Laser micro- and nano-processing: applications in modern dentistry

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Lasers have become irreplaceable devices in modern medicine and dentistry, covering a wide range of applications every day. Laser micro- and nano-processingare an important part of production and development (fabrication, integration, and assembly) of dental devices. They are also utilised as tools for diagnostics and treatments. Their usage has increased significantly given that laser devices are now much more inexpensive yet precise processing tools that can structure materials witha high degree of control, precision, and reduced residual impairment. However, there are still roadblocks for laser-based systems (such as temperature build-up effects, melting, burr formation, and cracking). Typically, only a limited number ofmaterials are compatible with each laser device. The precise mechanism of laser irradiation and laser–biological material interaction is also not fully understood, which presents some barriers in their application.

11.1 Laser surface structuring

In the field of dentistry the interaction between cells and implant surfaces plays an essential role. The bone marrow mesenchymal stem cells adhere to the implant and become mature osteoblasts. This process is influenced by different events, such as the microtopography and the chemical composition of implants' surfaces. The ideal surface should be obtained through processes that do not modify its chemical composition maintaining the right degree of roughness and a cell-attractive microtopography [1–3].The main advantage of using lasers within dentistry is their ability to fabricate a wide range of surface structures on a variety of metals and alloys, at the micro- and submicro-scale levels. Clearly, laser structuring of materials depends on a large number of parameters, related to the laser itself (the average laser power, pulse energy, pulse duration, repetition rate, wavelength etc), but also connected tospecific sample properties such as type of material or its roughness [4]. Examination

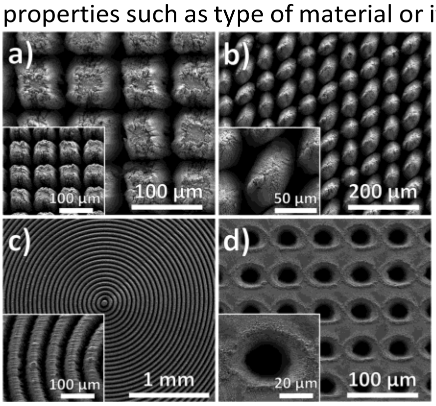

Figure 11.1. SEM micrograph patterns produced by laser processing Cu surfaces. (a) Square pillar, inset: sample tilted at 20° angle; (b) parallelogram structures in a hexagonal arrangement; (c) circular grooves; and (d) micro hole pattern. Reprinted from [4] with permission from MDPI.

of the influence of material topography on cellular behavior has shown that various structures such as pores, grooves and pits at the micrometer and nanometer dimensions influence cell morphology, adhesion, and proliferation of cells, leading to the definition of biologically favorable surfaces (figure 11.1).

In modern dentistry, namely, in implantology, the major issue relevant to the stability of implants is the fact that implants can withstand separation from the host tissue due to inadequate biocompatibility and poor implant osseointegration [5–10]. However, changing the surface chemistry and physical topography of the implant surface has been proven to influence biocompatibility and osseointegration. To date, several research studies report that the creation of nano- and microstructures on titanium implant material using lasers boosts the adherence of osteoblasts and helps fibroblasts to build up, which contributes to advanced implant osseointegration [5–10]. Laser processing is also effective in increasing the thickness of the surface oxide on titanium with a strong positive impact on bone–implant integration [9, 10]. Laser surface texturing can be seen therefore as is a relatively straightforward, flexible, precise, and affordable solution.

While titanium is a popular material for biomedical implants, several other materials, such as stainless steel, titanium/niobium/zirconium alloys, nickel/titanium alloy, and platinum [9–14], have been investigated and shown to result in similarly beneficial properties for biocompatibility. Apart from osteoblasts and fibroblasts, selective proliferation of neurons was demonstrated on a silicon surface micro-structured by a femtosecond laser [11]. The improved osseointegration is correlated with superhydrophobic surface structures, also known as the lotus leaf effect [15]. In nature, the lotus leaf has a superhydrophobic surface with self-cleaning effects [15–19]. Large varieties of nano- and microstructures that result in superhydrophobic surfaces have been created on different metal surfaces by femtosecond laser micro-machining [15–19]. Moreover, Kietzig *et al* noted that it takes some time for super-hydrophobicity to develop on intrinsically hydrophilic metals, which they attributed to the formation of a carbonaceous surface layer after laser treatment that alters the chemistry of the surface [18].

Further, in modern dentistry, lasers on micro- and submicrometer levels have been proposed as an alternative effective way for treating zirconia surfaces in an attempt to improve the adhesion of dental cements and orthodontic brackets. This isachieved by etching the surface with precision, without producing mechanicaldegradation of the materials and without raising the temperature of the irradiated surface [20].

Laser machining of biocompatible materials has also been used to create scaffoldsfor tissue engineering with controlled pore size and porosity, and furthermore with controlled cell orientation and location. In the most commonly used polymers for tissue engineering, laser micro- and nanomachining can be used to improve the proliferation of cells within interior regions of these materials [21]. The implemen-tation of trial laser parameters for laser micromachining can be taken from those already implemented from the production of microchannels in microfluidic devices [22, 23].

11.2 Laser tissue bonding

To date, the most desirable wound healing is healing by primary intention (i.e. the healing of a clean wound without tissue loss). In clinical practice, it is achieved via surgical sutures, staples and clips. However, these methods can cause a foreign body reaction due to the nature of the materials used, resulting in inflammation, granuloma formation, and scarring [24, 25]. Regardless of the methods used, an impermeable seal over the repair is rarely obtained. Furthermore, traditional methods are almost inapplicable to tissue closure in microsurgery such as vascular anastomosis and closure of nerves [26]. For these reasons new methods of wound closure have been sought and introduced, such as laser tissue bonding (LTB). LTB isa minimally invasive technique that can be faster, nonimmunogenic (does not produce an immune response), less traumatic, and easier to apply than conventionaltissue closure methods under optimum circumstances [25]. To date, LTB has been used to repair a variety of tissues, such as skin, liver, cartilage, urinary tract and nerves, as well as vascular anastomoses [27]. LTB is divided into three types, namely, laser tissue welding, laser tissue soldering (LTS), and dye-enhanced LTS, which areshown in figure 11.2.

Laser tissue welding is a surgical technique which uses a laser energy to join or bond tissues (photothermal and/or photochemical bonds). In general, this energy results in some alteration of the molecular structure of the tissues being joined [26]. Laser tissue soldering is an alternative approach for tissue bonding. This technique is based on photo-enhancement by applying some soldering material(liquid and semi-solid biological glues based on proteins and other compounds) ontothe approximated edges of the cut. The solder and the underlying tissues are then

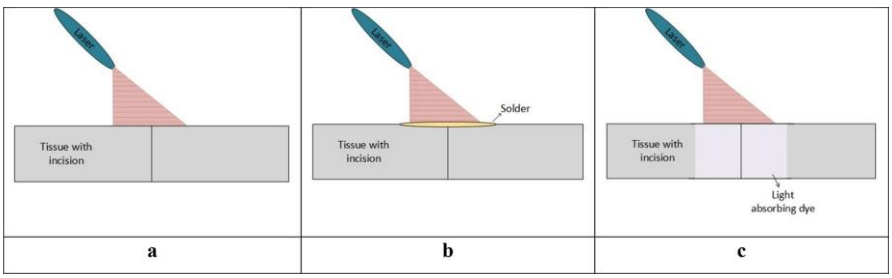

Figure 11.2. Schematics of tissue repair using: (a) laser welding, (b) laser soldering, and (c) dye-enhanced laser soldering.

heated by a laser light. Since laser tissue soldering does not involve a foreign body, it offers some advantages over conventional techniques such as watertight seals, and faster and scarless healing [28]. Furthermore, laser solders can include chromo- phores that are used to control the laser penetration. A known concentration of absorbing chromophore is added to the solder in order to focus light absorption in the solder itself, without changing the native tissue or body fluids. This technique allows the use of a lower power density, known to be safer for use (less of an eye safety hazard), smaller in size and less expensive, thus, resulting in reduced collateralthermal damage [29, 30]. For optimum results, the combination of tightly controlledlaser exposure parameters and thermal diffusion characteristics of the solder gives predictable and reproducible tissue welding [31]. In the early stages of this process,the introduction of fibrinogen-based solders, like cryoprecipitate in humans, were used but this raised concerns over infection risks, stability, and handling properties [29]. Since then, typical additives trialed have included native collagen, gelatinous collagen, fibrin, elastin, and albumin [26].

Regardless of the choice of solder, generally more energy is absorbed near the upper portion of the solder, near the laser spot. A temperature gradient is established over the depth of the solder. Depending on the temperature gradient and the laser exposure, the upper portion of the solder can become overcoagulated, while the most critical region, the solder/tissue interface, does not get fully coagulated. Such undercoagulated solder has been shown to create unstable bonds. Temperature-controlled laser soldering offers an accelerated wound reparative process with numerous advantages over the conventional methods [32].

Dye-enhanced laser tissue soldering is a more recent soldering technique, where laser tissue welding is improved by use of solder and photodynamic therapy (laser energy and wavelength specific absorbing dye). Most recently, it has been successfully applied both experimentally and clinically in the bowel, urethra, ureter, and blood vessels with excellent results. With this method a rapid and safe watertight seal can be achieved, with minimal foreign body reaction [33].

A main issue that needs attention within the LTB processes is the potential for thermal damage to the surrounding tissue. The available literature suggests that lasers with powers of 0.5–1 W, even with typical small spot sizes, result in imperceptible thermal damage [32]. The maximum tissue temperature is effected by different laser process parameters, wavelengths, and spot sizes being used. To overcome these disadvantages, laser wavelengths within the near infrared spectrumare used [27]. This means that wavelengths which are highly absorbed by water andwith shallow tissue penetration depths are recommended to be used. In this case, thedepth of thermal damage can be restricted to the most superficial adventitia (the outer layer of the blood vessel wall).

Precise temperature control is a crucial issue in laser bonding and has led to the development of more refined welding techniques, such as temperature-controlled tissue laser soldering and/or the use of temperature feedback control systems. This innovative approach is awaiting solid experimental data to become the gold- standard surgical procedure for incision closure [34].

Although many researchers agree that laser tissue welding is a promising new tissue welding technique in clinical practice, major gaps in basic understanding of the actual mechanism involved in the process prevent it from being introduced into everyday practice. Furthermore, the fact that different researchers are using significantly different laser irradiation parameters, different laser wavelengths, and different tissues to be welded in their research, makes it difficult to generate a single laser system that can be used broadly for different tissues.

11.3 Additive manufacturing (3D printing) of dental implants

The term additive manufacturing (3D printing) is generally used to describe a manufacturing approach in which objects are built one layer at a time, adding multiple layers to form an object. The low cost of manufacturing and less material waste are noted advantages of using additive manufacturing technology [35]. It has revolutionized medicine and dentistry. In comparison to restoration done by dental technicians, restorative dentistry using additive manufacturing can provide shorter processing time, reduced overall costs, improved availability, and allows for the printing of items with complex structures [36]. Additive manufacturing classification includes stereolithography (SLA), selective laser sintering (SLS), fused deposition modeling (FDM), selective laser melting (SLM), ink-jetting, and electronic beam melting (EBM). Also, it can be classified as liquid-based, solid-based, or powder- based materials. The advantages and disadvantages of different additive manufac- turing techniques are listed in table 11.1. Table 11.2 also indicates the material used in each technique and their potential applications in dentistry [33, 37–41].

SLA is an additive manufacturing process which originated as a vat photo-polymerization technique. In this method an object is created by selectively curing a liquid polymer resin layer-by-layer using an ultraviolet (UV) laser beam. In spite ofthe fact that this method is a high cost process for making large objects, it is widelyused in the production of 3D printed implant drill guides [42, 43].

In-jetting printers usually consist of two or more jetting heads. One head is used to jet out build material, and the other head is used to jet out support material. Using multiple print heads is a comparative advantage of this technology that allows concurrent printing with different materials. Adjusting the mixture of materials allows for the production of various properties within the printed object which can

Table 11.1. Additive manufacturing techniques.

Techniques	Advantages	Disadvantages
Stereolithography	• Rapid fabrication • Customized coloring • Able to create complex shapes with high feature resolution • Low material consumption	• Depending on the material, components may be brittle • High cost technology • Support materials must be removed • Photosensitive resin is a problem • Limited shelf life and vat life. Cannot be heat sterilized
Jetting	• Relatively fast • Lower cost technology • Excellent resolution • High quality • Rigid, opaque, multi-color, trans- parent and flexible materials	• Tenacious support material can be difficult to remove completely • Support material may cause skin irritation • Cannot be heat sterilized • High cost materials
	melting	
Selective laser sintering		• Range of polymeric materials including nylon, elastomers, and composites • Fast • Excellent layer adhesion • Strong and accurate parts • No need for support structures • Polymeric materials—commonly nylon may be autoclaved • Printed object may have full mechanical functionality • Lower cost materials
	Electronic beammelting	
Selective laser		• High mechanical load capacity • Variety of materials including

titanium, titanium alloys, cobalt chrome, and stainless steel • Almost no restriction on the shape of the product • Shorter assembly times	• Significant infrastructure required • Produces a lot of waste • Lower cost in bulk • Inhalation risk • Messy • Expensive • Produces rough surfaces
• Metal alloy may be recycled • Does not require expensive production equipment	• Elaborate infrastructure requirements • High initial costs • Dust and nanoparticle condensate may be hazardous to health • Acute size restrictions • Explosive risk • Produces rough surfaces • Elaborate post-processing is required • Hard to remove support materials • Relatively slow process
• Residual stress reduction due toincreased process temperature • Minimum material waste • High speed	• Limited commercially availablematerials • Dust may be hazardous to health • Explosive risk • Produces rough surfaces

	• Flexible process without tooling and set-up costs • Dense parts with controlled porosity • Geometric freedom for engineering product designers	• Limited build size • Less post-processing required • Lower resolution
Fused deposition modeling	• Less time consuming • High porosity • Simple to use • Variable mechanical strength • Low to mid-range cost materials and equipment • Low accuracy in low cost equipment • Broad range in materials	• Low cost but limited materials—only thermoplastics • Limited shape complexity for biological materials • Support material must be removed

Table 11.2. 3D printers, the materials used and their application in dentistry.

Techniques	Materials	Application in dentistry
Stereolithography	A wide variety of resins such as high temperature resin, dental resin, castable resin, etc	Dental replica models, surgical guides and splints, orthodontic devices, temporary and definitive crowns, temporary bridges
Jetting	A wide variety of photopolymers	Orthodontic models, implantology case planning, cast partial frames and sophisticated anatomical models
Selective laser sintering and selective laser melting	Powder such as alumide, polyamide, glass-particle filled polyamide, rubber-like polyurethane, etc; stainless steel, cobalt chrome, titanium alloy	Hospital set-up for metal crowns, copings and bridges, metal or resin partial denture frameworks
Fused deposition modeling	Thermoplastic polymers such as polylactic acid, acrylonitrile butadiene styrene, nylon, polyethylene terephthalate glycol-modified, polycarbonate, polyether ether ketone, etc	Custom impressions, custom bite registrations, wax set-up for tray-in

affect, for example, the flexibility of the object. It can, for instance, be used in production of indirect orthodontic bracket splints. A linear actuator moves the print heads in the *X*–*Y* plane above a build plate and a UV lamp located next to the print heads instantly cures the droplets. For the next layer to be printed, the build plate moves down by an increment. The thickness of each layer is usually between 14 and28 µm to achieve a fine level of detail [44–46].

Selective laser sintering (SLS) technology has been available since the 1980s. This technique employs a high-energy laser beam to heat and fuse polymer particles into complex, net-shaped, 3D components as the laser beam repeatedly scans over a single layer of powder granules and consolidates them via full or partial melting. This method results in a high level of precision and since the printed structure is supportedby surrounding powder, further support material is not required. [47–49]. As a rapid and accurate process, it allows straightforward batch production of implants for orthopedic and dental applications. It is also considered a leading technology in the production of titanium cranioplasties for oral and maxillofacial surgery [50–53].

Selective laser melting (SLM) is a specific 3D printing technique, which utilizes a high power-density laser to fully melt and fuse metallic powders and produce near net-shape parts with near full density. SLM is one of the most exciting technologies available today and is utilized both for rapid prototyping and mass production. The range of metal alloys available is fairly extensive. Via process parameter control, the properties of parts produced in this manner can be made to a similar standard to those manufactured via traditional manufacturing processes. SLM is similar to SLSin that both processes are covered under the powder bed fusion umbrella. The major difference is the type of feedstock or powder being used; while SLS uses polymer materials, metal powders are used with SLM. Aside from this, due to constraints ofthe SLM process and the weight of the material, SLM may require support structures for overhanging features. This is a significant difference from SLS, wherein SLS the surrounding powder material can provide enough support, allowing freeform shapes and features to be readily realized [48, 54].

Electron beam melting (EBM) is used to manufacture parts by melting the metal powder layer-by-layer using a high power electron beam in a high vacuum. The electron beam is used to provide the energy needed for a high level of melting capacity and productivity. The process is often performed at an evaluated temperature thus allowing parts to be produced with no or low levels of residual stress. The vacuum also ensures a clean and controlled environment. EBM and SLM technol- ogy offers good freedom of design with higher volume possible due to its ability to tightly stack parts. A combination that allows for the manufacture of complex and detailed orthopedic implants [55, 56].

Fused deposition modeling (FDM) printers are more common in the medical and dental industry due to their widespread availability, ease of installation, and economic affordability. In this technique, the material is supplied into a hot nozzle which melts and extrudes material in two dimensions (*X*–*Y*). Notwithstanding the fact that it permits printing of relatively low resolution anatomical models with less complexity, it is less capable for printing complex anatomies due to limitations of color selection, resolution, and the requirement for removal of support material [57, 58].

In order to fabricate 3D printed biomodels, digital imaging such as intraoral scanning, cone beam computed tomography (CBCT), and magnetic resonance imaging (MRI) have been used together with 3D printing [59]. CBCT provides volumetric data for 3D printing [33]. It has become more popular due to the advantages of CBCT over conventional radiography and other three-dimensional imaging modalities such as its high-resolution imaging procedure in oral and maxillofacial radiology [60]. CBCT has a 2D sensor and instead of a fan-shaped beam (as is used in CT) it uses a cone-shapedX-ray beam. By a single 360° rotation of the beam and sensor around the skull, volume data can be acquired [61, 62]. In comparison with conventional CT, CBCT provideshigher resolution at lower radiation doses [63, 64]. This revolutionary technology iswidely used in different areas of dentistry, especially in orthodontics, restorative dentistry, prosthodontics and maxillofacial, and oral and implant surgery [65].

Nowadays, with the advent of 3D printing technology, scanning and modelingof dental casts are possible. In order to correct malpositioned teeth and jaws, orthodontists use 3D software to customize the treatment plan via a virtual 3D interface. This can include algorithms to calculate the amount of force needed on an individual tooth to achieve the desired movement [66, 67].

In surgery, a large amount of lost tissues (tumor- or trauma-related tissue loss) can be replaced by detailed 3D replicas [68]. It is a less invasive approach that leadsto more efficient, affordable, and predictable surgery for patients. Above all, it allows dentists to create patient-tailored dentistry or personalized dentistry, which isan imperative of modern dentistry, especially in dental surgery [33]. Interestingly, the use of laser devices delivering nanosecond pulses have also been shown to be able toinduce sterilization or decontamination of the biomaterials, extending the usage of biomaterials and surgical instruments [11, 69].

As a wide range of dental materials such as thermoplastic polymers, waxes, metals and alloys, ceramics and thermoplastic composites can be utilized for manufacturing dental constructions, as well as the need for complex geometries and customization capability of the dental prostheses, SLS/SLM technology becomes suitable for application in dental medicine. Using SLS, the maxilla-facial prostheses, functional skeletons and individual scaffolds for tissue engineering can be fabricated of polymers and composites. When the metals and alloys are processed by SLM, bulk as well asporous orthopedic and dental implants, dental crowns, bridges and frameworks for partial prostheses can be produced [70–72].

SLS/SLM technology is suitable for application in dental medicine as it can be utilized on an entire range of dental materials such as thermoplastic polymers, waxes, metals and alloys, ceramics and thermoplastic composites for manufacturingdental constructions, also for its ability to manufacture complex geometries and forits customization capability of the dental prostheses. Using SLS, the maxilla-facial prostheses, functional skeletons and individual scaffolds for tissue engineering can be fabricated of polymers and composites. When the metals and alloys are processedby SLM, bulk as well as porous orthopedic and dental implants, dental crowns, bridges and frameworks for partial prostheses can be produced [73–75].

In medical applications, high porosity of implants is one of the most important factors since it improves the attachments between muscle and implant. A fully digital method for designing and manufacturing of personal frameworks for complex dental prostheses has been developed by SLM of titanium or cobalt– chromium. The framework is the metal base structure of the prosthesis and supports the artificial teeth (figure 11.3) [76–78].

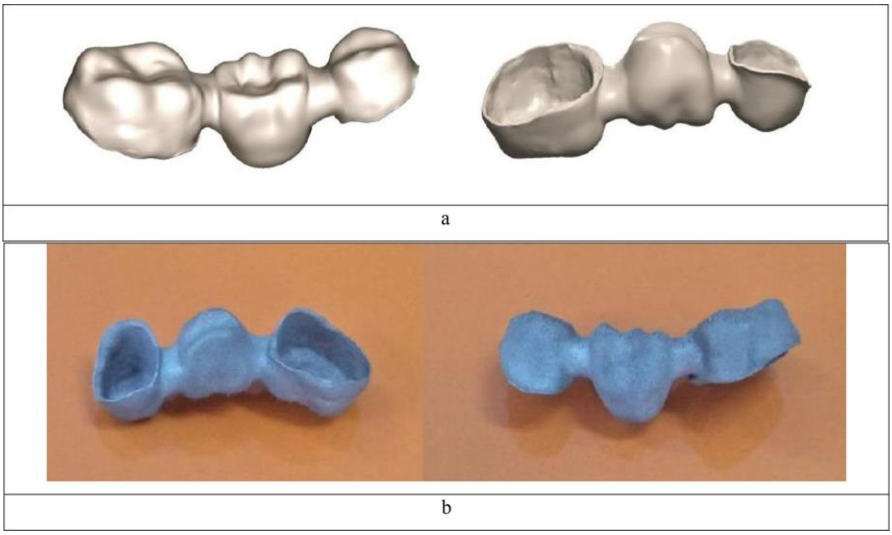

Figure 11.3. (a) 3D CAD models of a dental bridge, and (b) SLM-manufactured dental bridge. Reprinted from [78] with permission from MDPI.

In comparison with cast alloys, selective laser melting of cobalt–chromium alloys have high mechanical and tribocorrosion properties, comparatively good fitting ability, and higher adhesion strength of the porcelain. All this is a good precondition for successful application of the SLM process in the production of fixed dental prostheses, mainly of frameworks for metal–ceramic and constructions covered with polymer-composite, intended for areas with high loading [79, 80].

11.4 Conclusion

Additive manufacturing has attracted the interest of researchers in various applications and fields. In dentistry, computerization has come to the fore with the introduction of 3D imaging, modeling and CAD technologies, which are hugely impacting all aspects in this market. 3D printing makes it possible to accurately make one-off, complex geometrical forms from digital data, in a variety of materials, in localor large industrial centers. Nowadays, the main focus is on surgical planning and the indirect production of implants or orthodontic aligners by printing the molds for them.A suitable printing system is normally selected by considering availability and medical properties of the material, the time required and the desired resolution [81, 82]. Based on the findings of reviews, the following conclusions can be noted:

- Additive manufacturing is an effective alternative for the manufacture of custom implants.
- 3D printing techniques and materials should be chosen based on the required accuracy, strength and biocompatibility of the orthodontic appliance.
- This technique is a cost-effective fabrication method for dental implants and can allow better osseointegration.

- Additive manufacturing of implants brings advantages such as customization, flexibility, and freedom in design and enables also manipulation of chemical and physical properties.
- Obtaining the required surface quality and dimensional accuracy still remain a main challenge for the advancement of some additive manufacturing technologies for dental implants.

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