ISSN 1330–0008
CODEN FIZAE4

NITROGEN LASER BEAM INTERACTION WITH TITANIUM SURFACE

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Received 7 April 1995

Revised manuscript received 14 August 1995

UDC 533.9

PACS 52.50.Jm, 61.80.Ba

Solid titanium target was irradiated with a N_2 laser beam of a maximal energy density of 1.1 J/cm^2 per pulse and of a duration of 6 ns. The plasma, formed near the titanium surface, was analyzed by emission spectroscopy, and the irradiated Ti surface was studied by a metallographic microscope. The results of both investigations reveal the influence of resonant absorption of the laser radiation by the generated plasma. The plasma is dense and strongly ionized, with an electron density of 1.5×10^{18} cm^{-3} and electron temperature of 2.7 eV. The surface heating was found to be several times more efficient than in the cases when resonant absorption is absent. Most of the observed surface patterns appear to be caused by nonuniform surface heating and a very rapid cooling. The other features are interpreted as a possible consequence of plasma–hot surface interactions.

1. Introduction

The interaction of laser radiation and solid surfaces has been extensively studied. Some experiments were devoted to the study of surface damage [1,2], others to the study of emitted particles and plasma generation [3,4]. Many experiments correlate the surface damage and the resulting plasma [5–8]. In the special case when the laser radiation is tuned to the resonant atomic line of the target material, a sharp decrease of the plasma formation threshold was observed [9].

A similar situation is encountered in the case of N_2 laser radiation and a titanium target. The nitrogen laser radiates at the wavelength of 337.1 nm. The laser line overlaps with two Ti I lines, the 337.04 nm resonant line and the 337.145 nm line, and with two Ti II lines at 337.221 nm and at 337.280 nm. In such conditions, a stronger interaction of the generated plasma and the laser radiation is expected. The surface topology of the damaged area should be influenced by this effect as well.

In this paper the plasma parameters and the surface damage in such experimental conditions are described.

2. Experimental setup

The nitrogen laser produced 9 mJ pulses of a full width at half maximum of 6 ns and a repetition rate of about 0.2 Hz. The target surface was perpendicular to the laser beam axis. It was finely ground and cleaned in an ultrasonic bath immediately before the measurements. During the irradiation, the target was in vacuum at a base pressure of 0.1 mbar. The laser radiation was focused onto the target surface to achieve an average energy density of 0.8 J/cm^2 per pulse. The laser beam profile was not uniform and shows irregular spatial distribution, with two hot spots (see Fig. 1a). The peak energy density was 1.1 J/cm^2. Some 100 pulses were needed to produce stabilized damage patterns. They were studied with a methalographic microscope (Leitz "Aristomet").

Optical emission of the plasma produced during the irradiation was recorded with a quartz prism spectrograph (Carl Zeiss Q24) in the spectral region between 240 and 500 nm. The optical axis of the spectrograph was parallel to the target surface and perpendicular to the laser beam axis. It was at a height of 0.1 mm above the target surface [10].

The plasma spectra were used to deduce time-averaged plasma parameters. Standard diagnostic procedures [11] were used. The electron temperature was deduced from the spectral line intensity ratio of two lines of successive ionization stages. Electron density was deduced from Stark broadening of spectral lines.

The approximate target surface temperature in the hot spot was estimated using a 1-D numerical model of solid metal target heating described in Ref. 11. This model assumes that all energy is deposited within a surface layer whose thickness is comparable to the optical depth of the target material. If thermal diffusion is neglected and blackbody-like radiation losses are assumed, the model predicts a surface temperature that is in satisfactory agreement with experimental results [11,12].

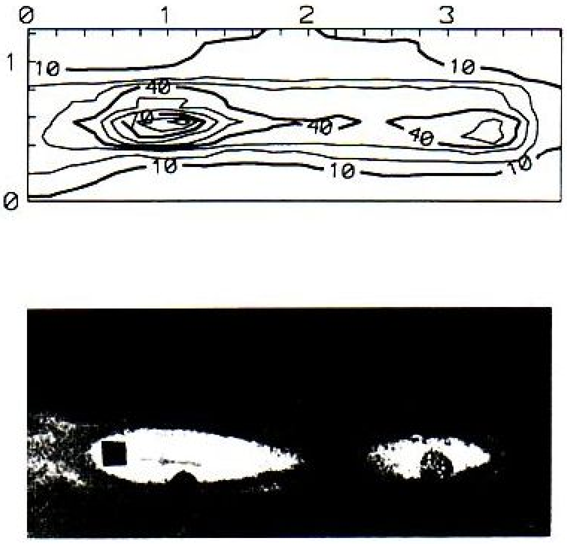

Fig. 1. a. (top) The spatial laser beam energy density distribution on the target surface. The numbers on the isophotes indicate the percentage of the maximal value of the intensity.

b. (bottom) The irradiated target area after 100 laser pulses. Note the general correspondence of the target damage and the intensity distribution. The filled circle in Fig. 1b indicates the area that is shown enlarged in Fig. 2a, and the filled square the area that is shown enlarged in Fig. 2b.

3. Results

Due to the nonuniformity of the laser beam profile, two craters were created on the target surface (Fig. 1b). Different energy densities present in the focal spot produced a varied topography of the affected region of the target, parts of which were created by different physical mechanisms. Going from the outside of the affected region towards the hot spot, we first encounter a region where the onset of exfoliation can be seen. This area is marked by a filled circle in Fig. 1b and magnified in Fig. 2a. In this region, a rapid thermal expansion of the target material caused large thermal stresses inside the material with the end result that the surface layer detaches from the bulk material under it [13]. The exfoliation process was not complete and flakes remain attached to the bulk material. Near the edges of the flakes, a start of melting is observed due to the poorer conduction of the heat energy into the bulk material. All this leads to the conclusion that in this region maximal temperature was near the melting temperature, although the laser beam intensity was only 40% of the peak value (see Figs. 1a and b).

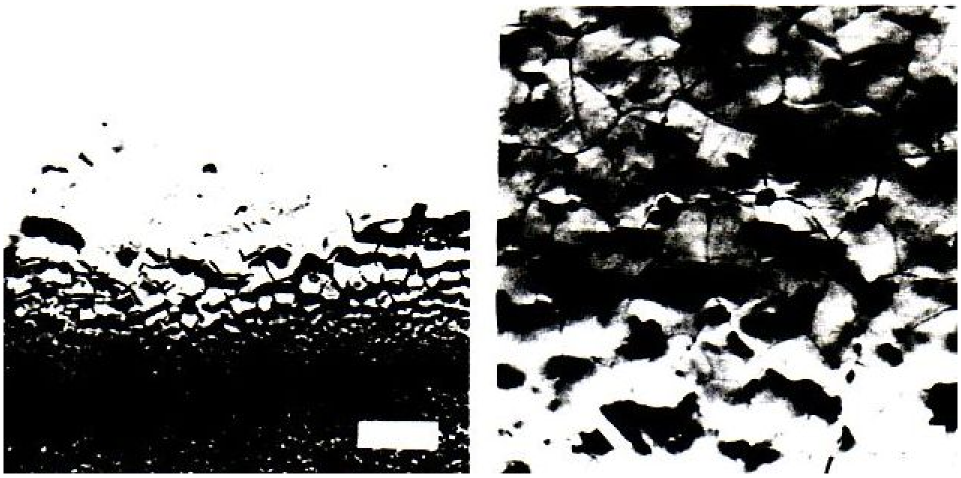

Fig. 2. The damaged titanium surface caused by the laser radiation of the energy density per pulse of:

a. (left) $0.4 - 0.5$ J/cm^2 *(the enlarged area marked with the filled circle in Fig. 1b).*

b. (right) about 0.7 J/cm^2 *(the enlarged area marked with the filled square in Fig. 1b). The long white bar in the figures indicates the length of 10* μm.

Closer to the hot spot, we encounter a region where material was clearly melted for a significant time during the laser pulse. This area is marked by a filled square in Fig. 1b and magnified in Fig. 2b. Note the absence of sharp edges and reduced surface roughness which indicate a melted surface layer. The cracks are most probably generated during the phase of rapid cooling and solidifying of the melt after the laser pulse (so called quenching [14]). Small craters with diameter of about 3 μm, and small domes with diameter of about 1 μm attached to the surface, marked by an arrow in the Fig. 2b, are also present.

At the hot spot itself, a very deep grove is generated (Fig. 1b). The grove has very steep sides and melted bottom, indicating that the dependence of ablation rate on input power is highly nonlinear. It is also possible that the grove generation is accelerated by the beam guiding effects [15]. In such a case, the sides of the grove act as a waveguide to guide the laser beam down to the bottom of the grove. This process is often observed and leads to the very deep holes or groves. In our case, the grove is so deep and rugged that the microscope failed to give a sharp image of its bottom.

The figures show an unexpected result: the molten surface and ejected droplets are produced with only 1.1 J/cm^2, while experiments performed in similar experimental conditions [13] with intensities up to 2.5 J/cm^2, but without resonant laser light absorption, showed less pronounced melting and absence of droplet formation on metals with similar melting points.

The plasma generated during the laser pulse above the titanium surface is observed to be more ionized and hotter than metallic plasmas generated under the same experimental conditions from other metallic targets (Al, Ref. [11], Mg and Cu, unpublished). The observed electron temperature of (2.7± 0.2) eV [10] is twice that expected for the beam intensity used. The observed electron density at 0.1 mm above the surface was $(1.5 \pm 0.5) \times 10^{18}$ cm^{-3}.

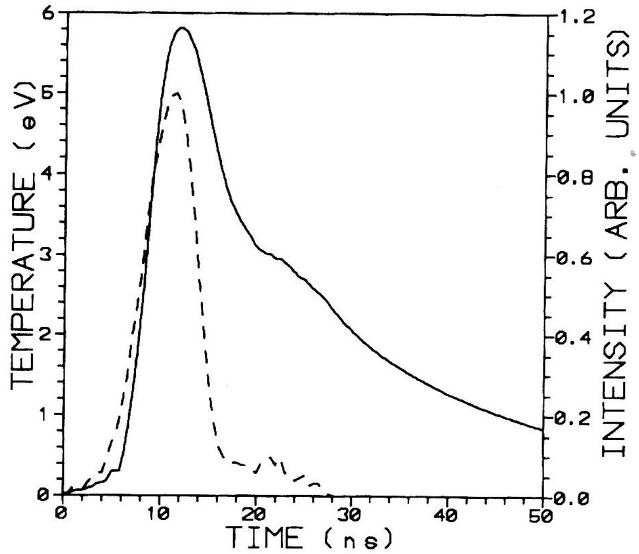

Fig. 3. Time evolution of the surface temperature predicted by the 1–D numerical model of target heating (solid line, left ordinate), calculated for the hot-spot region. Temporal laser pulse profile is indicated by the dashed line (right ordinate).

The estimated surface temperature is shown in Fig. 3, where surface temperature versus time is plotted. Although only radiation losses are accounted for, the temperature drops very rapidly after the end of the laser pulse. The whole temperature pulse lasts only several tens of nanoseconds, which is consistent with observed cracking of the surface that is assigned to a very rapid cooling.

4. Discussion

The high ionization rate and the high electron temperature in the plasma cloud is a straightforward consequence of the resonant absorption in the evaporated target material. For explanation of the unexpectedly high surface temperature, we propose the plasma "bleaching" effect. The initial strong absorption of the laser photons by the evaporated target material leads to a predominantly transparent plasma. Therefore, the laser radiation penetrates through the plasma cloud without substantial absorption, thus exposing the target surface to more laser energy than in the cases when the resonant absorption is absent.

The appearance of small craters and domes in the vicinity of the central grove (see Fig. 2b) is very interesting. The domes are possibly a consequence of solidification of small droplets on the surface. In the grove itself, the material is melted during the laser pulse and strong atom, ion, electron and microparticle emission occurs. While atoms, ions and electrons move apart forming the plasma cloud, the microparticles are solidified near the grove surfaces. These solidified droplets form small domes. During the next laser pulse, these domes are the origin of surface irregularities. At the beginning of the laser pulse, the surface starts to heat. The first emitted particles are hot electrons [5] and a potential difference between emitting particles and surface arises. The small domes, causing the local field enhancement [16], act as local spots where the strong ion current occurs. This current is, together with laser preheating of the surface, a possible cause of the crater formation. This model is quite similar to the model of unipolar vacuum arc formation [17], which assumes the strong ion or electron emission from the small surface areas. This "explosive charged particle emission" requires sufficient electric field towards the surface, in the range of 5–10× 10^9 V/m [18].

In order to estimate whether this field is expected to appear in our case, we evaluate the simple relation for the potential difference between non-biased metal surface and the surrounding plasma [19]:

$$\phi = \frac{kT_e}{2e} \ln \left(\frac{m_i}{2\pi m_e} \right) \tag{1}$$

where kT_e is the electron thermal energy, e is elementary charge, m_i and m_e are ion and electron masses, respectively. With the observed electron temperature, Eq. (1) gives $\phi \approx 12$ V. By assuming the electric field enhancement coefficient β to be around 50, the plasma–metal surface distance should be less or about 100 nm what is a quite plausible expectation. However, it should be noted that for this effect, the electron density should have somewhat lower value than the observed one. This implies that this process could appear in the early phase of the plasma formation.

5. *Conclusions*

The study of N_2 laser beam–titanium target interaction leads to the conclusion that the generated plasma, as well as the surface damage, were strongly influenced by the presence of the resonant absorption of the laser beam energy by the evaporated titanium atoms. This strong absorption has, as a consequence, almost two times higher electron temperature of the produced plasma than in similar cases when resonant absorption is absent.

The analysis of metalographic images reveals the surface topography that is common to metallic surfaces irradiated with laser beams with energy densities several-fold larger than in our case. The high efficiency of the surface heating is most probably a consequence of plasma bleaching caused by a strong resonant absorption of the laser radiation. Some elements of the surface topography show consequences of a very rapid solidification of the melted target material, thus supporting our calculations of time evolution of the surface temperature.

The small craters observed near the hot-spot area seem to be a result of a strong ion current through the spots in the vicinity of the surface irregularities, superimposed on the laser beam surface heating in the early phase of the plasma formation.

Acknowledgments

The authors thank to Dr. Nikola Radić for valuable comments concerning the plasma–metal surface interactions.

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DJELOVANJE DUŠIKOVOG LASERA NA POVRŠINU TITANA

Meta od titana ozračena je snopom iz N_2 lasera maksimalne gustoće energije 1,1 J/cm^2 po impulsu trajanja 6 ns. Plazma nastala uz površinu titana analizirana je emisijskom spektroskopijom, a ozrčena površina titana proučavana je metalografskim mikroskopom. Oba istraživanja ukazuju na važnost rezonantne apsorpcije laserskog zračenja u stvorenoj plazmi. Plazma je gusta i jako ionizirana, s elektroskom gustoćom $1,5 \times 10^{18}$ cm $^{-3}$ i elektronskom temperaturom od 2.7 eV Zagrijavanje površine je višestruko djelotvornije nego u slučajevima kada nema rezonantne apsorpcije. Najveći dio površinskih oblika čini se uzrokovanim nejednolikim zagrijavanjem površine i vrlo naglim hladenjem. Druge odlike se tumače kao posljedica uzajamnog djelovanja plazme s vrućom površinom.