implant but in a more rapid and cost-effective way. The cytocompatibility of laser-treated implant surface was found to be at par with grit blasting/acid-etched implant surface without any difference in the bone-to-implant contact at 8 weeks after the implantation [115]. Laser treated titanium implants demonstrated osteogenic activity and higher removal torque compared to other non-laser treated implants [64,116,117]. Few studies have reported no improvement in removal torque values compared to modified SLA implants [118,119]. However, laser-treated/acid-etched surface was reported to be more uniform and free from any contaminants compared to sandblasted/acid-etched surface [120].

In the quest for obtaining the ideal surface for a dental implant, researchers also explored additional surface texturing of laser treated implants. Implants with laser surface modification associated with hydroxyapatite coating were reported to possess shorter implant healing periods because of increased bone-implant interaction and potentially greater osseointegration compared to a machined and non-hydroxyapatite coated implants [59,121].

Laser Beam Melting 3D printing technique has been used to fabricate porous Ti6Al4V dental implant prototypes with three controlled pore sizes (200, 350, and 500 μm) and 350 μm pore size exhibited less stress shielding as well as superior osteoinduction [68]. Nanostructured Ti6Al7Nb implants fabricated using Selective Laser Melting (SLM) demonstrated better tolerance and osseointegration in rabbits [122]. Similarly, Ti disks treated with SLM exhibited higher proliferation of human gingival fibroblast (HGF-1) cells and enhanced biocompatibility due to favorable alteration of their surface topography, roughness, and wettability [73]. SLM-super finished Ti6Al4V implants were also found to exhibit greater yield strength, higher bone–implant contact, and removal torque compared to SLA and pure titanium implants [75]. Representative scanning electron microscopic pictures of titanium surfaces modified with pico and femtosecond lasers are presented in Fig. 7(a and b).

3.2.2. Other implant materials

Although Titanium and its alloys are frequently used as dental implant materials primarily because of their mechanical properties and biocompatibility, ceramics are gaining popularity in recent times [123]. Compromised esthetics due to metallic color of Titanium, its corrosion and in some cases hypersensitivity reactions can be overcome by replacing them with ceramics such as zirconia, which possess good mechanical properties, better esthetics, and biocompatibility [124]. Conventional methods of sandblasting, though increases the surface area of ceramics, may have deleterious effect on its mechanical characteristics due to the creation of microcracks. Hence, the use of lasers for modification of ceramic surfaces is a better alternative than conventional methods [125–127].

Micro-patterns with regular geometry produced by laser irradiation instead of the random surface roughness enhanced the osseointegration potential of the material [128–130]. Zirconia implants with the modified surface using fiber laser or Nd:YVO_4 laser exhibited higher removal torque values, bone-to-implant contact and peri-implant bone area compared to smooth surface implants. Compared to Nd:YVO_4 laser, fiber laser produced greater surface roughness (1.84 ± 0.690 μm), higher removal torque and bone-to-implant contact suggesting its superiority for surface treatment of zirconia implants [131]. Research has shown that Q-switched Nd:YAG (355 nm) laser at high fluences and low number of pulses can alter the topography of zirconia and improves biological response and mechanical performance [132]. Similarly, Q-switched Nd:YAG laser of 1064 and 532 nm shown to be capable of modifying zirconia surface favorably for enhanced osseointegration. Irradiation with both the wavelengths resulted in crack-free surfaces with greater surface porosity. A linear relationship was also observed between the surface roughness and exposure time [133]. Femtosecond laser was also used to create micro-grooved surface textures on alumina-zirconia nanocomposite to be used for dental implants [134].

A regular and ordered texture created by laser patterning has been shown to promote guided cell growth where the mesenchymal stem cells aligned themselves along the groove direction on the zirconia surface [135]. Several studies have reported enhanced metabolic activity and osteogenic differentiation on ordered surface patterns which may aid in reducing the healing time and accelerate formation of bone [130,136,137].

Along with laser texturing, the surface chemistry of ceramic implants may also influence the osseointegration. Yttrium-stabilized tetragonal zirconia (Y-TZP) implants treated with nanosecond-pulsed laser and implanted into a rat femur showed an increased bone-to-implant contact whereas implants made of zirconia/alumina nanocomposite stabilized with cerium oxide (Ce-TZP/Al_2O_3) showed much lower bone-to-implant contact [138].

Similarly, increased bone-to-implant contact and bone density were reported with laser textured Y-TZP dental implants compared to sandblasted zirconia implants and acid-etched titanium implants [129,139]. More transverse collagen fibers, blood vessels and bone cells were observed on the surface as well as inside the microgrooves.

Laser texturing of abutment surfaces have shown to produce better soft tissue attachment to their surfaces. Madeira et al., 2020, reported higher bond strength between artificial soft tissue and laser textured Y-TZP surfaces [140].

Carvalho et al., 2016 modified zirconia substrate by a novel technique, wherein CO_2 laser was first used to create cavity on the surface, after which hydroxyapatite was sintered to it using laser demonstrating that this technique can be used to produce different patterning and also to sinter different materials over the surface and cavities (selective laser sintering/melting). The adhesion and degradation of hydroxyapatite were shown to be affected by cavities, roughness, and laser power used [141]. Laser surface modification of porcelain implants modified by bioglass using Nd:YAG and Er:YAG laser has been reported to exhibit accelerated hydroxyapatite formation, enhancing their bioactivity [142]. A direct laser melting technique was used to fabricate β-tricalcium phosphate (β-TCP) coated zirconia implants by applying a long-pulsed Nd:YAG laser of 1064 nm, thereby demonstrating that laser processes can be used to build a coat with optimum bonding and desirable mechanical properties [143]. Creation of a biologically active surface by deposition of fluorinated hydroxyapatite on zirconia implant by pulsed laser was reported by Min Li et al., 2022 [144]. Similarly, a laser-assisted biomimetic process was used for coating Calcium phosphate (CaP) on the surface of poly(ether ketone) which made the surface osteoconductive and improved its cytocompatibility [145]. Surface treatment with Nd:YAG laser was used to modify stainless steel implants to increase their surface roughness without any significant change in the bone-implant contact area [49].

From the foregoing discussions we can conclude that the osseointegration of dental implants is largely affected by its surface characteristic features and any modifications in the surface architecture can alter the osseointegration potential. Surface characteristic features of dental implants such as surface texture, roughness, wettability and adhesion characteristics have been altered conventionally by sand blasting or acid etching techniques. However, the use of lasers for altering the surface features is increasingly gaining attention as lasers can create a wide variety of controlled surface features without significant effect on the bulk properties of the materials. By varying laser parameters such as power, speed of translation stage, vertical spacing and other parameters, dental implant surfaces with varying surface parameters can be created. In general, the use of lasers for modifying the surface features of titanium implants resulted in surfaces with higher oxide content, superior roughness, better wettability and cell adhesion. In addition, variations in laser patterning parameters resulted in variations in the bacterial adhesion to the implant surfaces thus facilitating the development of microbial resistant surfaces. Similar observations were also noted with the surface modification of ceramic based dental implants.

3.3. Application of lasers for the surface modification of various dental restorative materials

Resin cements are commonly used for cementation of ceramic restorations [146]. The pre-cementation process of a ceramic restoration involves treating the restoration's inner surface with procedures like grit blasting or hydrofluoric acid etching followed by silane coating. The primary purpose of these treatments is to increase the surface roughness to promote better mechanical bond at the ceramic-cement interface. These conventional methods are reported to cause loss of significant material, create microscopic flaws, cracks, or induce stresses in the material, which may catastrophically affect the restoration's service life. Several researchers have explored the suitability of lasers for surface modification of the inner surface of ceramic restorations to produce surface roughness capable of promoting bonding with the cement [147].

Feldspathic ceramics irradiated with Er:YAG or Nd:YAG laser showed higher bond strength to the tooth [148]. Similarly, CO_2 laser irradiation has been suggested as an effective alternative for hydrofluoric acid etching of feldspathic ceramics for better bond strength [149]. No significant difference in bond strength was found between acid etched and Er:YAG and Nd:YAG laser-treated pressable lithia based glass-ceramics [150]. Similar shear bond strengths for acid etched and Er:YAG laser etched pressable lithia based all-ceramics suggest that laser etching can be used as an alternative for hydrofluoric acid etching [151]. Er,Cr:YSGG laser system was shown to produce greater surface roughness in a pressable lithia-based glass-ceramic than untreated or acid etched and sand blasted surface [152,153]. Laser ablation of Feldspathic and pressable IPS Empress e-Max ceramics with Femtosecond laser was found to be effective in increasing the bond strength with resin cement [154]. Nd:YAG laser irradiation was shown to be an effective surface treatment for bonding between glass infiltrated Zirconia and resin cement [155]. The surface roughness of machinable zirconia ceramics increased by Nd:YAG, CO_2 and Er,Cr:YSGG CO_2 laser treatments, thus increasing their bonding ability to resin cement [156–159]. Use of CO_2 and Er:YAG laser irradiation alone or Nd:YAG laser irradiation after air abrasion has been suggested as an alternative method to increase the bond strength between resin cement and machinable yttrium stabilized tetragonal polycrystalline zirconia (Y-TZP) [160]. Femtosecond laser produced significantly higher roughness on machinable zirconia and was suggested to be an effective method for enhancing its bonding with resin cement [161]. Nd:YAG, CO_2 and Er,Cr:YSGG laser irradiation may be considered for the surface treatment of dental ceramics as an alternative to sand blasting and hydrofluoric acid etching, especially with ceramics that are less amenable for etching by hydrofluoric acid and to reduce the incidence of microcracks and their deleterious effect on the service life of the restoration. Apart from dental implant materials and ceramic restorations, laser mediated surface modification has been investigated in few other areas of dentistry. Few studies have reported application of laser for surface modification to achieve better bonding between metal core and porcelain veneer in metal-fused to-porcelain restorations. Researchers have explored the utility of lasers for roughening the substructures for improving their bond strength to porcelain veneers [162,163]. Nd:YAG laser treatment of titanium and zirconium oxide substructures was reported to enhance the shear bond strength with porcelain more successfully compared to Er:YAG and holmium doped yttrium-aluminum-garnet (Ho:YAG) lasers [164] Pretreatment of zirconia ceramic via Nd:YAG laser improved the bond strength of the resin cement to the zirconia ceramic; however no improvement was seen with glass ionomer cement [165]. Nd:YAG laser irradiation was found to increase the shear bond strength of Ni–Cr alloy to porcelain compared to sandblasting [166]. Surface treatment via CO_2 laser enhanced primary bond strength between resin cement and zirconia ceramic [167]. Similarly, use of ultra-short pulse laser altered surface morphology, increased wettability and bond strength of zirconia with resin cement [168]. However, no improvement in bond strength of zirconia crown irradiated with nanosecond pulsed fibre laser with resin cement, was reported by Fornaini et al., 2021 [169]. Irradiation with an Er:YAG laser increased the surface roughness but decreased the flexural strength of dental zirconia [170].

As an alternative for acid etching with phosphoric acid during placement of composite restorations, lasers have also been tried for enamel etching. However, shear bond strength of composite resin bonded to enamel pretreated with an acid etchant was found to be higher than enamel etched with Er, Cr:YSGG laser [171]. More recently, Er:YAG and CO_2 laser treatments have been tried with some success to increase the shear bond strength of poly(ether ketone) to composite resin veneers [172]. A summary of significant studies on the application of lasers for the surface modification of various dental restorative materials and their observations are presented in Table 4.

Based on the foregoing discussions, it can be concluded that short and ultrashort pulsed lasers, such as nano-, pico-and femtosecond lasers are utilized for laser surface texturing for improving the bond strength between zirconia ceramics and resin cement.

The laser textured surfaces seem to have better bond durability compared to other common surface treatment methods.

4. Conclusion and future directions

Dentistry is a constantly evolving field with a never-ending quest for newer and improved materials and innovative technologies to offer superior treatment options. Lasers offer promising opportunities and possibilities towards realizing this goal. Application of lasers for modifying the surface topography of biomaterials and thereby tuning their biological and other surface properties is being widely explored. Based on the review of articles included in our study, following conclusions can be drawn:

In dentistry, several types of lasers with varying laser parameters have been used to modify surfaces of implant materials specially titanium based materials. *In vitro* and *in vivo* studies strongly suggest using lasers for surface modification as it accords more precision and control over the patterning/texturing process than conventional methods and can yield better results in terms of osseointegration, stability and mechanical performance of the dental implants. Laser texturing is presently emerging as an effective technique to reduce microbial adhesion on implant surfaces to prevent peri-implantitis. As was observed with titanium based implant materials, surface modification of ceramic based implant materials using lasers was also investigated. However, additional research in this area is required to ascertain the suitability of lasers for the surface modification of ceramic based implant materials.

As the research thrust in optimizing laser parameters for the surface patterning of dental biomaterials continue, it is expected that more supporting evidence, as well as techniques or both, may become available in the near future that would make it possible to predict the interaction between the materials or between the material and biological systems more accurately.

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Data availability statement

Data included in article/supplementary material/referenced in article.

Table 4
Important studies on application of lasers for the surface modification of various dental restorative materials.

Author, Year	Material	Laser	Observations
S. Da Silva Ferreira et al., 2010 [148]	Feldspathic porcelain	Er:YAG or Nd:YAG laser	Good bond strength with tooth
F. Ahrari et al., 2013 [149]	Feldspathic porcelain	CO_2 laser	Better bond strength of ceramic with resin cement
B. Gökçe et al., 2007 [151]	Pressable lithia-based ceramic	Er:YAG laser	Same bond strength as acid etched
E.A. Erdur et al., 2015 [154]	Feldspathic porcelain & Pressable lithia-based ceramic	Femtosecond	Better bond strength with resin cement
A.M. Spohr et al., 2007 [155]	Glass infiltrated Zirconia and resin cement	Nd:YAG laser	Improved bonding between glass infiltrated Zirconia and resin cement
G. Ergun Kunt, I. Duran, 2018 [158]	Machinable zirconia ceramics	CO_2 laser	Increased surface roughness and improved bonding with resin cement
J. Saade, 2019 [159]	Zirconia	Er,Cr:YSGG	Use of laser enhanced the surface roughness and the zirconia-resin bonding
A. Goze Saygin et al., 2017 [164]	Titanium and zirconium oxide substructures	Nd:YAG Er:YAG Ho:YAG	Nd:YAG laser treated substructures showed better bond strength with porcelain compared to Er:YAG and Ho:YAG lasers
N. Asadzadeh et al., 2019 [165]	Zirconia	Nd:YAG	Better bond strength of pre- treated zirconia with resin cement
M. Abu Ruja, 2019 [168]	Zirconia	Ultra-short pulse laser	Altered surface morphology, increased wettability and bond strength of zirconia with resin cement
C. Fornaini et al., 2021 [169]	Zirconia	Nanosecond pulsed fiber laser	Improvedsurface roughnessand minimal thermal damage, no improvement in bond strength with resin cement
B.T.F. Silva et al., 2021 [170]	Zirconia	Er:YAG	Increased the surface roughness but lowered the flexural strength of zirconia

Declaration of competing interest

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.

Acknowledgment

The authors are thankful to the Department of Atomic Energy (DAE), Board of Research in Nuclear Sciences (BRNS), and Government of India for the financial support through the research grant with Ref. No. 34/14/04/2014-BRNS. Runki Saran also acknowledge the support of Manipal Academy of Higher Education, Manipal, India for the seed money grant (Ref. ID 00000208).

References

[1] R. Wadhwani, Lasers in dentistry-An introduction to new technology, Int. Dent. SA. 9 (n.d.) 6–20.
[2] T.H. Maiman, Stimulated optical radiation in Ruby, Nature 187 (1960) 493–494, https://doi.org/10.1038/187493a0.
[3] L. Goldman, J.M. Igelman, D.F. Richfield, Impact of the laser on nevi and melanomas, Arch. Dermatol. 90 (1964) 71–75, https://doi.org/10.1001/archderm.1964.01600010077016.
[4] L. Goldman, J.A. Gray, J. Goldman, B. Goldman, R. Meyer, Effect of laser beam impacts on teeth, J. Am. Dent. Assoc. 70 (1965) 601–606, https://doi.org/10.14219/jada.archive.1965.0260.
[5] R.H. Stern, R.F. Sognnaes, Laser effect on dental hard tissues. A preliminary report, J. South Calif. Dent. Assoc. 33 (1965) 17–19.
[6] J.C. Adrian, J.L. Bernier, W.G. Sprague, Laser and the dental pulp, J. Am. Dent. Assoc. 83 (1971) 113–117, https://doi.org/10.14219/jada.archive.1971.0267.
[7] T.D. Myers, W.D. Myers, R.M. Stone, First soft tissue study utilizing a pulsed Nd:YAG dental laser, NW. Dent. 68 (1989) 14–17.
[8] S. Parker, Verifiable CPD paper: introduction, history of lasers and laser light production, Br. Dent. J. 202 (2007) 21–31, https://doi.org/10.1038/bdj.2006.113.
[9] A. Spaveras, A. Tsakanikou, F. Karkazi, M. Antoniadou, Caries detection with laser fluorescence devices, Limitations of their use, Stomatol. Edc. J. 4 (2017) 44–52, https://doi.org/10.25241/stomaeduj.2017.4(1).4.
[10] M. Tassoker, S. Ozcan, S. Karabekiroglu, Occlusal caries detection and diagnosis using visual ICDAS criteria, laser fluorescence measurements, and near-infrared light transillumination images, Med. Princ. Pract. 29 (2020) 25–31, https://doi.org/10.1159/000501257.
[11] T. Gurbuz, Y. Yilmaz, F. Sengul, Performance of laser fluorescence for residual caries detection in primary teeth, Eur. J. Dermatol. 2 (2008) 176–184.
[12] K. Glockner, J. Rumpler, K. Ebeleseder, P. Städtler, Intrapulpal temperature during preparation with the Er:YAG laser compared to the conventional burr: an in vitro study, J. Clin. Laser Med. Surg. 16 (1998) 153–157, https://doi.org/10.1089/clm.1998.16.153.
[13] N.P. Louw, C.H. Pameijer, W.D. Ackermann, T. Ertl, H.J. Cappius, G. Norval, Pulp histology after Er:YAG laser cavity preparation in subhuman primates–a pilot study, SADJ 57 (2002) 313–317.
[14] M.S. Castilho, A.E. De Souza-Gabriel, M.A. Marchesan, L.J. Floriam, M.D. Sousa-Neto, Y.T.C. Silva-Sousa, Temperature changes in the deciduous pulp chamber during cavity preparation with the Er:YAG laser, J. Dent. Child. 74 (2007) 21–25.
[15] S. Nammour, K. Kowaly, G.L. Powell, J. Van Reck, J.P. Rocca, External temperature during KTP-Nd:YAG laser irradiation in root canals: an in vitro study, Laser Med. Sci. 19 (2004) 27–32, https://doi.org/10.1007/s10103-004-0303-0.
[16] A. Stabholz, R. Zeltser, M. Sela, B. Peretz, J. Moshonov, D. Ziskind, A. Stabholz, The use of lasers in dentistry: principles of operation and clinical applications, Comp. Cont. Educ. Dent. 24 (2003) 811–824.
[17] Y. Kimura, P. Wilder-Smith, K. Matsumoto, Lasers in endodontics: a review, Int. Endod. J. 33 (2000) 173–185, https://doi.org/10.1046/j.1365-2591.2000.00280.x.
[18] L. Rapp, S. Madden, J. Brand, L.J. Walsh, H. Spallek, O. Zuaiter, A. Habeb, T.R. Hirst, A.V. Rode, Femtosecond laser dentistry for precise and efficient cavity preparation in teeth, Biomed. Opt Express 13 (2022) 4559, https://doi.org/10.1364/BOE.463756.
[19] S. Vaddamanu, R. Vyas, K. Kavita, R. Sushma, A. Aboobacker, A. Dixit, A. Kumar, In vitro evaluation of laser vs. handpiece for tooth preparation, J. Pharm. BioAllied Sci. 14 (2022) 526, https://doi.org/10.4103/jpbs.jpbs_95_22.
[20] W. Buchalla, T. Attin, External bleaching therapy with activation by heat, light or laser—a systematic review, Dent. Mater. 23 (2007) 586–596, https://doi.org/10.1016/j.dental.2006.03.018.
[21] R.J.G. De Moor, J. Verheyen, P. Verheyen, A. Diachuk, M.A. Meire, P.J. De Coster, M. De Bruyne, F. Keulemans, Laser teeth bleaching: evaluation of eventual side effects on enamel and the pulp and the efficiency in vitro and in vivo, Sci. World J. 2015 (2015) 1–12, https://doi.org/10.1155/2015/835405.
[22] A. Strobl, N. Gutknecht, R. Franzen, R.-D. Hilgers, F. Lampert, J. Meister, Laser-assisted in-office bleaching using a neodymium:yttrium–aluminum–garnet laser: an in vivo study, Laser Med. Sci. 25 (2010) 503–509, https://doi.org/10.1007/s10103-009-0675-2.
[23] R.M. Pick, M.D. Colvard, Current status of lasers in soft tissue dental surgery, J. Periodontol. 64 (1993) 589–602, https://doi.org/10.1902/jop.1993.64.7.589.
[24] J.M. White, S.I. Chaudhry, J.J. Kudler, N. Sekandari, M.L. Schoelch, S. Silverman, Nd:YAG and CO 2 laser therapy of oral mucosal lesions, J. Clin. Laser Med. Surg. 16 (1998) 299–304, https://doi.org/10.1089/clm.1998.16.299.
[25] L. Walsh, The current status of laser applications in dentistry, Aust. Dent. J. 48 (2003) 146–155, https://doi.org/10.1111/j.1834-7819.2003.tb00025.x.
[26] I. Murias, K. Grzech-Leśniak, A. Murias, K. Walicka-Cupryś, M. Dominiak, J. Golob Deeb, J. Matys, Efficacy of various laser wavelengths in the surgical treatment of ankyloglossia: a systematic review, Life 12 (2022) 558, https://doi.org/10.3390/life12040558.
[27] V. Hiranmayi, R. Shyamala, Dental biomaterials- A boon to dentistry, Acta. Sci. Dent. Sci. 4 (2020) 1, https://doi.org/10.31080/ASDS.2019.03.0580.
[28] M. Martínez-Calderon, M. Manso-Silván, A. Rodríguez, M. Gómez-Aranzadi, J.P. García-Ruiz, S.M. Olaizola, R.J. Martín-Palma, Surface micro- and nano-texturing of stainless steel by femtosecond laser for the control of cell migration, Sci. Rep. 6 (2016), 36296, https://doi.org/10.1038/srep36296.
[29] A. Riveiro, A.L.B. Maçon, J. del Val, R. Comesaña, J. Pou, Laser surface texturing of polymers for biomedical applications, Front. Physiol. 6 (2018) 16, https://doi.org/10.3389/fphy.2018.00016.
[30] M.D. Perry, B.C. Stuart, P.S. Banks, M.D. Feit, V. Yanovsky, A.M. Rubenchik, Ultrashort-pulse laser machining of dielectric materials, J. Appl. Phys. 85 (1999) 6803–6810, https://doi.org/10.1063/1.370197.
[31] E. Ukar, A. Lamikiz, S. Martínez, I. Arrizubieta, Laser texturing with conventional fiber laser, in: Procedia Eng, Elsevier Ltd, 2015, pp. 663–670, https://doi.org/10.1016/j.proeng.2015.12.545.
[32] Industial Laser Solutions, Femtosecond Laser Micromachining: A Back-To-Basics Primer - Industrial Laser Solutions, Laser Micromachining, 2012. https://www.industrial-lasers.com/cutting/article/16488567/femtosecond-laser-micromachining-a-backtobasics-primer (accessed June 25, 2021).
[33] J. Yong, Q. Yang, C. Guo, F. Chen, X. Hou, A review of femtosecond laser-structured superhydrophobic or underwater superoleophobic porous surfaces/materials for efficient oil/water separation, RSC Adv. 9 (2019) 12470–12495, https://doi.org/10.1039/c8ra10673h.
[34] F.S. Tabatabaei, M. Torshabi, M.M. Nasab, K. Khosraviani, A. Khojasteh, Effect of low-level diode laser on proliferation and osteogenic differentiation of dental pulp stem cells, Laser Phys. 25 (2015), 095602, https://doi.org/10.1088/1054-660X/25/9/095602.
[35] T. Laoui, E. Santos, K. Osakada, M. Shiomi, M. Morita, S.K. Shaik, N.K. Tolochko, F. Abe, M. Takahashi, Properties of titanium dental implant models made by laser processing, Proc. Inst. Mech. Eng. C J. Mech. Eng. Sci. 220 (2006) 857–863, https://doi.org/10.1243/09544062JMES133.
[36] R. John, Industrial Applications of Lasers, second ed., Academic Press, 1997.

[37] W. Xue, B.V. Krishna, A. Bandyopadhyay, S. Bose, Processing and biocompatibility evaluation of laser processed porous titanium, Acta Biomater. 3 (2007) 1007–1018, https://doi.org/10.1016/j.actbio.2007.05.009.

[38] A. Hindy, F. Farahmand, F. sadat Tabatabaei, In vitro biological outcome of laser application for modification or processing of titanium dental implants, Laser Med. Sci. 32 (2017) 1197–1206, https://doi.org/10.1007/s10103-017-2217-7.

[39] J.R. Hupp, Introduction to implant dentistry: a student guide, J. Oral Maxillofac. Surg. 75 (2017) 28–41.

[40] D. Siegele, U. Soltesz, Numerical investigations of the influence of implant shape on stress distribution in the jaw bone, Int. J. Oral Maxillofac. Implants 4 (1989) 333–340.

[41] S. Tetè, V. Zizzari, A. De Carlo, B. Sinjari, E. Gherlone, Macroscopic and microscopic evaluation of a new implant design supporting immediately loaded full arch rehabilitation, Ann. Stomatol. 3 (2012) 44–50.

[42] R. Krishna Alla, K. Ginjupalli, N. Upadhya, M. Shammas, R. Krishna Ravi, R. Sekhar, Surface roughness of implants: a review, Trends Biomater. Artif. Organs 25 (2011) 112–118.

[43] J.-T. Lee, S.-A. Cho, Biomechanical evaluation of laser-etched Ti implant surfaces vs. chemically modified SLA Ti implant surfaces: removal torque and resonance frequency analysis in rabbit tibias, J. Mech. Behav. Biomed. Mater. 61 (2016) 299–307, https://doi.org/10.1016/j.jmbbm.2016.03.034.

[44] S.A. Cho, S.K. Jung, A removal torque of the laser-treated titanium implants in rabbit tibia, Biomaterials 24 (2003) 4859–4863, https://doi.org/10.1016/S0142-9612(03)00377-6.

[45] G.A.F. Silva, F. Faot, W.J. da Silva, A.A. Del Bel Cury, Does implant surface hydrophilicity influence the maintenance of surface integrity after insertion into low-density artificial bone? Dent. Mater. 37 (2021) e69–e84, https://doi.org/10.1016/j.dental.2020.10.024.

[46] A. Gaggl, G. Schultes, W.D. Müller, H. Kärcher, Scanning electron microscopical analysis of laser-treated titanium implant surfaces—a comparative study, Biomaterials 21 (2000) 1067–1073, https://doi.org/10.1016/S0142-9612(00)00002-8.

[47] J.C.M. Souza, M.B. Sordi, M. Kanazawa, S. Ravindran, B. Henriques, F.S. Silva, C. Aparicio, L.F. Cooper, Nano-scale modification of titanium implant surfaces to enhance osseointegration, Acta Biomater. 94 (2019) 112–131, https://doi.org/10.1016/j.actbio.2019.05.045.

[48] M. Filiberto, B. Daniele, B. Franco, S. Antonio, P. Adriano, I. Giovanna, Q. Raimondo, Histological and histomorphometric comparison of innovative dental implants laser obtained: animal pilot study, Materials 14 (2021) 1830, https://doi.org/10.3390/ma14081830.

[49] H.K. Kang, T.M. Chu, P. Dechow, K. Stewart, H.M. Kyung, S.S.Y. Liu, Laser-treated stainless steel mini-screw implants: 3D surface roughness, bone-implant contact, and fracture resistance analysis, Eur. J. Orthod. 38 (2016) 154–162, https://doi.org/10.1093/ejo/cjv017.

[50] M. Saini, Y. Singh, P. Arora, V. Arora, K. Jain, S.M. Singh, A.P. Arora, J.K. Implant, Implant biomaterials: a comprehensive review, A Comprehensive Review, World J. Clin. Cases 3 (2015) 52–57, https://doi.org/10.12998/wjcc.v3.i1.52.

[51] J.W. Nicholson, Titanium alloys for dental implants: a review, Prosthesis 2 (2020) 100–116, https://doi.org/10.3390/prosthesis2020011.

[52] M. Özcan, C. Hämmerle, Titanium as a reconstruction and implant material in dentistry: advantages and pitfalls, Materials 5 (2012) 1528–1545, https://doi.org/10.3390/ma5091528.

[53] I.G. Simões, A.C. dos Reis, M.L. da Costa Valente, Analysis of the influence of surface treatment by high-power laser irradiation on the surface properties of titanium dental implants: a systematic review, J. Prosthet. Dent 0 (2021), https://doi.org/10.1016/j.prosdent.2021.07.026.

[54] M. Radnai, T. Kinga, Z. Bor, Á. Fazekas, Surface modification of titanium dental implants by excimer laser, Acta Stomatol. Croat. 36 (2002).

[55] C. Hallgren, An in vivo study of bone response to implants topographically modified by laser micromachining, Biomaterials 24 (2003) 701–710, https://doi.org/10.1016/S0142-9612(02)00266-1.

[56] F.J.C. Braga, R.F.C. Marques, E. de A. Filho, A.C. Guastaldi, Surface modification of Ti dental implants by Nd:YVO 4 laser irradiation, Appl. Surf. Sci. 253 (2007) 9203–9208, https://doi.org/10.1016/j.apsusc.2007.05.048.

[57] M. Marticorena, G. Corti, D. Olmedo, M.B. Guglielmotti, S. Duhalde, Laser surface modification of Ti implants to improve osseointegration, J. Phys. Conf. Ser. 59 (2007) 662–665, https://doi.org/10.1088/1742-6596/59/1/139.

[58] A. Heinrich, K. Dengler, T. Koerner, C. Haczek, H. Deppe, B. Stritzker, Laser-modified titanium implants for improved cell adhesion, Laser Med. Sci. 23 (2008) 55–58, https://doi.org/10.1007/s10103-007-0460-z.

[59] R.S. Faeda, H.S. Tavares, R. Sartori, A.C. Guastaldi, E. Marcantonio, Biological performance of chemical hydroxyapatite coating associated with implant surface modification by laser beam: biomechanical study in rabbit tibias, J. Oral Maxillofac. Surg. 67 (2009) 1706–1715, https://doi.org/10.1016/j.joms.2009.03.046.

[60] M. Erdoğan, B. Öktem, H. Kalaycıoğlu, S. Yavaş, P.K. Mukhopadhyay, K. Eken, K. Özgören, Y. Aykaç, U.H. Tazebay, F.Ö. Ilday, Texturing of titanium (Ti6Al4V) medical implant surfaces with MHz-repetition-rate femtosecond and picosecond Yb-doped fiber lasers, Opt Express 19 (2011), 10986, https://doi.org/10.1364/oe.19.010986.

[61] A. Palmquist, L. Emanuelsson, R. Brånemark, P. Thomsen, Biomechanical, histological and ultrastructural analyses of laser micro- and nano-structured titanium implant after 6 months in rabbit, J. Biomed. Mater. Res. B Appl. Biomater. 97 B (2011) 289–298, https://doi.org/10.1002/jbm.b.31814.

[62] A. Cunha, A.P. Serro, V. Oliveira, A. Almeida, R. Vilar, M.C. Durrieu, Wetting behaviour of femtosecond laser textured Ti-6Al-4V surfaces, Appl. Surf. Sci. 265 (2013) 688–696, https://doi.org/10.1016/j.apsusc.2012.11.085.

[63] D. Baltriukiene, V. Sabaliauskas, E. Balčiunas, A. Melninkaitis, E. Liutkevičius, V. Bukelskiene, V. Rutkunas, The effect of laser-treated titanium surface on human gingival fibroblast behavior, J. Biomed. Mater. Res. 102 (2014) 713–720, https://doi.org/10.1002/jbm.a.34739.

[64] N.S. Kang, L.J. Li, S.A. Cho, Comparison of removal torques between lasertreated and SLA-treated implant surfaces in rabbit tibiae, J. Adv. Prosthodont. 6 (2014) 302–308, https://doi.org/10.4047/jap.2014.6.4.302.

[65] S.-F. Chu, M.-T. Huang, K.-L. Ou, E. Sugiatno, H.-Y. Cheng, Y.-H. Huang, W.-T. Chiu, T.-H. Liou, Enhanced biocompatible and hemocompatible nano/micro porous surface as a biological scaffold for functionalizational and biointegrated implants, J. Alloys Compd. 684 (2016) 726–732, https://doi.org/10.1016/j.jallcom.2016.05.134.

[66] I. Gnilitskyi, M. Pogorielov, D. Dobrota, R. Viter, L. Orazi, O. Mischenko, Cell and tissue response to modified by laser-induced periodic surface structures biocompatible materials for dental implants, 2016 Conference on Lasers and Electro-Optics, Cleo 2016 (2016) 1–2, https://doi.org/10.1364/cleo_at.2016.aw4o.6.

[67] K. Katahira, A. Ezura, K. Ohkawa, J. Komotori, H. Ohmori, Generation of bio-compatible titanium alloy surfaces by laser-induced wet treatment, CIRP Ann.-Manuf. Technol. 65 (2016) 237–240, https://doi.org/10.1016/j.cirp.2016.04.053.

[68] F. Yang, C. Chen, Q. Zhou, Y. Gong, R. Li, C. Li, F. Klämpfl, S. Freund, X. Wu, Y. Sun, X. Li, M. Schmidt, D. Ma, Y. Yu, Laser beam melting 3D printing of Ti6Al4V based porous structured dental implants: fabrication, biocompatibility analysis and photoelastic study, Sci. Rep. 7 (2017) 1–12, https://doi.org/10.1038/srep45360.

[69] Z. Yu, G. Yang, W. Zhang, J. Hu, Investigating the effect of picosecond laser texturing on microstructure and biofunctionalization of titanium alloy, J. Mater. Process. Technol. 255 (2018) 129–136, https://doi.org/10.1016/j.jmatprotec.2017.12.009.

[70] A.C. Ionescu, E. Brambilla, F. Azzola, M. Ottobelli, G. Pellegrini, L.A. Francetti, Laser microtextured titanium implant surfaces reduce in vitro and in situ oral biofilm formation, PLoS One 13 (2018), e0202262, https://doi.org/10.1371/journal.pone.0202262.

[71] L. Orazi, M. Pogorielov, V. Deineka, E. Husak, V. Korniienko, O. Mishchenko, B. Reggiani, Osteoblast cell response to LIPSS-modified Ti-implants, Key Eng. Mater. 813 (2019) 322–327. https://dx.doi.org/10.4028/www.scientific.net/KEM.813.322.

[72] S. Shaikh, S. Kedia, D. Singh, M. Subramanian, S. Sinha, Surface texturing of Ti6Al4V alloy using femtosecond laser for superior antibacterial performance, J. Laser Appl. 31 (2019), 022011, https://doi.org/10.2351/1.5081106.

[73] O. Arifagaoglu, S. Oncul, A. Ercan, O. Olcay, B. Ersu, HGF-1 proliferation on titanium dental implants treated with laser melting technology, Niger. J. Clin. Pract. 22 (2019) 251–257, https://doi.org/10.4103/njcp.njcp_364_18.

[74] L. Tiainen, P. Abreu, M. Buciumeanu, F. Silva, M. Gasik, R. Serna Guerrero, O. Carvalho, Novel laser surface texturing for improved primary stability of titanium implants, J. Mech. Behav. Biomed. Mater. 98 (2019) 26–39, https://doi.org/10.1016/j.jmbbm.2019.04.052.

[75] Y. Duan, X. Liu, S. Zhang, L. Wang, F. Ding, S. Song, X. Chen, B. Deng, Y. Song, Selective laser melted titanium implants play a positive role in early osseointegration in type 2 diabetes mellitus rats, Dent. Mater. J. 39 (2020) 214–221, https://doi.org/10.4012/dmj.2018-419.
[76] M. Gheisarifar, G.A. Thompson, C. Drago, F. Tabatabaei, M. Rasoulianboroujeni, In vitro study of surface alterations to polyetheretherketone and titanium and their effect upon human gingival fibroblasts, J. Prosthet. Dent 125 (2021) 155–164, https://doi.org/10.1016/j.prosdent.2019.12.012.
[77] N. Eghbali, H. Naffakh-Moosavy, S. Sadeghi Mohammadi, H. Naderi-Manesh, The influence of laser frequency and groove distance on cell adhesion, cell viability, and antibacterial characteristics of Ti-6Al-4V dental implants treated by modern fiber engraving laser, Dent. Mater. 37 (2021) 547–558, https://doi.org/10.1016/j.dental.2020.12.007.
[78] M. Filiberto, B. Daniele, B. Franco, S. Antonio, P. Adriano, I. Giovanna, Q. Raimondo, Histological and histomorphometric comparison of innovative dental implants laser obtained: animal pilot study, Materials 14 (2021), https://doi.org/10.3390/ma14081830.
[79] F. Florian, F.P.S. Guastaldi, M.A. Cominotte, L.C. Pires, A.C. Guastaldi, J.A. Cirelli, Behavior of rat bone marrow stem cells on titanium surfaces modified by laser-beam and deposition of calcium phosphate, J. Mater. Sci. Mater. Med. 32 (2021), https://doi.org/10.1007/s10856-021-06528-4.
[80] I. Singh, S.M. George, A. Tiwari, J. Ramkumar, K. Balani, Influence of laser surface texturing on the wettability and antibacterial properties of metallic, ceramic, and polymeric surfaces, J. Mater. Res. 36 (2021) 3985–3999, https://doi.org/10.1557/s43578-021-00273-8.
[81] A.K. Meinshausen, M. Herbster, C. Zwahr, M. Soldera, A. Müller, T. Halle, A.F. Lasagni, J. Bertrand, Aspect ratio of nano/microstructures determines Staphylococcus aureus adhesion on PET and titanium surfaces, J. Appl. Microbiol. 131 (2021) 1498–1514, https://doi.org/10.1111/jam.15033.
[82] L. Lu, J. Zhang, K. Guan, J. Zhou, F. Yuan, Y. Guan, Artificial neural network for cytocompatibility and antibacterial enhancement induced by femtosecond laser micro/nano structures, J. Nanobiotechnol. 20 (2022) 365, https://doi.org/10.1186/s12951-022-01578-4.
[83] C. Du, C. Wang, T. Zhang, L. Zheng, Antibacterial performance of Zr-bmg, stainless steel, and titanium alloy with laser-induced periodic surface structures, ACS Appl. Bio Mater. 5 (2022) 272–284, https://doi.org/10.1021/acsabm.1c01075.
[84] G.G.S.M. Godoy, V.M. de Andrade, F. Dondeo, K. Conceição, A. Capella, Effect of laser thermochemical treatment of Ti–6Al–4V alloy on Candida albicans biofilm growth, Mater. Chem. Phys. 294 (2023), https://doi.org/10.1016/j.matchemphys.2022.127055.
[85] M.H. Tsai, C.F. Haung, S.S. Shyu, Y.R. Chou, M.H. Lin, P.W. Peng, K.L. Ou, C.H. Yu, Surface modification induced phase transformation and structure variation on the rapidly solidified recast layer of titanium, Mater. Char. 106 (2015) 463–469, https://doi.org/10.1016/j.matchar.2015.06.004.
[86] K.M. Łęcka, J. Gąsiorek, A. Mazur-Nowacka, B. Szczygieł, A.J. Antończak, Adhesion and corrosion resistance of laser-oxidized titanium in potential biomedical application, Surf. Coat. Technol. 366 (2019) 179–189, https://doi.org/10.1016/j.surfcoat.2019.03.032.
[87] K. Rafiee, H. Naffakh-Moosavy, E. Tamjid, The effect of laser frequency on roughness, microstructure, cell viability and attachment of Ti6Al4V alloy, Mater. Sci. Eng. C 109 (2020), 110637, https://doi.org/10.1016/j.msec.2020.110637.
[88] G. Romanos, R. Crespi, A. Barone, U. Covani, Osteoblast attachment on titanium disks after laser irradiation, Int. J. Oral Maxillofac. Implants 21 (2006) 232–236.
[89] B. Oktem, H. Kalaycioglu, M. Erdoğan, S. Yavaş, P. Mukhopadhyay, U.H. Tazebay, Y. Aykaç, K. Eken, F.O. Ilday, Surface texturing of dental implant surfaces with an ultrafast fiber laser, Opt. InfoBase Conf. Pap. (2010) 1–2, https://doi.org/10.1364/cleo.2010.jtud15.
[90] S.A.X. Stango, D. Karthick, S. Swaroop, U.K. Mudali, U. Vijayalakshmi, Development of hydroxyapatite coatings on laser textured 316 LSS and Ti-6Al-4V and its electrochemical behavior in SBF solution for orthopedic applications, Ceram. Int. 44 (2018) 3149–3160, https://doi.org/10.1016/j.ceramint.2017.11.083.
[91] S. Allegrini, M. Yoshimoto, M.B. Salles, M.R.F. Allegrini, L.C.Y. Pistarini, F.J.C. Braga, A.H. De Almeida Bressiani, Evaluation of bone tissue reaction in laser beamed implants, Appl. Surf. Sci. 307 (2014) 503–512, https://doi.org/10.1016/j.apsusc.2014.04.065.
[92] D.W. Lee, J.G. Kim, M.K. Kim, S. Ansari, A. Moshaverinia, S.H. Choi, J.J. Ryu, Effect of laser-dimpled titanium surfaces on attachment of epithelial-like cells and fibroblasts, J. Adv. Prosthodont. 7 (2015) 138–145, https://doi.org/10.4047/jap.2015.7.2.138.
[93] C. Liang, H. Wang, J. Yang, Y. Cai, X. Hu, Y. Yang, B. Li, H. Li, H. Li, C. Li, X. Yang, Femtosecond laser-induced micropattern and Ca/P deposition on Ti implant surface and its acceleration on early osseointegration, ACS Appl. Mater. Interfaces 5 (2013) 8179–8186, https://doi.org/10.1021/am402290e.
[94] Á. Györgyey, K. Ungvári, G. Kecskeméti, J. Kopniczky, B. Hopp, A. Oszkó, I. Pelsöczi, Z. Rakonczay, K. Nagy, K. Turzó, Attachment and proliferation of human osteoblast-like cells (MG-63) on laser-ablated titanium implant material, Mater. Sci. Eng. C 33 (2013) 4251–4259, https://doi.org/10.1016/j.msec.2013.06.020.
[95] M. Khandaker, S. Riahinezhad, F. Sultana, M.B. Vaughan, J. Knight, T.L. Morris, Peen treatment on a titanium implant: effect of roughness, osteoblast cell functions, and bonding with bone cement, Int. J. Nanomed. 11 (2016) 585–595, https://doi.org/10.2147/IJN.S89376.
[96] C. Zwahr, R. Helbig, C. Werner, A.F. Lasagni, Fabrication of multifunctional titanium surfaces by producing hierarchical surface patterns using laser based ablation methods, Sci. Rep. 9 (2019) 6721, https://doi.org/10.1038/s41598-019-43055-3.
[97] M. Koopaie, A. Kia Darbandsari, N. Hakimiha, S. Kolahdooz, Cr Er, YSGG laser surface treatment of gamma titanium aluminide: scanning electron microscopy–energy-dispersive X-ray spectrometer analysis, wettability and Eikenella corrodens and Aggregatibacter actinomycetemcomitans bacteria count—in vitro study, Proc. Inst. Mech. Eng. H 234 (2020) 769–783, https://doi.org/10.1177/0954411920924517.
[98] K. Yang, J. Shi, L. Wang, Y. Chen, C. Liang, L. Yang, L.-N. Wang, Bacterial anti-adhesion surface design: surface patterning, roughness and wettability: a review, J. Mater. Sci. Technol. 99 (2022) 82–100, https://doi.org/10.1016/j.jmst.2021.05.028.
[99] I.G. Simões, A.C. dos Reis, M.L. da C. Valente, Influence of surface treatment by laser irradiation on bacterial adhesion on surfaces of titanium implants and their alloys: systematic review, Saudi Dent. J. (2023) 111–124, https://doi.org/10.1016/j.sdentj.2023.01.004.
[100] E. Uhlmann, L. Schweitzer, H. Kieburg, A. Spielvogel, K. Huth-Herms, The effects of laser microtexturing of biomedical grade 5 Ti-6Al-4V dental implants (abutment) on biofilm formation, in: Procedia CIRP, Elsevier B.V., 2018, pp. 184–189, https://doi.org/10.1016/j.procir.2017.12.044.
[101] D. Porrelli, M. Mardirossian, N. Crapisi, M. Urban, N.A. Ulian, L. Bevilacqua, G. Turco, M. Maglione, Polyetheretherketone and titanium surface treatments to modify roughness and wettability – improvement of bioactivity and antibacterial properties, J. Mater. Sci. Technol. 95 (2021) 213–224, https://doi.org/10.1016/j.jmst.2021.04.023.
[102] A. Poulon-Quintin, I. Watanabe, E. Watanabe, C. Bertrand, Microstructure and mechanical properties of surface treated cast titanium with Nd:YAG laser, Dent. Mater. 28 (2012) 945–951, https://doi.org/10.1016/j.dental.2012.04.008.
[103] J. Zhou, Y. Sun, S. Huang, J. Sheng, J. Li, E. Agyenim-Boateng, Effect of laser peening on friction and wear behavior of medical Ti6Al4V alloy, Opt Laser. Technol. 109 (2019) 263–269, https://doi.org/10.1016/j.optlastec.2018.08.005.
[104] V.P. Shiju, N. V Abhijith, U. Sudeep, Experimental study on the influence of hydrophilicity on bacterial adhesion in bioimplants, J. Phys. Conf. Ser. 1355 (2019), 012028, https://doi.org/10.1088/1742-6596/1355/1/012028.
[105] F.P.S. Guastaldi, C.C. de Foggi, L.C.L. Santana, L.G. Vaz, C.E. Vergani, A.C. Guastaldi, Lower susceptibility of laser-irradiated Ti-15Mo surface to methicillin-resistant Staphylococcus aureus cells adhesion, Mater. Res. 22 (2019), https://doi.org/10.1590/1980-5373-mr-2019-0012.
[106] R.C. Costa, B.E. Nagay, M. Bertolini, B.E. Costa-Oliveira, A.A. Sampaio, B. Retamal-Valdes, J.A. Shibli, M. Feres, V.A.R. Barão, J.G.S. Souza, Fitting pieces into the puzzle: the impact of titanium-based dental implant surface modifications on bacterial accumulation and polymicrobial infections, Adv. Colloid Interface Sci. 298 (2021), 102551, https://doi.org/10.1016/j.cis.2021.102551.
[107] J. Heitz, C. Plamadeala, M. Muck, O. Armbruster, W. Baumgartner, A. Weth, C. Steinwender, H. Blessberger, J. Kellermair, S.V. Kirner, J. Krüger, J. Bonse, A. S. Guntner, A.W. Hassel, Femtosecond laser-induced microstructures on Ti substrates for reduced cell adhesion, Appl. Phys. Mater. Sci. Process 123 (2017), https://doi.org/10.1007/s00339-017-1352-0.
[108] R.S. Faeda, H.S. Tavares, R. Sartori, A.C. Guastaldi, E. Marcantonio, Evaluation of titanium implants with surface modification by laser beam. Biomechanical study in rabbit tibias, Braz. Oral Res. 23 (2009) 137–143, https://doi.org/10.1590/S1806-83242009000200008.
[109] N. Jamal, M.S. Al_Rawi, B.D.S. Msc, B.M.A. Hussein, N.M. Hadi, B.S. Phys, Biomechanical effect of Nd.YAG laser ablation on commercially pure titanium dental implant (in vivo study), Int. J. Sci. Res. 6 (2015) 2319–7064, https://doi.org/10.21275/ART2017977.
[110] P. Trisi, M. Berardini, M. Colagiovanni, D. Berardi, G. Perfetti, Laser-treated titanium implants: an in vivo histomorphometric and biomechanical analysis, Implant Dent. 25 (2016) 575–580, https://doi.org/10.1097/ID.0000000000000457.

[111] A. Palmquist, F. Lindberg, L. Emanuelsson, R. Brånemark, H. Engqvist, P. Thomsen, Biomechanical, histological, and ultrastructural analyses of laser micro- and nano-structured titanium alloy implants: a study in rabbit, J. Biomed. Mater. Res. 92 (2010) 1476–1486, https://doi.org/10.1002/jbm.a.32439.
[112] S. Allegrini Jr., M. Yoshimoto, M. Barbosa Salles, A.H. de Almeida Bressiani, Biologic response to titanium implants with laser-treated surfaces, Int. J. Oral Maxillofac. Implants 29 (2014) 63–70, https://doi.org/10.11607/jomi.3213.
[113] K. Grandfield, A. Palmquist, H. Engqvist, Three-dimensional structure of laser-modified Ti6Al4V and bone interface revealed with STEM tomography, Ultramicroscopy 127 (2013) 48–52, https://doi.org/10.1016/j.ultramic.2012.07.007.
[114] K.M. Rath Saroj Kumar, Ankit Gupta, Comparative evaluation of laser-microtextured implant versus machined collar implant for soft and hard tissue attachment: a clinical and radiological study, Indian J. Dent. Res. 28 (2017) 298–303, https://doi.org/10.4103/ijdr.IJDR_578_15.
[115] L. Prodanov, E. Lamers, J. Wolke, R. Huiberts, J.A. Jansen, X. Frank Walboomers, In vivo comparison between laser-treated and grit blasted/acid etched titanium, Clin. Oral Implants Res. 25 (2014) 234–239, https://doi.org/10.1111/clr.12109.
[116] A. Joób-Fancsaly, T. Divinyi, A. Fazekas, G. Petó, A. Karacs, [Surface treatment of dental implants with high-energy laser beam], Fogorv. Sz. 93 (2000) 169–180.
[117] S.H. Kang, S.A. Cho, Comparison of removal torques for laser-treated titanium implants with anodized implants, J. Craniofac. Surg. 22 (2011) 1491–1495, https://doi.org/10.1097/SCS.0b013e31821d4d98.
[118] J.T. Lee, S.A. Cho, Biomechanical evaluation of laser-etched Ti implant surfaces vs. chemically modified SLA Ti implant surfaces: removal torque and resonance frequency analysis in rabbit tibias, J. Mech. Behav. Biomed. Mater. 61 (2016) 299–307, https://doi.org/10.1016/j.jmbbm.2016.03.034.
[119] K.S. Park, A.G.I. Al Awamleh, S.A. Cho, Comparison of removal torques between laseretched and modified sandblasted acid-etched Ti implant surfaces in rabbit tibias, J. Adv. Prosthodont. 10 (2018) 73–78, https://doi.org/10.4047/jap.2018.10.1.73.
[120] M. Rong, H. Lu, L. Wan, X. Zhang, X. Lin, S. Li, L. Zhou, Y. Lv, Y. Su, Comparison of early osseointegration between laser-treated/acid-etched and sandblasted/acid-etched titanium implant surfaces, J. Mater. Sci. Mater. Med. 29 (2018) 43, https://doi.org/10.1007/s10856-018-6049-1.
[121] K.E. Sisti, R. De Rossi, A.M.B. Antoniolli, R.D. Aydos, A.C. Guastaldi, T.P. Queiroz, I.R. Garcia, A. Piattelli, H.S. Tavares, Surface and biomechanical study of titanium implants modified by laser with and without hydroxyapatite coating, in rabbits, J. Oral Implantol. 38 (2012) 231–237, https://doi.org/10.1563/AAID-JOI-D-10-00030.
[122] M. Janeczek, P. Szymczyk, M. Dobrzynski, O. Parulska, M. Szymonowicz, P. Kuropka, Z. Rybak, B. Zywicka, G. Ziolkowski, K. Marycz, A. Chroszcz, A. Skalec, S. Targonska, R.J. Wiglusz, Influence of surface modifications of a nanostructured implant on osseointegration capacity-preliminary: in vivo study, RSC Adv. 8 (2018) 15533–15546, https://doi.org/10.1039/c8ra01625a.
[123] R. Patil, Zirconia versus titanium dental implants: a systematic review, J. Dent. Implants 5 (2015) 39, https://doi.org/10.4103/0974-6781.154430.
[124] M. Andreiotelli, H.J. Wenz, R.-J. Kohal, Are ceramic implants a viable alternative to titanium implants? A systematic literature review, Clin. Oral Implants Res. 20 (2009) 32–47, https://doi.org/10.1111/j.1600-0501.2009.01785.x.
[125] J. Fischer, A. Schott, S. Märtin, Surface micro-structuring of zirconia dental implants, Clin. Oral Implants Res. 27 (2016) 162–166, https://doi.org/10.1111/clr.12553.
[126] M. Albakry, M. Guazzato, M. Vincent Swain, Effect of sandblasting, grinding, polishing and glazing on the flexural strength of two pressable all-ceramic dental materials, J. Dent. 32 (2004) 91–99, https://doi.org/10.1016/j.jdent.2003.08.006.
[127] W. Cunha, O. Carvalho, B. Henriques, F.S. Silva, M. Özcan, J.C.M. Souza, Surface modification of zirconia dental implants by laser texturing, Laser Med. Sci. 37 (2022) 77–93, https://doi.org/10.1007/s10103-021-03475-y.
[128] J.L. Calvo-Guirado, A. Aguilar Salvatierra, J. Gargallo-Albiol, R.A. Delgado-Ruiz, J.E. Maté Sanchez, M. Satorres-Nieto, Zirconia with laser-modified microgrooved surface vs. titanium implants covered with melatonin stimulates bone formation. Experimental study in tibia rabbits, Clin. Oral Implants Res. 26 (2015) 1421–1429, https://doi.org/10.1111/clr.12472.
[129] R.A. Delgado-Ruiz, M. Abboud, G. Romanos, A. Aguilar-Salvatierra, G. Gomez-Moreno, J.L. Calvo-Guirado, Peri-implant bone organization surrounding zirconia-microgrooved surfaces circularly polarized light and confocal laser scanning microscopy study, Clin. Oral Implants Res. 26 (2015) 1328–1337, https://doi.org/10.1111/clr.12461.
[130] A.C. De Luca, M. Zink, A. Weidt, S.G. Mayr, A.E. Markaki, Effect of microgrooved surface topography on osteoblast maturation and protein adsorption, J. Biomed. Mater. Res. 103 (2015) 2689–2700, https://doi.org/10.1002/jbm.a.35407.
[131] K. Yasuno, K. Kakura, Y. Taniguchi, Y. Yamaguchi, H. Kido, Zirconia implants with laser surface treatment: peri-implant bone response and enhancement of osseointegration, J. Hard Tissue Biol. 23 (2014) 93–100, https://doi.org/10.2485/jhtb.23.93.
[132] E. Roitero, F. Lasserre, M. Anglada, F. Mücklich, E. Jiménez-Piqué, A parametric study of laser interference surface patterning of dental zirconia: effects of laser parameters on topography and surface quality, Dent. Mater. 33 (2017) e28–e38, https://doi.org/10.1016/j.dental.2016.09.040.
[133] S.R. Muhy, B.M.A. Hussein, Analysis of Nd: YAG laser (1064 and 532 nm) interaction with zirconia dental implant after different exposure time, J. Res. Med. Dent. Sci. 7 (2019) 40–47.
[134] M. Aivazi, M. hossein Fathi, F. Nejatidanesh, V. Mortazavi, B. HashemiBeni, J.P. Matinlinna, O. Savabi, The evaluation of prepared microgroove pattern by femtosecond laser on alumina-zirconia nano-composite for endosseous dental implant application, Laser Med. Sci. 31 (2016) 1837–1843, https://doi.org/10.1007/s10103-016-2059-8.
[135] A. Carvalho, L. Cangueiro, V. Oliveira, R. Vilar, M.H. Fernandes, F.J. Monteiro, Femtosecond laser microstructured Alumina toughened Zirconia: a new strategy to improve osteogenic differentiation of hMSCs, Appl. Surf. Sci. 435 (2018) 1237–1245, https://doi.org/10.1016/j.apsusc.2017.11.206.
[136] C.H. Seo, H. Jeong, Y. Feng, K. Montagne, T. Ushida, Y. Suzuki, K.S. Furukawa, Micropit surfaces designed for accelerating osteogenic differentiation of murine mesenchymal stem cells via enhancing focal adhesion and actin polymerization, Biomaterials 35 (2014) 2245–2252, https://doi.org/10.1016/j.biomaterials.2013.11.089.
[137] C.N. Elias, L. Meirelles, Improving osseointegration of dental implants, Expet Rev. Med. Dev. 7 (2010) 241–256, https://doi.org/10.1586/erd.09.74.
[138] M. Hirota, T. Harai, S. Ishibashi, M. Mizutani, T. Hayakawa, Cortical bone response toward nanosecond-pulsed laser-treated zirconia implant surfaces, Dent. Mater. J. 38 (2019) 444–451, https://doi.org/10.4012/dmj.2018-153.
[139] R.A. Delgado-Ruiz, J.L. Calvo-Guirado, M. Abboud, M.P. Ramirez-Fernandez, J.E. Mate-Sanchez, B. Negri, D. Rothamel, Histologic and histomorphometric behavior of microgrooved zirconia dental implants with immediate loading, Clin. Implant Dent. Relat. Res. 16 (2014) 856–872, https://doi.org/10.1111/CID.12069.
[140] S. Madeira, A. Barbosa, F.S. Silva, O. Carvalho, Micro-grooved surface laser texturing of zirconia: surface characterization and artificial soft tissue adhesion evaluation, Ceram. Int. 46 (2020) 26136–26146, https://doi.org/10.1016/j.ceramint.2020.07.109.
[141] F.S. S, G.M. Oscar Samuel Novais Carvalho, S. Madeira, Surface modification and hydroxyapatite coating by laser on zirconia substrate for dental implants Oscar, J. Biotechnol. Biomater. (2016) 1, https://doi.org/10.4172/2155-952x.c1.050.
[142] A. Beketova, M. Manda, D. Charoulis, D. Christofilos, L. Papadopoulou, O.M. Goudouri, E. Polychroniadis, K.M. Paraskevopoulos, P. Koidis, Laser-induced bioactivity in dental porcelain modified by bioactive glass, Ceramics 56 (2012) 323–330.
[143] I.N. Safi, B.M.A. Hussein, A.M. Al Shammari, T.A. Tawfiq, Implementation and characterization of coating pure titanium dental implant with sintered β-TCP by using Nd:YAG laser, Saudi Dent. J. 31 (2019) 242–250, https://doi.org/10.1016/j.sdentj.2018.12.004.
[144] M. Li, S. Komasa, S. Hontsu, Y. Hashimoto, J. Okazaki, Structural characterization and osseointegrative properties of pulsed laser-deposited fluorinated hydroxyapatite films on nano-zirconia for implant applications, Int. J. Mol. Sci. 23 (2022) 2416, https://doi.org/10.3390/ijms23052416.
[145] A. Oyane, M. Nakamura, I. Sakamaki, Y. Shimizu, S. Miyata, H. Miyaji, Laser-assisted wet coating of calcium phosphate for surface-functionalization of PEEK, PLoS One 13 (2018) 1–15, https://doi.org/10.1371/journal.pone.0206524.
[146] R. Saran, N.P. Upadhya, K. Ginjupalli, A. Amalan, B. Rao, S. Kumar, Effect on physical and mechanical properties of conventional glass ionomer luting cements by incorporation of all-ceramic additives: an in vitro study, Int J Dent 2020 (2020) 1–9, https://doi.org/10.1155/2020/8896225.
[147] V. Murthy, 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. 8 (2014) C65–ZC68, https://doi.org/10.7860/jcdr/2014/10104.4872.

[148] S. Da Silva Ferreira, F.S. Hanashiro, W.C. De Souza-Zaroni, M.L. Turbino, M.N. Youssef, Influence of aluminum oxide sandblasting associated with Nd:YAG or Er:YAG lasers on shear bond strength of a feldspathic ceramic to resin cements, Photomed Laser Surg. 28 (2010) 471–475, https://doi.org/10.1089/pho.2009.2528.

[149] F. Ahrari, F. Heravi, M. Hosseini, CO2 laser conditioning of porcelain surfaces for bonding metal orthodontic brackets, Laser Med. Sci. 28 (2013) 1091–1097, https://doi.org/10.1007/s10103-012-1152-x.

[150] H.B. Kara, E. Dilber, O. Koc, A.N. Ozturk, M. Bulbul, Effect of different surface treatments on roughness of IPS Empress 2 ceramic, Laser Med. Sci. 27 (2012) 267–272, https://doi.org/10.1007/s10103-010-0860-3.

[151] B. Gökçe, B. Özpinar, M. Dündar, E. Çömlekoglu, B.H. Sen, M.A. Güngor, Bond strengths of all-ceramics: acid vs laser etching, Operat. Dent. 32 (2007) 173–178, https://doi.org/10.2341/06-52.

[152] P. Kursoglu, H. Yurdaguven, E. Kazazoglu, S. Calikkocaoglu, T. Gursoy, T. Bu, P. Mp, H. Jd, Effect of Er,Cr:YSGG laser on ceramic surface, Balkan J. Stomatol. 10 (2006) 1–7.

[153] P. Kursoglu, P.F.K. Motro, H. Yurdaguven, Shear bond strength of resin cement to an acid etched and a laser irradiated ceramic surface, J. Adv. Prosthodont. 5 (2013) 98–103, https://doi.org/10.4047/jap.2013.5.2.98.

[154] E.A. Erdur, F.A. Basciftci, Effect of Ti:sapphire laser on shear bond strength of orthodontic brackets to ceramic surfaces, Laser Surg. Med. 47 (2015) 512–519, https://doi.org/10.1002/lsm.22371.

[155] A.M. Spohr, G.A. Borges, L.H. Burnett, E.G. Mota, H.M.S. Oshima, Surface modification of In-Ceram Zirconia ceramic by Nd:YAG laser, Rocatec system, or aluminum oxide sandblasting and its bond strength to a resin cement, Photomed Laser Surg. 26 (2008) 203–208, https://doi.org/10.1089/pho.2007.2130.

[156] V. Akhavan Zanjani, H. Ahmadi, A. Nateghifard, A. Ghasemi, H. Torabzadeh, M. Abdoh Tabrizi, F. Alikhani, R. Razi, A. Nateghifard, Effect of different laser surface treatment on microshear bond strength between zirconia ceramic and resin cement, J. Investig. Clin. Dent. 6 (2015) 294–300, https://doi.org/10.1111/jicd.12105.

[157] A. Usumez, N. Hamdemirci, B.Y. Koroglu, I. Simsek, O. Parlar, T. Sari, Bond strength of resin cement to zirconia ceramic with different surface treatments, Laser Med. Sci. 28 (2013) 259–266, https://doi.org/10.1007/s10103-012-1136-x.

[158] G. Ergun Kunt, I. Duran, Effects of laser treatments on surface roughness of zirconium oxide ceramics, BMC Oral Health 18 (2018) 1–7, https://doi.org/10.1186/s12903-018-0688-y.

[159] J. Saade, H. Skienhe, H. Ounsi, J.P. Matinlinna, Z. Salameh, Effect of different combinations of surface treatment on adhesion of resin composite to zirconia, Clin. Cosmet. Invest. Dent. 11 (2019) 119–129, https://doi.org/10.2147/CCIDE.S204986.

[160] M.Ş. Akyil, I.H. Uzun, F. Bayindir, Bond strength of resin cement to yttrium-stabilized tetragonal zirconia ceramic treated with air abrasion, silica coating, and laser irradiation, Photomed Laser Surg. 28 (2010) 801–808, https://doi.org/10.1089/pho.2009.2697.

[161] O. Kara, H.B. Kara, E.S. Tobi, A.N. Ozturk, H.S. Kilic, Effect of various lasers on the bond strength of two zirconia ceramics, Photomed Laser Surg. 33 (2015) 69–76, https://doi.org/10.1089/pho.2014.3841.

[162] S. Bitencourt, L. Ferreira, L. Mazza, D. Dos Santos, A. Pesqueira, L. Theodoro, 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. 21 (2021) 125–137, https://doi.org/10.4103/jips.jips_590_20.

[163] O. Kirmali, H. Akin, A.K. Ozdemir, Shear bond strength of veneering ceramic to zirconia core after different surface treatments, Photomed Laser Surg. 31 (2013) 261–268, https://doi.org/10.1089/pho.2013.3487.

[164] A. Goze Saygin, A. Kemal Ozdemir, O. Gorler, Influence of Various Laser Surface Modifications on SBS of Titanium and Zirconium Oxide Substructures, vol. 38, Cumhuriyet University Faculty of Science Science Journal (CSJ), 2017, https://doi.org/10.17776/cumuscij.297820.

[165] N. Asadzadeh, F. Ghorbanian, F. Ahrary, H. Rajati Haghi, R. Karamad, A. Yari, A. Javan, Bond strength of resin cement and glass ionomer to Nd:YAG laser-treated zirconia ceramics, J. Prosthodont. 28 (2019) e881–e885, https://doi.org/10.1111/jopr.12651.

[166] E. Moslehifard, N. Khosronejad, F. Fahimipour, Comparison of the effect of Nd : YAG laser and sandblasting on shear bond strength of a commercial Ni-Cr alloy to porcelain, JDMT 114 (2016) 5.

[167] S. Kasraei, M. Atefat, M. Beheshti, N. Safavi, M. Mojtahedi, L. Rezaei-Soufi, Effect of surface treatment with carbon dioxide (CO2) laser on bond strength between cement resin and zirconia, J. Laser Med. Sci. 5 (2014) 115–120.

[168] M. Abu Ruja, G.M. De Souza, Y. Finer, Ultrashort-pulse laser as a surface treatment for bonding between zirconia and resin cement, Dent. Mater. 35 (2019) 1545–1556, https://doi.org/10.1016/j.dental.2019.07.009.

[169] C. Fornaini, F. Poli, E. Merigo, A. Lutey, A. Cucinotta, M. Chevalier, S. Mckee, N. Brulat, J.-P. Rocca, G. Trevisi, Nanosecond pulsed fiber laser irradiation for enhanced zirconia crown adhesion: morphological, chemical, thermal and mechanical analysis, J. Photochem. Photobiol., B 219 (2021), 112189, https://doi.org/10.1016/j.jphotobiol.2021.112189.

[170] B.T.F. Silva, L.T. Trevelin, A.C. Schroeter, A.E. Willers, P.F. Cesar, A.B. Matos, Effect of silica coating and laser treatment on the flexural strength, surface characteristics, and bond strength of a dental zirconia, Eur. J. Oral Sci. 129 (2021), https://doi.org/10.1111/eos.12754.

[171] A. Alagl, S. Bedi, K. Hassan, Comparative study of the shear bond strength of composite resin bonded to enamel treated with acid etchant and erbium, chromium: yttrium, scandium, gallium, garnet laser, Indian J. Dent. Sci. 8 (2016) 238, https://doi.org/10.4103/0976-4003.196807.

[172] Y. Jahandideh, M. Falahchai, H. Pourkhalili, Lasers on shear bond strength of polyether ether, Laser Appl. Med. Sci. Res. Center 11 (2020) 153–159, https://doi.org/10.34172/jlms.2020.26.