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Effect of Surface Plasma on Nanosecond Laser Ablation

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Abstract—For the first time, the effect of target surface plasma on nanosecond laser ablation is studied. Surface plasma was generated by a high-power cw fiber laser beam incident on an iron target. A comparison of laser ablation by nanosecond Nd:YAG laser pulses (1064 nm, 5 ns) was performed upon exposure to the cw laser and during its short-term (5 ms) turn off. It was found that the emission intensity twofold increases in the presence of surface plasma. The temperature and electron density of the laser plume induced by the nanosecond laser also increased.

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Keywords: nanosecond laser ablation, surface plasma, laser-induced plasma.

Introduction. The feasibility of a remote quantitative elemental analysis using laser-induced plasma spectroscopy (LIPS) is in high demand in various scientific and industrial applications [1–4]. Recently, we demonstrated the feasibility of a multi-element online analysis during the fabrication of a metal articles using coaxial laser cladding [5]. Coaxial cladding is one case of additive technologies in which a metal powder or powder mixture flow is molten using a high-power cw laser. An article is fabricated by layer-by-layer printing; therewith, articles with elemental composition gradients can be produced. It was shown that an elemental analysis requires sampling (laser ablation) immediately in a melt bath characterized by high temperatures (to 3000 °C), and the presence of surface plasma. Surface plasma can affect the interaction of nanosecond laser pulses with material, which is the subject of this study.

In a number of published works, only episodic studies of the effect of surface plasma on laser ablation can be found; however, the simultaneous effect of several parameters (surface temperature, presence of surface plasma or flame) was investigated in these studies. For example, Shoursheini et al. [6] used a cw CO_2 laser beam to heat a target to increase the laser plasma luminosity intensity; however, the separate effects of each factor (surface temperature, surface plasma) were not evaluated. Liu et al. [7, 8] studied the effect of the burner flame plasma on properties of laser-induced plasma, and found that the intensity of spectral lines was four times higher in the case of laser ablation in flames. An increase in the intensity was explained by the higher temperature and electron density of laser plasma, which was associated with the presence of plasma flame over the target surface. Wiggins et al. [9] studied laser breakdown of gases by nanosecond pulses in plasma generated by another cw laser. They demonstrated that inverse bremsstrahlung absorption controls to a large extent the interaction of nanosecond laser pulses with rarefied plasma generated by a cw laser beam. This leads to an increase in the temperature and electron density of "nanosecond" laser plasma, in comparison with gas breakdown. Recently, Colonna et al. [10] performed systematic theoretical studies of the effect of rarefied plasma on laser ablation by nanosecond pulses, and found that the electron density of plasma in which laser breakdown occurs has a significant effect in initial stages of the laser plume evolutions.

The objective of this study is to evaluate the effect of surface plasma on laser ablation by nanosecond pulses and laser plume dynamics. Surface plasma was generated by a cw laser beam incident on an iron

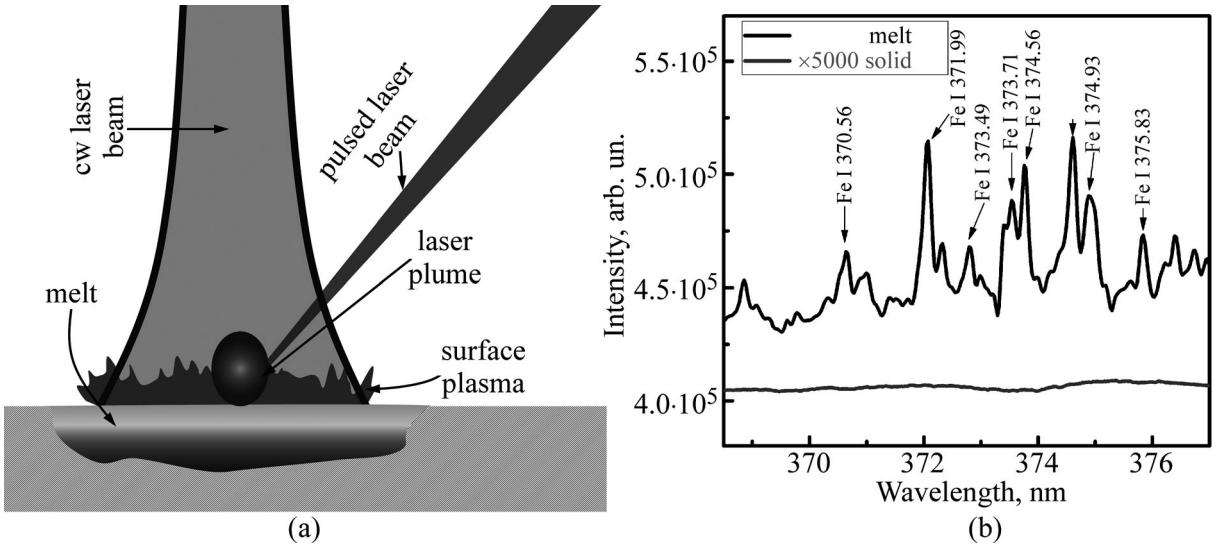

Fig. 1. (a) Experimental scheme for evaluating the effect of surface plasma generated by a high-power cw laser on nanosecond laser ablation. (b) Surface plasma spectra for a heated solid sample (gray) and melt (black) during exposure to cw laser radiation.

target until its melting; for surface plasma dissipation, the cw laser was turned off for several milliseconds during which the melt surface temperature remained unchanged.

Experimental. The experimental setup was described previously in detail in [5] and here it will be presented briefly (Fig. 1). The beam of the LS-5 cw fiber laser (1068 nm, 2 kW, Research Institute "Polus", Russia) was focused by a quartz lens ($F = 200$ mm) at 20 mm above the target surface (the beam diameter on the surface – is 2.5 mm). To prevent oxide film formation on the iron sample surface (Fe 99%), the system was blown by argon (Ar 99.9%). The laser beam of the nanosecond Nd:YAG laser (1064 nm, 5 ns, 130 mJ/pulse, $M^2 \approx 90$, 10 Hz) was focused on the melt surface at an angle of 45° using a quartz lens ($F = 280$ mm, laser spot diameter is 0.5 mm) through a hole in an aluminum mirror. Laser plume radiation was collected using this aluminum mirror and was focused by a quartz lens ($F = 70$ mm) on an end of a fiber cable which delivered radiation to the spectrometer (Shamrock 303i, Andor) equipped with a CCD camera with an image intensifier (iStar, Andor). To synchronize the time point of the influence of the nanosecond laser pulse and the cw laser operation, a photodiode (FD-24K) was used which triggered a DG-535 pulse generator which triggered the nanosecond laser. The sync pulse from the nanosecond laser generator was used to trigger the spectrometer. The target surface temperature was measured using a disappearing filament pyrometer ("Promin") to which a digital CMOS camera (acA1920-40um, Basler) was connected to provide gated measurements (minimum exposure is 50 μs, step is 50 μs). The temperature measurement accuracy by the pyrometer was estimated as ± 60 °C using a calibrated tungsten lamp. Before experiments, the iron sample was polished (to R2500) to remove oxide films.

Results and discussion. The high temperature of the target surface and presence of an external field of the cw laser lead to the surface plasma formation; therefore, the cw laser power was increased to 2 kW; in this case the sample was molten and a melt bath ~5 mm in diameter was formed. According to the NIST spectral database [11], the plasma spectrum was simulated at a temperature of 2000 K, which showed that the strongest spectral lines should be in the range of 360–375 nm for iron and in the range of 415–425 nm for argon. Figure 1(b) shows the spectra of the surface of the solid heated target (1200 °C) and melt (1590 °C) upon exposure to the cw laser beam. For a solid hot target we failed to record spectral lines; whereas iron lines were detected for the melt, which indicates the plasma presence over the melt surface. To estimate the surface plasma temperature, we used non-resonant atomic lines FeI 370.56, FeI 372.75, FeI 373.49, and FeI 374.56 nm [12]. The plasma electron density was calculated by the Stark broadening of the atomic line FeI 538.34 nm with correction to the spectrometer spectral function. The surface plasma temperature was estimated as 6500 K, and the electron density was $7 \cdot 10^{16}$ cm^{-3} which indicates a significant effect of the cw laser field on laser plasma properties.

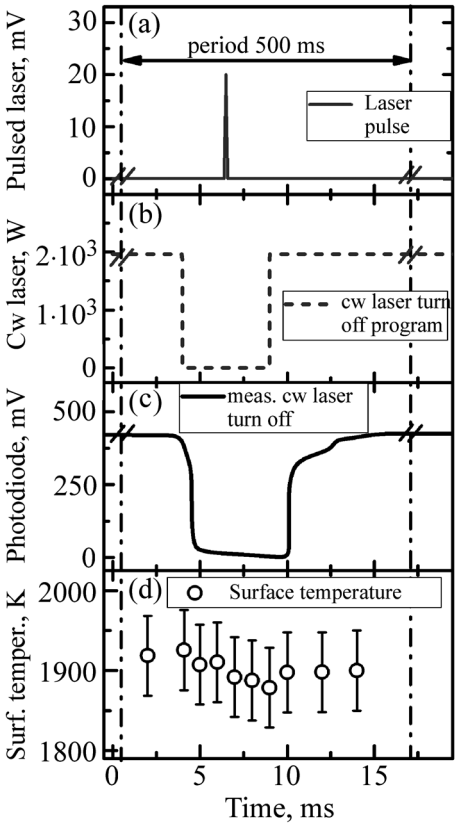

Fig. 2. Synchronization of the cw laser turn off and the time point of the nanosecond laser pulse influence: (a) nanosecond laser pulse with a 3-ms delay after turning off the cw laser; (b) programmed cw laser turn off for 5 ms each 500 ms; (c) measured intensity profile as the cw laser is turned off (FD24k photodiode, Tektronix 2024B oscilloscope); (d) target surface temperature at the time point of the cw laser turn off.

To correctly estimate the effect of surface plasma on nanosecond laser ablation, the effect of the high target temperature should be taken into account. When turning off the cw laser, not only surface plasma relaxation occurs, but also the target surface temperature decreases. However, due to a large volume of the melt bath, the melt surface cooling rate is significantly lower than the surface plasma dissipation rate. Turning off the cw laser for a short time, it can be achieved that surface plasma already dissipated, while the target surface temperature had no time to decrease. To experimentally test this assumption, a special program of the cw laser operation was set, according to which the laser should be turned off for 5 ms. The measured duration of the turn-off time (Fig. 2) was slightly longer (FD24K photodiode and Tektronix 2024B oscilloscope). To measure the melt bath temperature using the optical disappearing-filament pyrometer, CMOS camera measurements were synchronized by the leading edge of the photodiode signal. The pulsed measurements (Fig. 2(d), gate of 100 μs, step of 1 ms) of the melt surface temperature before and during the cw laser turn-off time showed that the melt temperature has no time to decrease at such a short turn off.

The effect of surface plasma on laser ablation by nanosecond pulses was studied by recording the evolution of the laser plume spectra (1-μs exposure and 1-μs delay step) at various synchronizations of time points of the pulsed laser operation and cw laser turn off: at a 3-ms delay after turning off the cw laser (OFF), surface plasma is absent; at a 450-ms delay (ON), surface plasma exists. A comparison of laser plasma spectra at one of time points of its evolution (1-μs exposure and 1-μs delay) is shown in Fig. 3. The intensities of main iron atomic lines for nanosecond laser plasma were two times higher in the case of laser breakdown in surface plasma. A comparison of the evolution of the iron atomic line emission, temperature, and electron density of plasma in the presence/absence of surface plasma is shown in Fig. 4. In the former case, the intensity of the FeI 372.75 nm atomic line was higher throughout the entire time of laser plume expansion. In this case, the plasma temperature and electron density differed only during the first 2 μs after laser breakdown. The results obtained are in good agreement with the previously

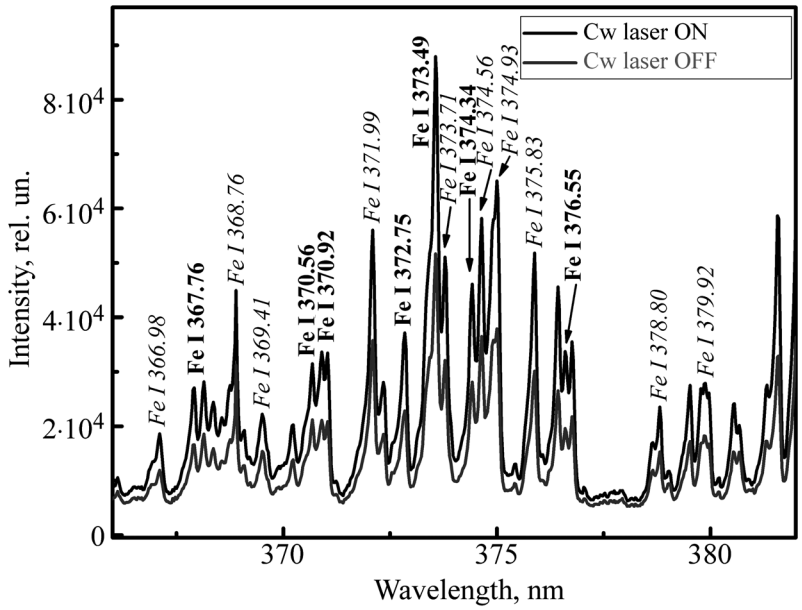

Fig. 3. Comparison of the spectra of plasma induced by nanosecond pulses in the presence (cw laser is turned on, black) and absence (cw laser is turned off, gray) of surface plasma. The bold font indicates the spectral lines used for calculating the temperature.

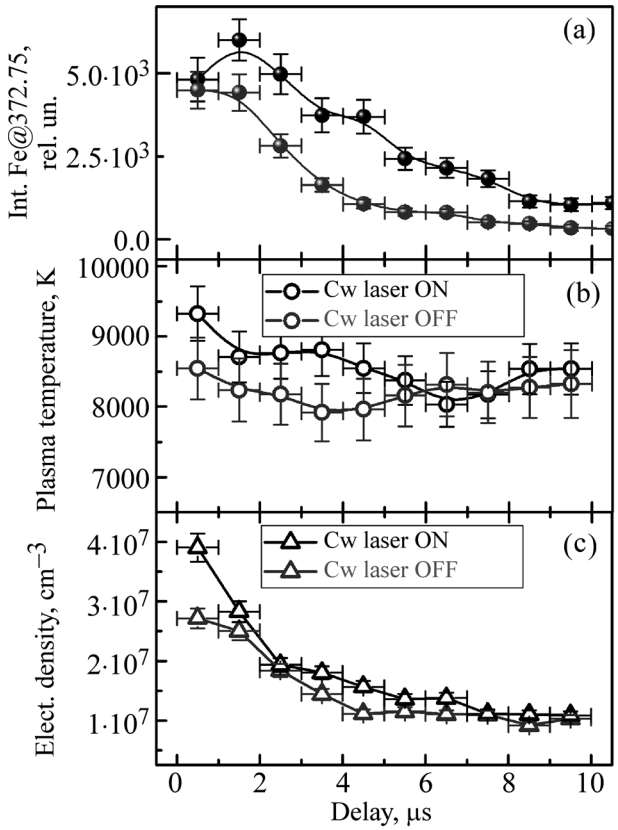

Fig. 4. Evolution of the (a) FeI 375.72 nm atomic line intensity, (b) temperature, and (c) electron density of plasma induced by nanosecond laser pulses.

published data by Liu et al. [7] where a fourfold increase in the laser plume luminosity was recorded

during nanosecond ablation in flame plasma. In the study by Wiggins et al. [9], it was found that the laser plume temperature and electron density increase by 5–10% during a nanosecond breakdown in nitrogen plasma generated by a cw fiber laser. In our experiments, the same increase in the temperature and electron density was recorded; however. the measurement accuracy was lower.

Conclusions. For the first time, the effect of surface plasma on the properties of the laser plume induced by nanosecond laser pulses was studied. Surface plasma was generated during melting an iron target by the cw fiber laser beam. To reveal the effect of only surface plasma on laser ablation, the cw laser was turned off for 5 ms; in this case. according to pyrometric measurements, the melt temperature remained unchanged. A comparison of the laser plume luminosity evolution revealed that the spectral line intensity is higher in the case of surface plasma, and the temperature and electron density are higher by 5–15% during the first 5 μs.

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REFERENCES

1. L. Peter, V. Sturm, and R. Noll, Appl. Opt. **42**, 6199 (2003); doi: 10.1364/AO.42.006199.
2. G. Hubmer, R. Kitzberger, and K. Mörwald, Anal. Bioanal. Chem. **385**, 219 (2006); doi: 10.1007/s00216-006-0321-9.
3. V. Sturm, R. Fleige, M. de Kanter, et al., Anal. Chem. **86**, 9687 (2014).
4. A.-M. Matiaske, I. B. Gornushkin, and U. Panne, Anal. Bioanal. Chem. **402**, 2597 (2012); doi: 10.1007/s00216-011-5165-2.
5. V. N. Lednev, M. Y. Grishin, P. A. Sdvizhenskii, et al., Addit. Manuf. **25**, 64 (2019); doi: 10.1016/j.addma.2018.10.043.
6. S. Z. Shoursheini, P. Parvin, B. Sajad, and M. A. Bassam, Appl. Spectrosc. **63**, 423 (2009).
7. L. Liu, S. Li, X. N. He, et al., Opt. Express. **22**, 7686 (2014); doi: 10.1364/OE.22.007686.
8. L. Liu, X. Huang, S. Li, et al., Opt. Express. **23**, 15047 (2015); doi: 10.1364/OE.23.015047.
9. D. L. Wiggins, C. T. Raynor, and J. A. Johnson, Phys. Plasmas. **17**, 103303 (2010); doi: 10.1063/1.3501995.
10. G. Colonna, A. Laricchiuta, and L. D. Pietanza, Spectrochim. Acta Part B: Atomic Spectrosc. **141**, 85 (2018); doi: 10.1016/j.sab.2018.01.009.
11. Y. Ralchenko, A. E. Kramida, J. Reader, and N. Team, NIST Atomic Spectra Database (version 5.4), (2018); http://physics.nist.gov/asd.
12. C. Aragón and J. A. Aguilera, Spectrochim. Acta Part B: At. Spectrosc. **63**, 893 (2008); doi: 10.1016/j.sab.2008.05.010.