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Surface Modification of Titanium by High Intensity Ultra-short Nd:YAG Laser

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Abstract. The effects of an Nd:YAG laser interaction with titanium target using laser radiation at wavelengths 1.064 or 0.532 μm (40 picoseconds pulse duration) were studied. Modification of target surfaces at laser energy densities of 2.4 and 10.3 J/cm^2 (λ_1^{laser}= 1.064 μm) and 1.1 J/cm^2 (λ_2^{laser}= 0.532 μm) are reported in this article. Qualitatively, the titanium surface modification can be summarized as follows: (i) ablation of the titanium surface in the central zone of the irradiated area for both laser wavelengths; (ii) appearance of a hydrodynamic feature like resolidified droplets of the material (λ_1^{laser}= 1.064 μm), as well as formation of the wave-like microstructures (λ_2^{laser}= 0.532 μm); and (iii) appearance of plasma, in front of the target, with both laser wavelengths.

Introduction

Surface modification studies by various types of energetic beams, including laser beams, are of great fundamental, technological, and medical importance. In the last two decades laser beam interaction with titanium has been extensively studied. Till now radiation of Nd:YAG [1-4], Ti:saphire [5], cw CO_2 [6], TEA CO_2 [7,8] and excimer [9,10] lasers have been utilized for the research. Experimental data on the interaction of picosecond Nd:YAG laser pulse with titanium are missing in literature, in contrast to nanosecond laser pulses. Titanium has desirable physical and chemical properties, such as strength, lightness, corrosion resistance, etc. It can thus be applied in various fields, e.g. electronics, metallurgy, space technology, medicine, etc. Applications in bio-medicine are of high importance due to titanium's good bio-compatibility, especially in the form of alloys [10].

The present paper deals with the effects of a picosecond pulsed Nd:YAG laser (having wavelengths 1.064 μm and 0.532 μm) interaction with titanium bulk target. Special attention was paid to morphological surface modification of titanium under multi-pulse irradiation.

Experimental

The targets, used in the experiment, were high purity commercial titanium. Surface was prepared by standard metallographic procedure, which included polishing, rinsing, and drying. Dimensions of rectangularly shaped bulk titanium were 15mm x 15 mm x 5 mm. Prior to the irradiation process, titanium showed a fine-polished surface with a roughness of less than 1 μm.

Targets were irradiated at normal incidence using a laser beam focused by quartz lens of 12 cm focal length. A focal spot up to 150 μm radius was achieved. The irradiation was carried out in air at atmospheric pressure and standard relative humidity.

The laser employed in this experiment is described in detail elsewhere [11]. It is an active-passive mode-locked Nd:YAG system, model SYL P2 produced by Quanta System Srl.- Solbiate, Italy. It consists of a laser oscillator, an amplifier, and a nonlinear crystal (KD*P). The KD*P crystal serves for second harmonic conversion. The oscillator is based on a self-filtering unstable resonator cavity. Pulse duration of about 40 picoseconds is obtained by using a saturable absorber dye (Exciton Q-switch 1 MW 763.33) and an Acuosto-Optic standing wave modulator. The laser pulse was obtained from the oscillator by cavity dumping through an intracavity Pockels cell. The laser was operated in the transverse fundamental mode with a typical repetition rate of 2 Hz. The choice of irradiation wavelength was either 1.064 or 0.532 μm depending on the experimental requirement.

Various analytical techniques, like Energy Dispersive Analysis (EDS), Optical Microscopy (OM) and Scanning Electron Microscopy (SEM), were used for characterization of the titanium sample. EDS was employed to determine surface composition, whereas the surface morphology was monitored by OM and SEM.

Results and Discussion

Composition of the non-irradiated titanium surface, determined by EDS analysis, was the following: titanium ~96%, balanced to 100% by O, C, Al and Si (Table 1, case A). All the results are given in weight %. Also, the complete element analysis was normalized. After the exposure of the targets (case-B) to 30 laser pulses having energy density 2.4 J/cm^2 at 1.064 μm wavelength, the compositions of targets were studied. It was observed that oxygen content was increased from 3 to 6 % (Table 1, case B). This effect may be attributed to a possible oxidation of the target.

Table 1 Analysis of elements on the titanium surface by EDS.

element	C	O	Al	Si	Ti	Total (%)
Case A	0.51	3.04	0.14	0.30	96.1	100.00
Case B	1.13	6.01	0.20	0.22	91.44	100.00

Laser-induced morphological changes on the titanium surface explicitly showed dependence on beam characteristics: primarily on the laser energy density, peak power density, number of accumulated pulses, laser pulse wavelength, etc.

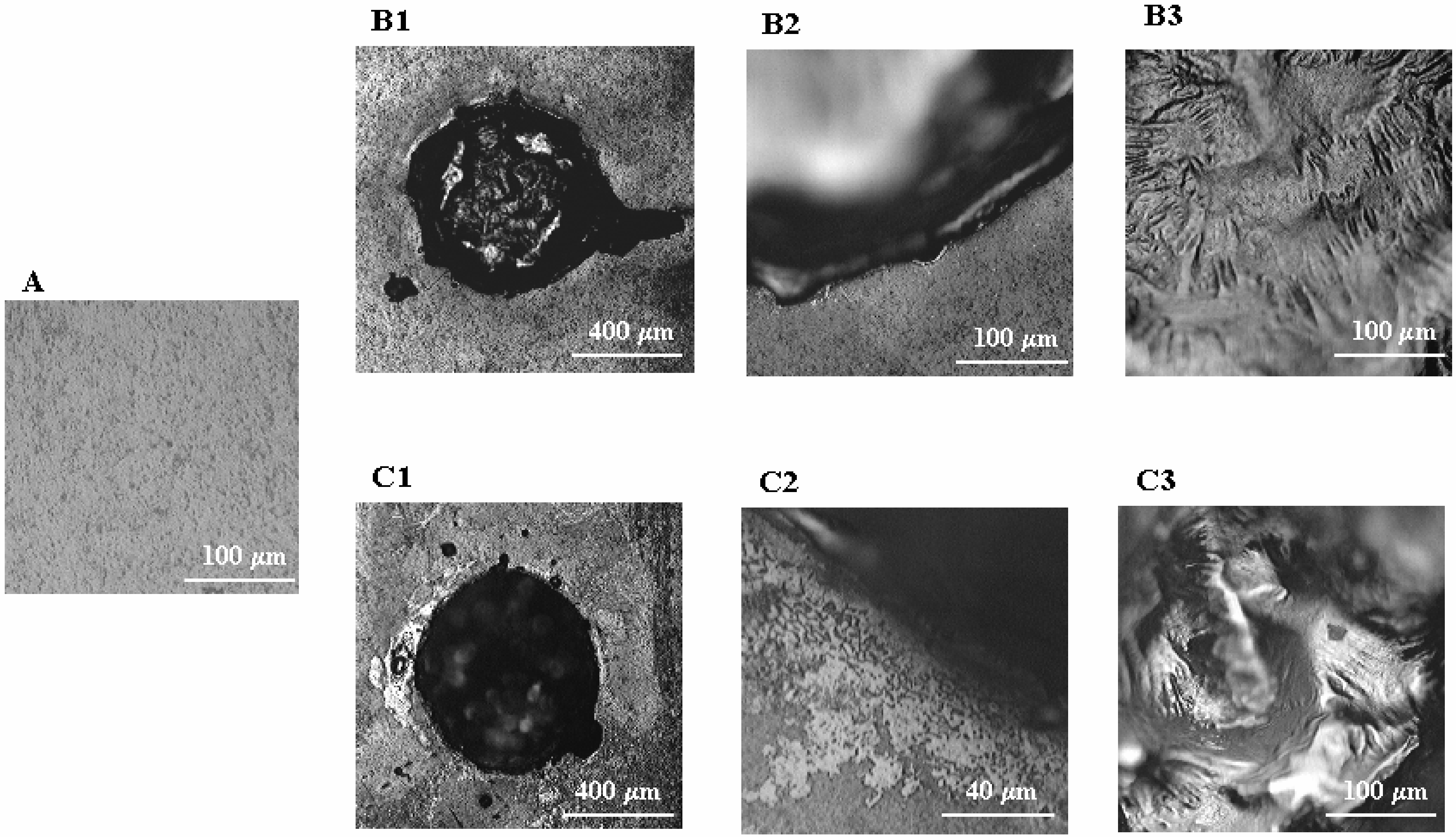

Fig. 1 Picosecond Nd:YAG laser-induced morphological changes of titanium (Optical Microscopy). Energy density, 10.3 J/cm^2, λ_1^{laser}= 1.064 μm; TEM$_{00}$ mode. (A) A view of the titanium surface prior to laser action; (B) titanium after 1 laser pulse ((1,2,3) entire spot, part of periphery, and center, respectively); (C) titanium after 5 pulses ((1,2,3) entire spot, periphery, and center of the damage area, respectively).

Morphological changes of titanium for 1, 5 and 30 accumulated laser pulses, λ_1^{laser}= 1.064 μm and λ_2^{laser}= 0.532 μm, are presented in Figs. 1 and 2, respectively. It is quite visible, Fig. 1 (B1,2), that only one laser pulse induced a high level of target damage. Accumulation of a greater number of pulses, Fig. 1 (C1), resulted primarily in enhanced depth of the damage. Generally, the action of the laser at 1.064 μm resulted in: (i) a clearly visible crater-like modification; (ii) presence of hydrodynamical effects expressed in the form of resolidified crater edge, corrugation (central part), and formation of droplets; and (iii) appearance of plasma in front of the titanium target.

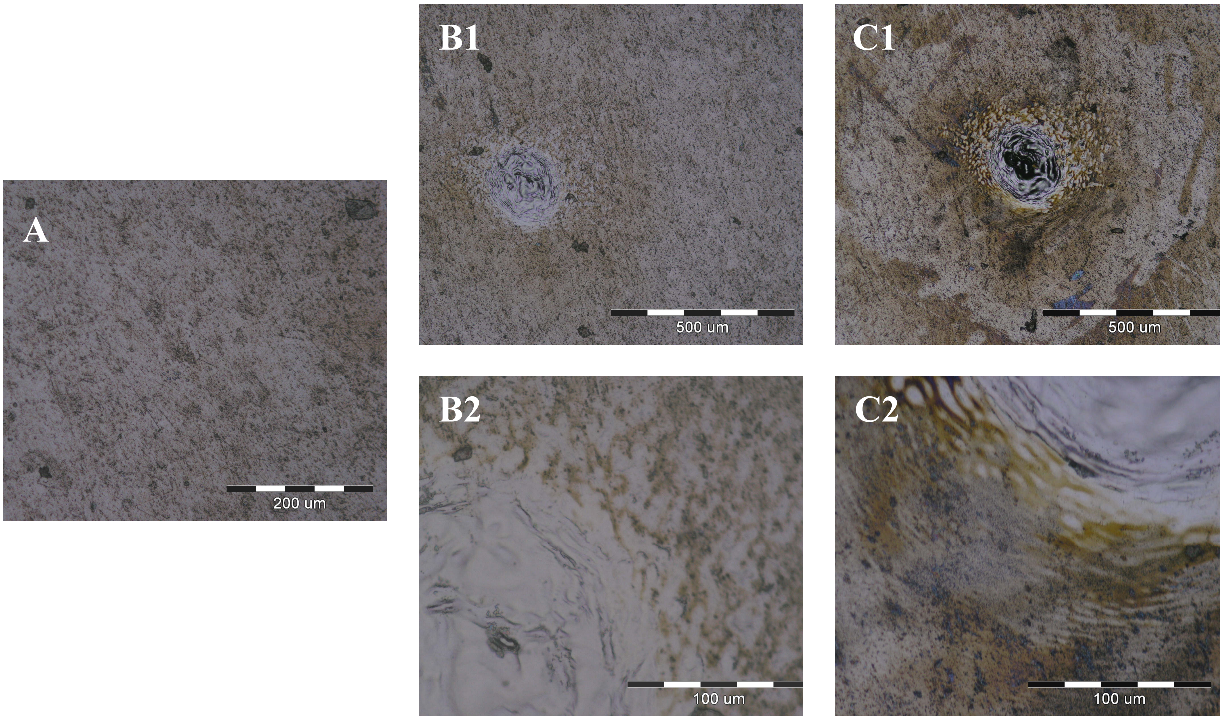

Fig. 2 Picosecond Nd:YAG laser-induced morphology changes of titanium (Optical Microscopy). Energy density, 1.1 J/cm^2, λ_2^{laser}= 0.532 μm; TEM$_{00}$ mode. (A) A view of titanium prior to laser action; (B) titanium after 5 laser pulses ((1,2) entire spot and part of the periphery, respectively); (C) titanium after 30 laser pulses ((1,2) entire spot and periphery of the damage area, respectively).

Morphological features of titanium upon irradiation with Nd:YAG laser at 0.532 μm are presented in Fig. 2. The general features are: (i) The damage area- crater is not sharp as in the case of Fig. 1; (ii) appearance of a periodic structure on titanium, Fig. 2 (C2), was recorded; and (iii) plasma appeared in front of the target during irradiation.

A more detailed view of morphological changes of titanium surface after 1-laser pulse irradiation (energy density was 10.3 J/cm^2, λ_1^{laser}= 1.064 μm) is given in Fig. 3, obtained by a scanning electron microscope. A clearly pronounced crater was registered, but also cracks and grainy-structured layers inside the irradiated area, Fig. 3B3, instead of melted material. The depth of the crater was smaller compared to the one in Fig. 1, but the sharpness was preserved.

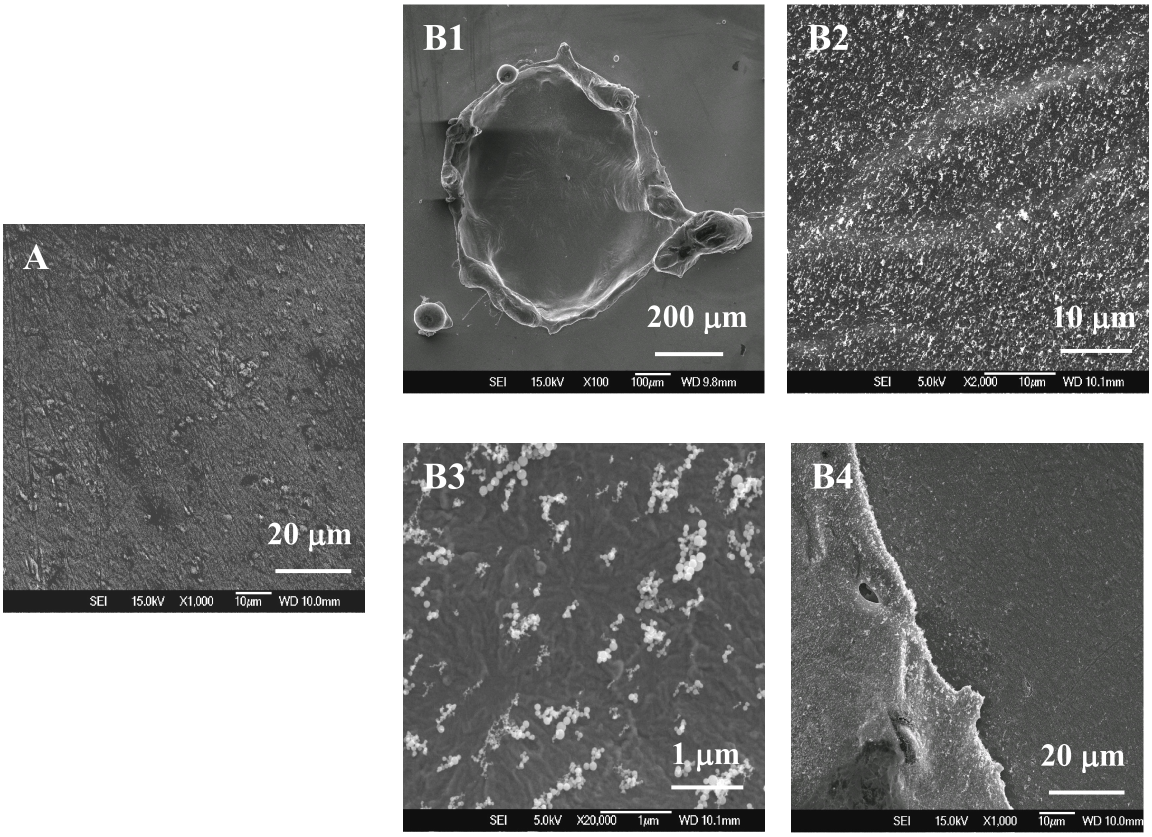

Fig. 3 Picosecond Nd:YAG laser-induced morphology changes of titanium (Scanning Electron Microscopy). Energy density, 10.3 J/cm^2, λ_1^{laser}= 1.064 μm; TEM$_{00}$ mode. (A) A view of titanium prior to laser action; (B) titanium after 1 laser pulses action ((1) entire spot, (2,3) center of modified surface at different magnification, and (4) near-periphery of irradiated area).

It is well known that for laser pulses shorter than 10 ps, electron thermal diffusivity can be neglected, whereas electron temperatures differ from lattice temperatures [12]. In our experiment, thermal effects cannot be neglected. It can be assumed that the energy deposited from the Nd:YAG laser beam, optical pulse duration of 40 ps, to the titanium target is partially converted into thermal energy. Generally, a series of effects such as: melting, vaporization of molten materials, dissociation and ionization of the vaporized material, shock waves in the vapor and in the solid, appearance of plasma, etc., were generated on the target. Essentially, these processes are extremely fast. In one approximation it can thus be assumed that a direct solid-vapor (or solid-plasma) transition takes place, especially when using higher energy densities.

Conclusion

A qualitative study of morphological changes on titanium induced by a Nd:YAG laser, operating at wavelengths 1.064 or 0.532 μm, is presented. It is shown that the Nd:YAG laser induces morphological changes of titanium. Laser energy densities of 10.3 and 2.4 J/cm^2 (λ_1^{laser}= 1.064 μm); as well as 1.1 J/cm^2 (λ_2^{laser}= 0.532 μm) were found to be sufficient for inducing surface modifications of the samples and to cause various hydrodynamic phenomenons.

The energy deposited from the Nd:YAG laser beam is partially converted into thermal energy. Generally, various effects are induced, e.g. melting, vaporization and shock waves in the vapor and solid state material, appearance of plasma, etc.

Qualitatively, the morphological modifications of the titanium target can be summarized as follows: (i) for both laser wavelengths used, ablation of titanium in the central zone of the irradiated area was recorded. Ablation was more pronounced in the case of λ_1^{laser}= 1.064 μm; (ii) appearance of a hydrodynamic feature in the form of resolidified rim droplets of the material, pronounced corrugation in the case of λ_1^{laser}= 1.064 μm, and formation of wave-like microstructures in the case of λ_2^{laser}= 0.532 μm.

It should be emphasized that Nd:YAG laser interaction with titanium targets caused ignition of plasma already during the first and all subsequent laser pulses at both laser wavelengths. Plasma showed the form of sparks and torch for laser wavelength of 1.064 and 0.532 μm, respectively.

The results also show that laser radiation in the near-IR region is a better choice in terms of the effectiveness and precision of material ablation compared to shorter wavelength used in present experiments.

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