Chapter 12

Laser Surface Texturing for Biomedical Applications

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12.1 Introduction

The research in the development of metallic bio-implants has gained attention due to their enormous demand in dental and orthopaedic applications. However, incidences of failure of implants immediately or within few years leading to complications like expensive re-surgery are not uncommon. Hence the necessity to improve the quality of the existing implants and the same can be achieved by altering their surface properties that make their initial interaction and subsequent integration inside the human body more bio-friendly. Different types of biomaterials and various techniques that can be used to modify their surface characteristics are discussed with a special emphasis on laser surface texturing (LST) method because of its multiple advantages.

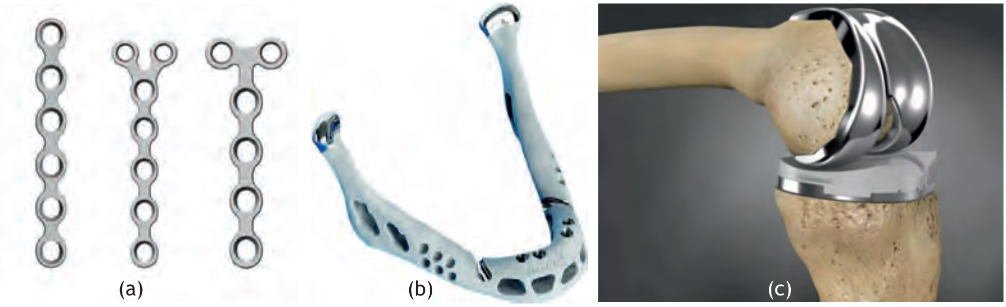

Figure 12.1: Examples of bio-implants used in various parts of the body: (a) Titanium compression plates [135], (b) patient-specific lower jaw implant [136], and (c) 3D printed knee replacement [137].

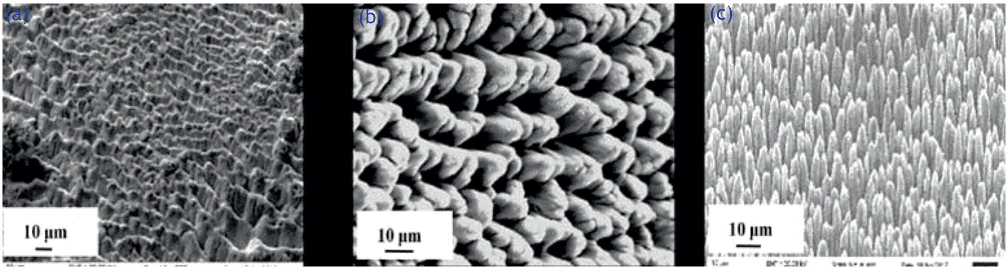

Figure 12.2: SEM images of Ti_6Al_4V surface textured using (a) nanosecond laser, (b) picosecond laser, and (c) femtosecond laser.

12.2 Implants and Their Properties

The materials which can be used for any period of time as part of a human body to treat, boost, or replace tissues, organs or function of the body are called biomaterials. The biomaterial in a desired shape and size can be implanted inside to replace a missing biological structure in the body, to support a damaged biological structure or to boost function of existing biological organs. The materials which can be chosen as biomaterials should essentially possess some critical properties such as, biocompatibility, bio-functionality, chemical inertness and similar mechanical properties as organ/tissue it is substituting [138]. A variety of metals, metal-alloys, ceramics, polymers and composition are in use as biomaterials and some of them are listed in table 12.1. The bio-implants, depending on the application and location where they are employed (Fig. 12.1a), are of different dimensions, different shapes and surface structures (Fig. 12.1b) and can also be a combination of two or more biomaterials (Fig. 12.1c). Inspite of being used extensively, observation of early and late implant failures is not uncommon [139]. When the implant fails within a few months after implantation, it is called early implant failure. The early implant failure can be a result of surgical trauma, poor osseointegration, bacterial infection, bone loss during healing, premature loading, excess loading and/or auto-immune diseases. When an implant is sustained in the body up to 10 years before a failure, it is called late implant failure and this can occur due to insufficient bone volume, progressive change of the loading/overloading, prolonged micro-movements, generation of fibrous tissues and ageing of the patient. Functionality of existing biomaterials needs to be improved to overcome such issues and it has been shown that, surface modification of the implants can enhance their surface properties and improve their integration with the body environment to a great extent [140]. The surface modification of biomaterials can be done mainly by two ways, functional coating and surface texturing. The functional coating can be ceramic coating, bio-molecular coating or sol-gel coating. The surface texturing can be done by following techniques [141–143]:

Table 12.1: List of biomaterials.

Metal & Alloy	**Ceramics**	**Polymers**	**Composition**
Ti & $\mathrm{Ti_6Al_4V}$	Bio-glass	Nylon	Carbon-fiber
Co-Cr alloys	Aluminum oxide	Silicone rubber	Bone cements
Cr-Ni alloys	Calcium phosphate, Carbon	Polyster	ALLOgraft
Stainless Steel	Zirconia	PMMA	Collapat
Platinum, Gold, Silver	Hydroxyapatite	UHMWPE	OsetoGenPlug

- Sand blasting,
- Acid etching,
- Chemical treatment,
- Thermal treatment,
- Electro-chemical treatment, and
- Laser treatment.

The first five techniques, along with altering the surface properties, also contaminate the surfaces. In addition, the processes lead to uncontrolled surface features. Unlike this, the LST is a contamination free, single step, fast, reproducible, confined and clean process [144]. The increased surface roughness by way of this treatment has been found to be responsible for improvement in the properties of the biomaterial. Further the type of micro-structuring plays a dominant role in determining the extent to which the efficacy is enhanced. The LST process has an advantage of precise control over topographical alteration of the samples such that, both antibacterial performance and biocompatibility of the sample can be enhanced simultaneously. The laser parameters, e.g., wavelength of the laser, pulse duration, repetition rate and power, and material properties, e.g., its absorption, thermal conductivity, melting temperature, specific heat, density and surface roughness play significant role in LST. Along with these, experimental conditions such as, beam focusing, sample scan speed and environment (air/vacuum/liquid) are also important. As one talks of LST of metallic bio implants, due to their better absorption in the visible and near IR region, available efficient lasers, e.g., Nd-YAG lasers with harmonics, fiber lasers are generally employed. The generated features on the surface depend on the peak power and repetition rate of the laser too. Higher the peak power, sharper the pulse duration. E.g, for laser pulses of 1ns, 1 ps and 1 fs of same energy per pulse, say 1 mJ, the peak powers in the three cases are ∼1 MW, 1 GW and 1000 GW, respectively. Due to this significant difference, the intensity and depth of heat penetration too differs and each laser interacts differently with the given material and shows notable difference in the surface modification. Figures 12.2a-12.2c show SEM images of Ti_6Al_4V biomaterial laser treated with ns, ps, and fs lasers, respectively. When a laser beam falls on the metal surface, the free electrons in the metal absorb energy from the photons through inverse-Bremsstrahlung process and thermalise among themselves (∼fs, time scale). When the energised electrons collide with the lattice, they transfer their energy leading to rise in temperature in ps time regime that leads to heat diffusion, ablation, vaporisation, and melting of the target material [145]. Therefore, in case of a fs laser, in the absence of heat conduction to the lattice, there is what is called cold ablation. The features so formed are very sharp with no heat affected zone (Fig. 12.2c). In case of ps pulse duration, on the other hand, there is moderate heat conduction to the lattice, surface temperatures are high and ablation/melting occurs. The heat conduction is understandably higher for ns pulses,

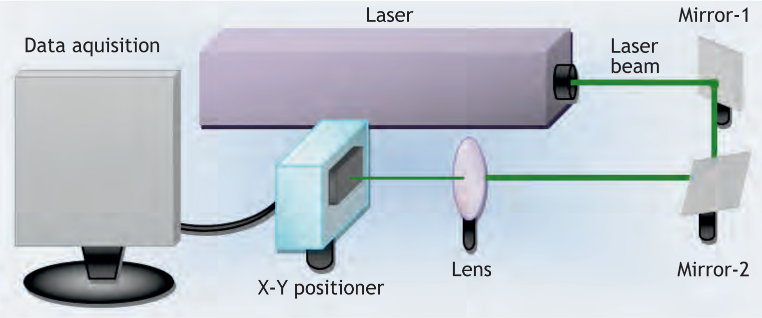

Figure 12.3: Typical experimental set-up used for LST.

with relatively lower rise in surface temperature and higher heat affected zone (Fig. 12.2a). Since, lasers with different pulse duration interact differently with material the topographical change are observed to be significantly different.

Figure 12.3 illustrates a typical experimental set-up used for LST of biomaterials. In this, a laser with optimized parameters is allowed to focus on the sample through a lens. The sample scan speed can be controlled by a computer controlled X-Y translational stage. The laser spot is made to scan the sample at an optimized speed along x-direction or along x-y directions to obtain desired beam overlap and surface topography. After LST, a detailed investigation is required to understand the physical and chemical changes on the surface of the sample that have a bearing on their effectiveness as bioimplants. Different techniques such as, optical microscope, scanning electron microscope (SEM) and atomic force microscope (AFM) can be used for topographical studies. Changes in surface roughness, wettability, surface energy are important to measure as these factors decide interaction of implant with body fluid. The changes in chemical composition of the sample can be determined by Raman analysis, X-ray diffraction and X-ray Photoelectron Spectroscopy (XPS). Detailed in-vitro biological tests involve assessment of osseointegration ability, biocompatibility and antibacterial behaviour of the laser treated sample and, the mechanical tests include measurement of corrosion resistance. They are briefly discussed below:

12.2.1 Osseointegration

This is assessed by immersing the LST sample in simulated body fluid (SBF) and the growth of 'bone cement' hydroxyapatite (HAP) is monitored as function of time. This growth depends upon the surface area of the sample and the roughness imparted by laser texturing and alongside other factors the nature.

12.2.2 Biocompatibility

This tells about the ease with which the implant integrates with the body,mainly in terms of growth of cells, and their proliferation. This test is a check of laser induced toxicity in the sample post LST.

12.2.3 Antibacterial performance

It is shown that the laser treated biomaterials can inhibit adhesion of bacteria and restrict biofilm formation. This test can be done by keeping the sample in bacterial environment for a known time followed with microscopic imaging and counting of adherent bacterial colonies.

12.2.4 Corrosion resistance

Electrochemical polarisation studies tell us about the corrosivity implant material may exhibit in the biological environment and the possible toxicity due to releasing of metal ions (if any) in the body over a period of time due to corrosion.

12.3 Summary

Laser surface texturing is an emerging field with an intense research activity towards increasing the effectiveness of bioimplants. The increased surface roughness and the type of micro-structuring created on the surface due to laser treatment is responsible for this improved effectiveness. Laser surface texturing, with tailored laser parameters and experimental conditions, has the potential to emerge as a one step, clean and fast technique of improving the biofunctionality of the existing biomaterials.

Frequently Asked Questions

Q1. What will be the difference in the peak intensity of 45 fs laser with repetition rate 3 kHz to a 30 ps laser of repetition rate 10 Hz when average power of both the lasers is 100 mW?

Q2. Compare the focal spot size of a 532 nm laser beam with divergence 0.5 mrad focused through a 10 cm spherical lens and a 10 cm focal length cylindrical lens.

Q3. Calculate average power and peak power of a 6 ns laser, emitting 1×10^3 numbers of laser pulses of energy 10 mJ.