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Laser surface texturing of Titanium for bioengineering applications

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Abstract

Titanium and alloys are common biomaterials used for orthopedic implant. The response of the host tissue to the titanium is well known to depend on the surface texture of the implanted medical devices; then, control of the cell response through the texture has the potential to enhance fixation of implants into bone. In this work, the potential use of millisecond pulse laser for texturing titanium is investigated. Damage of the titanium sample with Nd:YAG, and CO2 lasers is investigated using high-speed photography; furthermore, laser treated areas are chemically and morphologically characterized.

Keywords: laser texturing, titanium, plasma plume, roughness.

1. Introduction

Millions of people around the world suffer from bone and joint degeneration, or inflammatory problems [1]. Bone is a tissue with the capability to heal and regenerate; however, if a defect with dimensions exceeding a so called critical diameter is generated, this is no longer able to heal. In this case, surgery is normally required, and total joint replacement is performed. Different biomaterials, such as some polymers or metals, are used in these cases to repair or substitute the damaged tissue. Among them, titanium and alloys are the most common biomaterials used in total joint replacement. Their increased use as is due to their lower modulus of elasticity, superior biocompatibility, and larger corrosion resistance as compared to stainless steels and cobalt-based alloys, materials traditionally used for these biomedical applications [1, 2]. After implanted, titanium and alloys react with the host tissues. This reaction determines the healing speed or long-term performance of the implant. This depends on physicochemical surface parameters, such as surface free energy, wettability, or roughness [3]. Different surface treatments have been considered, and their advantages concerning healing speed, osteointegration, or long-term stability in the host bone have been demonstrated [4]. One main target of most of these treatments is the increment of the surface area of the implants because this improves the bone to implant contact [5, 6]. On the other hand, the surface topography of an implant can be modified at the macro-, micro-, or nanoscale in order to elucidate different responses. Macro-sized topographies help to the initial implant stability [7]. On the other hand, micron- and submicron-sized features have shown to be of large benefit on osteoblast response and bone growth along the

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implant surface [8-10]. Nano-sized topographies may play a role in the adsorption of proteins, and then in the rate of osseointegration.

Lasers have shown a great potential to modify the surface characteristics of biomaterials, especially in the case of polymers [11, 12]. Advantages of laser processing of biomaterials are evident. They can effectively modify the implant surface from the macro- to the nano-sized topography without direct contact (avoiding undesirable contamination); moreover, laser processing is fast, clean, easily automated, and it is possible to treat workpieces with complex geometry. In general, the interaction of a powerful laser beam with a solid sample results in the crater formation on the sample surface. Then, the topography can be tailored at the macroscale performing a matrix of individual craters onto the surface sample. Different topographies can be obtained using different patterns or different crater dimensions. In both cases, it is initially required the knowledge of the crater dimensions. These are determined by the laser spot diameter, and laser beam interactions with the sample and plasma. These interactions are complex and have not yet been satisfactorily explained. Such a multiparameter problem present difficulties for its theoretical analysis, and is mostly done on an empirical basis.

Most of the works dealing with the laser texturing of titanium and alloys for biomedical applications are performed using short pulse lasers [13-16]. These laser sources are very efficient to modify surfaces at the micro- or nanoscale, however, modification of the topography at the macroscale requires longer processing times as compared to the processing assisted by millisecond laser pulses. In the present work, the laser texturing of titanium using millisecond pulse lasers was investigated. The laser-induced damage was visualized by means of high-speed photography in order to determine the plasma plume characteristics due to their impact on the process. Furthermore, influence of laser fluence, and pulse length on the final dimensions of the damaged area was determined. Finally, laser texturing of titanium surfaces was studied and the chemical modifications on the treated area investigated.

2. Material and methods

2.1. Materials

The present study was carried out on flat samples of commercially pure titanium (ASTM 1). Samples of 10 mm x 30 mm x 2 mm were used in the experiments. Laser treated surfaces have an initial average surface roughness of R_a= 0.06 µm. Before and after the laser treatments, surfaces were ultrasonically cleaned in ethanol, acetone, and distilled water.

2.2. Laser treatment

Laser treatments were performed using two different laser sources in normal air under atmospheric pressure. No assist or shielding gases were used during the laser treatments.

A CO_2 laser (Rofin DC-35) emitting at the fundamental wavelength of λ=10600 nm was used during part of the experiments. The laser beam was focused onto the surface of the samples by means of a ZnSe lens 190 mm in focal length. Furthermore, a Nd:YAG laser (Rofin RSY-500 P) emitting at the fundamental wavelength of λ=1064 nm was also used. In this case, the laser beam was coupled to an optical fiber of 400 µm diameter and focused onto the upper surface of the sample by means of 80 mm of focal length lens. Pulses with a fluence in a range from $2.4\text{x}10^3$ J/cm^2 to $34\text{x}10^3$ J/cm^2 in the processing assisted by the CO_2 laser, and from $8.5\text{x}10^3$ J/cm^2 to 170 $\text{x}10^3$ J/cm^2 in the processing assisted by the Nd:YAG laser were investigated. Pulse durations from 1 ms to 5 ms were used under both treatments.

2.3. Sample characterization

Selected samples were inspected in frontal view to the laser treated area by means of an optical stereoscopic microscope (Nikon SMZ-10A) with a photographic system in order to record and store images. Furthermore, surface topography and elemental composition of the treated areas were examined via scanning electron microscopy (SEM, Philips XL-30) and energy dispersive X-ray spectroscopy (EDS) with an EDAX PV9760 spectrometer.

Roughness of the treated areas was measured by means of a Veeco Dektak 3ST surface profiler in several locations of the treated areas. Then, an average value for the average roughness (R_a) was extracted from obtained data in order to characterize the surface finishing. Measurements were made in accordance with the recommendations specified in the International Standard ISO 4288:1996.

3. Results

3.1. Process visualization

The interaction of the focused laser beam onto the surface of the titanium samples was visualized by means of high-speed photography during the Nd:YAG laser processing. The process was found to be quite similar in the case of the CO_2 laser processing. As observed in Fig. 1, a plasma plume is fully developed in less than 0.7 ms after the beginning of the laser pulse. The velocity of the front surface of the developing plume was measured as a function of the fluence for different pulse lengths (see Fig. 2). The