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Surface modifications of a titanium implant by a picosecond Nd:YAG laser operating at 1064 and 532 nm

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Abstract

Interaction of an Nd:YAG laser, operating at 1064 or 532 nm wavelength and pulse duration of 40 ps, with titanium implant was studied. Surface damage thresholds were estimated to 0.9 and 0.6 J/cm^2 at wavelengths 1064 and 532 nm, respectively. The titanium implant surface modification was studied by the laser beam of energy density of 4.0 and 23.8 J/cm^2 (at 1064 nm) and 13.6 J/cm^2 (at 532 nm). The energy absorbed from the Nd:YAG laser beam is partially converted to thermal energy, which generates a series of effects, such as melting, vaporization of the molten material, shock waves, etc. The following titanium/implant surface morphological changes were observed: (i) both laser wavelengths cause damage of the titanium in the central zone of the irradiated area, (ii) appearance of a hydrodynamic feature in the form of resolidified droplets of the material in the surrounding outer zone with the 1064 nm laser wavelength and (iii) appearance of wave-like microstructures with the 532 nm wavelength. Generally, both laser wavelengths and the corresponding laser energy densities can efficiently enhance the titanium/implant roughness. This implant roughness is expected to improve its bio-integration. The process of the laser interaction with titanium implant was accompanied by formation of plasma.

Keywords: Titanium implant surface modification; Picosecond Nd:YAG laser; Laser-induced damage

1. Introduction

Surface modification studies of titanium by laser beams are of great fundamental, technological and biomedical interest. Titanium exhibits excellent physical and chemical properties. It has a high melting point, high specific-to-weight ratio, admirable corrosion and erosion resistance, etc. [1]. It is therefore attractive for various applications in medicine, marine, nuclear, aero-space technology, etc.

The main uses of titanium and titanium-based alloys implants in medicine are based on the fact that they possess a high level of bio-compatibility and bio-integration with human body [2–9]. They are frequently used for joint replacement parts for hip, knee, shoulder, spine, wrist, etc. In dental field, these implants can be successfully employed, among other, for replacement of lost teeth [6]. Titanium of CP grade has typically been utilized for titanium implants [3,5,6,9], whereas Ti6Al4V [4] has been used for alloy-based implants. A comparative analysis of three types of metal implants, including titanium, in a case of fracture treatment has been reported [2], according to which the behavior of titanium was superior compared to stainless steel and cobalt–chromium–molybdenum implants. Generally, titanium and titanium-based implants show long-term durability. It is well known that the success of bio-integration with the surrounding host tissues depends on the efficiency of the cell/tissue-implant interaction [4,6,7]. The quality of this interaction, further depends on the state of the implants surface [5–7]. The implant surface must be contaminant-free, while roughness is its desirable morphological feature, as it plays a significant role in the tissue integration [5–7]. Rough surface, for example, promotes growth of the bone tissue around the implant [5,6]. One of

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the possible methods for enhancement of roughness is laser treatment. The knowledge of titanium surface, from previous mentioned reasons, is highly desirable. The present work deals with laser modifications of a titanium implant surface.

Other medical applications of titanium and titanium-based alloys include those in medical–engineering, e.g. artificial heart valves, surgical instruments, components of high-speed blood centrifuge, etc. [8].

Interest in the studies of laser beam interaction with titanium has generally relatively increased, especially in the last decade. The Nd:YAG [10–13], Ti:Sapphire [14], cw CO_2 [8,15], TEA CO_2 [16,17] and various excimer [6,7] laser systems have so far been employed for these purposes.

Interaction of titanium with an Nd:YAG laser beam pulsed in the picoseconds time domain has not been sufficiently described in literature [13], as that of the nanosecond domain [10–12]. In the present paper, our emphasis is on studying the effects of a picosecond laser emitting in the near-infrared (1064 nm) and also in the visible region (532 nm) on a titanium implant surface. Special attention was paid to morphological surface modifications of titanium at both wavelengths. Our initial results on the topic have been published [13].

2. Experimental

The titanium implant surface was prepared by a standard metallographic procedure. This included polishing, rinsing and drying. Bulk dimensions of the rectangularly shaped sample were typically 15 mm × 15 mm × 4 mm. The surface roughness of the sample was evaluated using AFM and it was observed to be less than 0.6 μm. The titanium samples used in the experiment were practically the same as those employed in Reference [13].

Samples were irradiated by focusing the laser beam using a quartz lens of 12 cm focal length. During the irradiation process, the laser was operated in the fundamental transverse mode. The angle of incidence of the laser beam with respect to the surface was 90°. The irradiation was carried out in air, at a pressure of 1013 mbar and standard relative humidity.

The laser employed is an active-passive mode-locked Nd:YAG system [18] model SYL P2 produced by Quanta System Srl.-Solbiate. It includes a laser oscillator, an amplifier and a non-linear crystal (KD*P). A pulse duration of about 40 ps is obtained by using a saturable absorber dye and an Acuosto-Optic standing wave modulator. The laser was operated with a typical repetition rate of 2 Hz. The choice of irradiation wavelength was either 1064 or 532 nm, depending on the experimental requirement.

Various analytical techniques were used for characterization of the titanium implant samples before and after laser irradiation. Identifying crystal phases was done by an X-ray diffractometer (XRD; Siemens D500, software-Diffracplus). Surface morphology was monitored by optical microscopy (OM), scanning electron microscopy (SEM; JOEL-JSM-6500F) as well as by atomic force microscopy (AFM; TM Microscopes-AutoProbe CP Research). The SEM was connected to an energy dispersive analyzer for determining surface compositions of the targets.

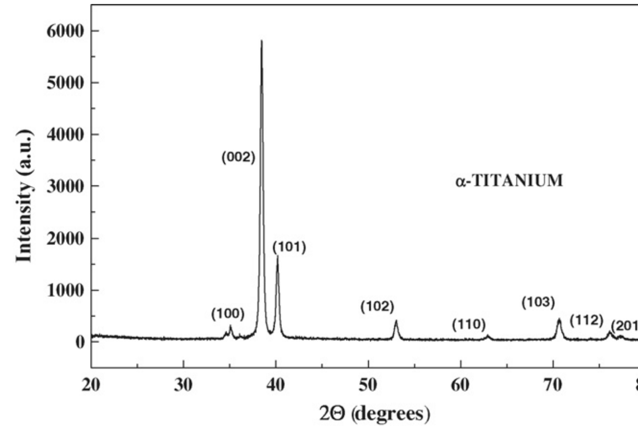

Fig. 1. XRD spectrum of non-irradiated titanium implant surface with the characteristic intensities of α-titanium marked. Ni-filtered Cu Kα radiation was used.

Profilometry (Taylor-Hobson Talysurf 2) was used for specifying the geometry of the ablated area.

3. Results and discussion

X-ray diffraction analyses of titanium prior to laser irradiation have confirmed its crystalline structure (Fig. 1). The sample exhibited a hexagonal structure with prominent (0 0 2) and (1 0 1) orientations. These orientations are characteristics to the α-phase titanium. The titanium implant surface was typically white-silvery-metallic color. Elemental analysis of the sample surface, carried out prior to irradiation by EDS (Table 1—spectrum 3; Fig. 6), showed the following sample content: titanium 93.41%, balanced to 100% by O (4.34%), C (2.15%) and Al (0.10%). All percentage data are by weight. The complete elemental analysis was normalized.

Investigation of the morphological changes induced by laser on titanium implant has shown their dependence on laser beam characteristics: primarily on the energy density, peak power density, pulse duration, number of accumulated pulses and wavelength.

Morphological changes of the titanium for 1, 5 and 30 accumulated laser pulses at 1064 nm, and after 30 accumulated pulses at 532 nm, are presented in Figs. 2, 4 and 5, respectively. The laser radiation energy densities (LRED), during experiment, were 4.0 and 23.8 (for 1064 nm), and 13.6 J/cm^2 (for 532 nm). These LRED induced significant surface modifications of the titanium implant surface. The results of the induced modifications can be presented as follows:

Table 1
An EDS elemental analysis of the titanium implant surface

Element	C	O	Al	Ti	Total
Spectrum 1	1.63	6.04	0.18	91.85	~100.00
Spectrum 2	1.57	8.85	0.17	89.41	100.00
Spectrum 3	2.15	4.34	0.10	93.41	100.00

Spectra 1 and 2 (Fig. 6): regions of laser radiation effects. Spectrum 1: region of intense laser action. Spectrum 2: farther periphery. Spectrum 3 (Fig. 6): non-irradiated area.