Comparative Study of Plasma Shielding in Nanosecond Pulse And Long Pulse Laser Ablation Using Pump–Probe Techniques

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Our earlier study revealed that the efficiency of laser drilling using long pulses (LPs) of a conventional Nd:YAG laser was significantly higher than that using nanosecond pulses (NSPs). To elucidate a factor attributable to the higher efficiency of LPs, plasma shielding in laser ablation of Ni foils using LPs and NSPs was investigated using pump–probe techniques. Results showed that probe laser attenuation caused by laser ablation using LPs was lower than that using NSPs. This result strongly suggests that the lower degree of plasma shielding contributes to the higher drilling efficiency of LPs. Additionally, it was suggested that plasma shielding in LP ablation is mainly due to metal vapor, whereas that in NSP ablation is caused by atoms and ions.

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1. Introduction

Improvement of energy efficiency is one of the most important issues of laser machining. Particularly, considering materials degradation caused by excessive heating, improvement of energy efficiency at low laser energy is significantly desirable. Although the use of ultrashort pulsed lasers such as picosecond and femtosecond lasers is a promising solution to improve energy efficiency [1-5], our earlier study showed that the use of long pulses (LPs, see Fig. A) of a conventional Nd:YAG laser can be an alternative technique to improve energy efficiency at low laser energy [6]. It was demonstrated that the depth of holes formed by an LP at 1 mJ for Fe-Si-B amorphous alloy foils (Metglas® 2605HB1M; Hitachi Metal Ltd.,) was 75 µm, which was 500 times larger than the that formed by an NSP at 20 mJ (3 µm) of a Q-switched Nd:YAG laser.

In that study, we attributed the markedly higher drilling efficiency of an LP to the characteristic temporal profile of an LP. An LP is composed of a train of sub-pulses with lower peak energy than that of an NSP with the same total energy (Fig. A). It has been suggested that the lower peak energy can suppress the plasma generation, thereby reducing plasma shielding [7-9], and that repeated irradiation by sub-pulses can promote continuous material heating. Regarding the effect of repeated irradiation, it was confirmed by high-speed camera observation that repeated ejection of material is caused by an LP [6]. However, the influence of plasma shielding was not experimentally confirmed in that study. It was only inferred from the fact that the intensity of optical emission—which can be correlated with the amount of plasma generated—was much lower for LPs than for NSPs.

Reportedly, pump-probe techniques are appropriate methods to confirm the influences of plasma shielding. Nammi et al. observed plasma shielding during the laser ablation of copper films using NSPs of a Nd:YAG laser [10]. They employed a single-laser-based pump-probe system, in which a portion of the ablation laser was extracted and used as the probe beam. This setup enabled the observation of attenuation of the probe laser pulse caused by its interaction with the laser-induced plasma. In contrast, Kukreja et al. [11] observed ejection of materials caused by laser ablation of polyethylene terephthalate films using a pump-probe system in which continuous wave (CW) probe laser beam was used. They demonstrated that the ejection of excited atoms and ions occurs on a nanosecond timescale, whereas vapor ejection is observed on a microsecond timescale. Jeong et al. [12] observed shockwaves and vapor generated by laser ablation of aluminum plates using a similar pump-probe system. Material ejections in such a timescale are considered important in LP laser ablation, because

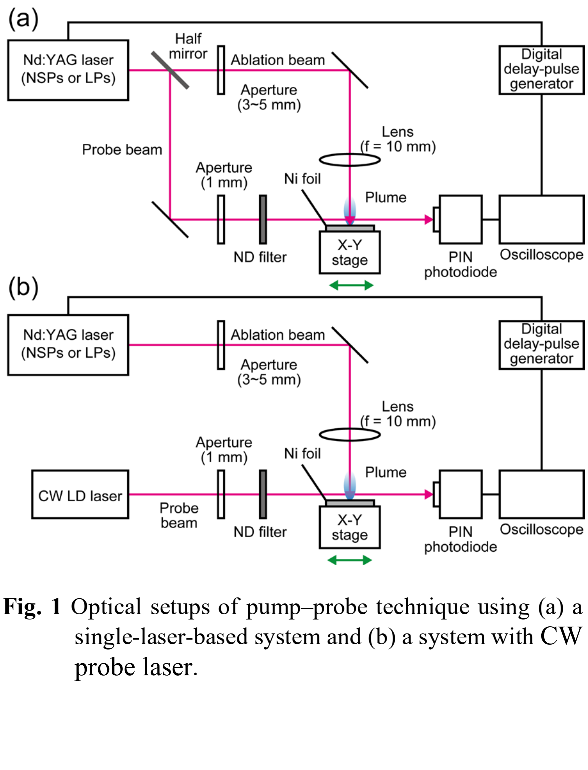

Fig. 1 Optical setups of pump–probe technique using (a) a single-laser-based system and (b) a system with CW probe laser.

the interval between sub-pulses in an LP is 3–7 μs (Fig. A). It has been shown that plasma generated by an earlier pulse can affect subsequent pulses when the pulse interval is shorter than the plasma lifetime [13,14].

In the present study, the influence of plasma shielding during laser ablation for Ni plates using NSPs and LPs were investigated using these two types of pump-probe techniques to clarify the difference in drilling efficiency between NSP and LP ablation.

2. Experimental

Fig. 1 portrays pump-probe systems used in the present study. The system shown in Fig. 1a is a single-laser-based system, in which a portion of the ablation laser was extracted using a half mirror and used as the probe beam. In the system shown in Fig. 1b, CW diode laser (MIL-S-1064-B; CNI laser, wavelength 1064 nm) was used as the probe beam.

In both systems, laser ablation was conducted using NSPs or LPs at 1064 nm generated by the pulsed Nd:YAG laser (GCR-200; Spectra-Physics KK). The repetition rate was 10 Hz. The pulse width of an NSP measured by our system was 40 ns (see Fig. 4a). A temporal profile of an LP without averaging is shown in Appendix (Fig. A). We confirmed that no significant difference was found between the spatial profile of an NSP and that of an LP [6]. The ablation beam was passed through a 5 mm aperture and then focused onto the target by a lens (f = 100 mm). To reduce the laser energy from 10 mJ to 5 mJ, the aperture size was decreased to approximately 3 mm, since adjusting the flashlamp power alters the temporal profiles of both NSPs and LPs. Strictly speaking, this method also affects the spatial beam profile. However, since the present study focused on the relative changes in drilling depth and plasma generation with respect to laser energy, this method was chosen for its simplicity over an optical setup incorporating an attenuator.

A Ni foil (99.9%; Nilako) was used as the target. Ni foils of 25 μm thickness were used to observe the drilling efficiency, while thicker (500 μm) foils were used in the pump-probe observation to avoid penetration. The Ni foil was set on a X–Y motorized stage, and the stage was moved during laser ablation.

The probe beam was aligned to pass just above the ablation spot. The distance between the ablation spot and the probe beam is ca. 0.5 mm. The diameter of the probe beam was adjusted to 1 mm using an aperture. The probe laser intensity was adjusted to less than 1 mW using ND filters. The probe laser intensity was monitored using a photodiode (S1722-02; Hamamatsu photonics) and a digital oscilloscope (TDS3032; Tektronix). The laser and the oscilloscope were synchronized using a digital delay pulse generator (DG535; Stanford Research Systems).

The optical emission spectra of laser plume were observed using a multichannel spectrometer (PMA-10; Hamamatsu Photonics KK) with an optical fiber.

The craters and holes formed by laser ablation were observed using a SEM (JCM-6000Plus; JEOL). The depth profiles of craters were observed using a three-dimensional optical interferometer (VS1800; Hitachi High-Technologies Corp.). The depth of holes was estimated by counting numbers of through-holes formed by laser ablation for stacked foils (20 layers).

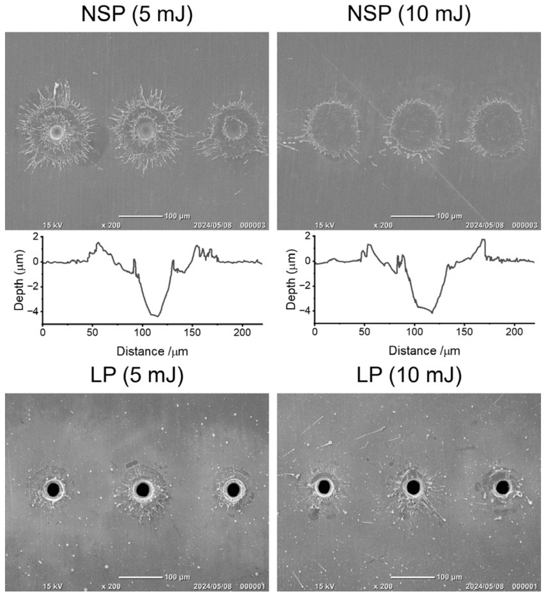

Fig. 2 SEM images of Ni foils of 25 μm thickness after laser ablation using NSPs and LPs at 5 and 10 mJ. Each crater and hole were formed by single pulse. Depth profiles of craters formed by NSPs are also shown.

Table 1 Depth of crater or holes formed by an NSP and an LP, and corresponding energy efficiency of drilling.

Laser energy mJ	Depth μm		Energy efficiency μm/mJ	
	NSP 1)	LP 2)	NSP	LP
5	5.0 ± 2.3	180 ± 25	1.0	36
10	3.7 ± 0.9	284 ± 27	0.4	28

1) Estimated from the depth profile of craters.
2) Estimated by counting numbers of holes formed on stacked foils (20 layers).

3. Results and Discussion

3.1 Comparison of drilling efficiency between NSPs and LPs for Ni foils

First, we observed drilling efficiency of an NSP and an LP for Ni foils. Fig. 2 shows morphology of Ni foils after laser ablation by an NSP and an LP at 5 and 10 mJ. The drilling depth obtained by these conditions is shown in Table 1. Similarly to the results obtained for amorphous alloy foils [6], a crater of less than 10 μm depth can be formed by an NSP, and a through hole of a several hundred μm depth can be formed by an LP at these intensities, indicating that the energy efficiency of an LP was significantly higher than that of an NSP. Additionally, the energy efficiencies of both an NSP and an LP decreased with the increasing laser energy.

Fig. 3 shows optical emission spectra observed for laser ablation using NSPs and LPs. The intensity of the optical emissions generated by an NSP is higher than that generated by an LP, and the optical emission intensity increased with increasing laser energy. These results indicate that energy efficiency of the drilling is decreased with increas-

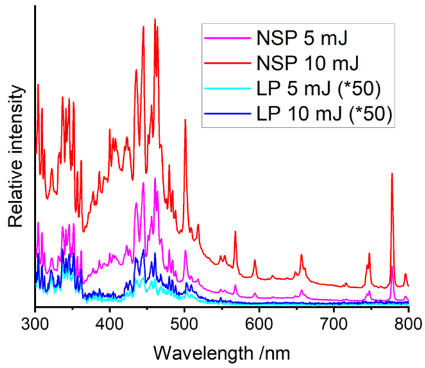

Fig. 3 Optical emission spectra of plasma generated by laser ablation using NSPs and LPs at 5 and 10 mJ for a Ni plate. The intensity of the emission spectra observed for LPs are multiplied by a factor of 50. Each spectrum was obtained by averaging optical emissions of plasma generated by 10 laser shots.

ing optical emission intensity. As proposed in an earlier study [6], this relationship between the energy efficiency of drilling and the optical emission intensity suggests that the generation of plasma would influence the drilling efficiency, particularly on NSP ablation compared to LP ablation.

3.2 Observation of plasma shielding and material ejection caused by NSPs and LPs

To confirm the above assumption, the effects of plasma shielding on NSP ablation and LP ablation were compared using the pump-probe technique shown in Fig. 1a. In NSP ablation (Fig. 4a), attenuation of the probe laser was clearly observed. The probe laser intensity decreased by 30% at an ablation laser energy of 5 mJ and by 60% at 10 mJ. Similar results were reported for laser ablation of copper foils using NSPs of a Nd:YAG laser [10].

In LP ablation (Fig. 4b), although the temporal profile of LPs was significantly deformed by shot-to-shot timing jitter in the LPs, decrease in the probe laser intensity was observed. From the intensity of the first 6 sub-pulses, the average rate of the reduction caused by ablation laser at 5 and 10 mJ was estimated to be 16% and 19%, respectively, indicating that the influence of plasma shielding was smaller in laser ablation using LPs than in that using NSPs. This result strongly supports the assumption that the lower degree of plasma shielding of LPs than that of NSPs would contribute to the higher drilling efficiency.

To gain a deeper understanding of the relation between material ejection and plasma shielding, material ejection phenomena caused by laser ablation was observed using the pump–probe system shown in Fig. 1b. The results are shown in Fig. 5. When NSPs ablation was conducted, a sharp dip appearing immediately after the laser pulse and a broad dip on the order of several tens of microseconds were observed. According to an earlier study [11], the former is attributable to the ejection of excited atoms and ions, while the latter is attributable to ejection of metal vapor. Therefore, it is reasonable to conclude that the attenuation of NSPs observed in Fig. 4a is mainly due to atoms and ions. Furthermore, the optical emissions observed in Fig. 2 must be due to these components.

In contrast, when LP ablation was conducted, no sharp dips corresponding to each sub-pulses were observed, and only a broad dip extending over the entire pulse duration

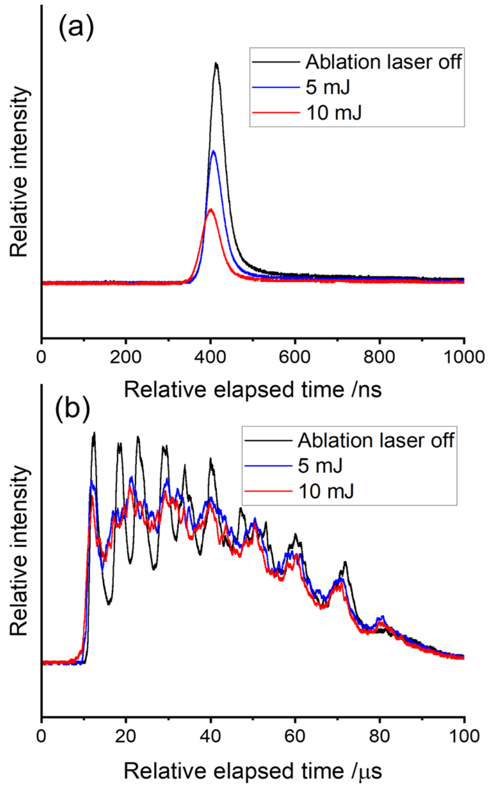

Fig. 4 Temporal profile changes of (a) an NSP and (b) an LP probe beam caused by laser ablation. Each data was obtained by averaging results from 16 pulses. The temporal profile of an LP shown in Fig. 4b was deformed from that of an original pulse (Fig. A) after averaging due to jitter and fluctuation of relative intensity of sub-pulses in LPs.

was observed. Based on the assignment of dips made for the NSP ablation, it is suggested that these broad dips are mainly due to vapor, and the contribution from atoms or ions is considered to be small. This assignment is consistent with the lower intensity of optical emissions observed in LP ablation (Fig. 2). Since the dip overlaps with an LP, it is considered that the shielding of LP is mainly due to vapor. The results of an earlier study suggested that

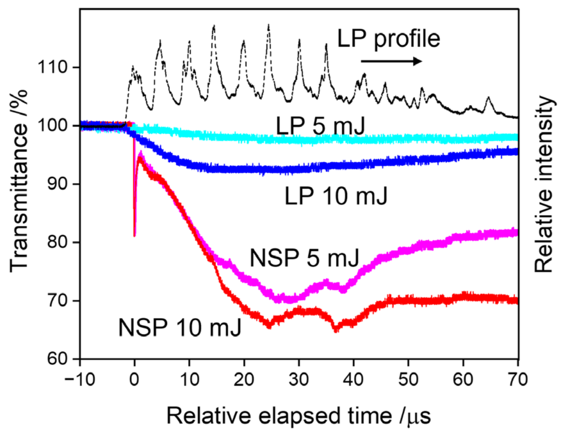

Fig. 5 Temporal transmittance changes of CW probe-laser caused by (a) NSP laser ablation and (b) LP laser ablation. Each data was obtained by averaging results from 32 pulses. A temporal profile of an LP is also shown.

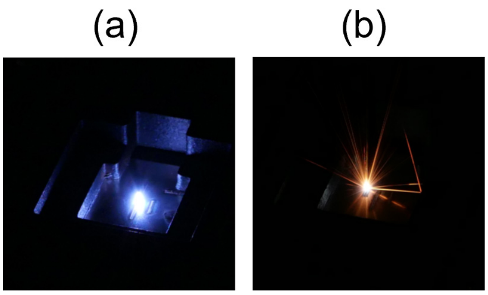

Fig. 6 Pictures of ablation plume generated by laser ablation using (a) an NSP and (b) an LP at 10 mJ. These pictures were taken using a conventional still camera.

LP drilling proceeds mainly through evaporation and melting of the material [6]. The present results support this view.

Additionally, the depth of the dips in Fig. 5 indicates that the amount of vapor generated by LPs is less than that generated by NSPs. This finding seems to be inconsistent with the fact that LP drilling is more efficient than NSP drilling. One possible explanation is that drilling in LP ablation proceeds through the ejection of droplets, which will occur more slowly than vapor. As shown by picture of ablation plume, compared to the gaseous plume generated by NSPs (Fig. 6a), the plume produced by LPs seems to contain metal droplets (Fig. 6b). Moreover, these droplets travel in various directions, unlike the gaseous plume. It is suggested that these droplets would not influence the ablation or probe laser. In other words, the progress of drilling via droplet ejection is considered a key factor increasing the efficiency of LP ablation. Moreover, as suggested previously [6], metal melting generating the droplets is likely to proceed through repeated irradiation by sub-pulses in LP ablation.

4. Conclusion

Plasma shielding during laser ablation of Ni foils using LPs and NSPs was observed using pump-probe techniques. Results showed that probe laser attenuation caused by laser ablation using LPs was lower than that using NSPs. This result strongly suggests that the higher drilling efficiency of LPs compared to NSPs is attributable to a lower degree of plasma shielding, in addition to repeated irradiation of a material by sub-pulses in LP ablation. It was suggested that shielding in LP ablation is mainly caused by metal vapor, whereas that in NSP ablation is caused by atoms and ions.

It must be noted that, in the present study, plasma shielding for a probe laser transmitted horizontally through the plume was observed, rather than that for an ablation laser transmitted vertically through the plume. Therefore, a quantitative discussion of the relationship between drilling efficiency and shielding rate is difficult. To conduct such a discussion, numerical simulations must be necessary.

Appendix

See Fig. A

Acknowledgment

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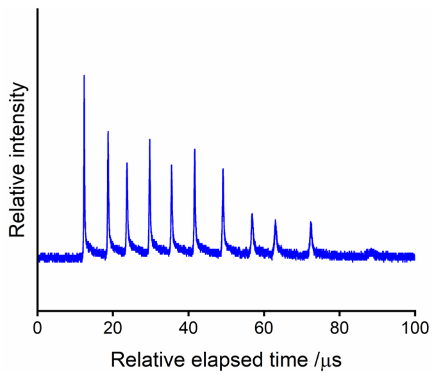

Fig. A Temporal profile of an LP generated by the Nd:YAG laser used in this study. An LP is generated by one flashlamp pumping without using Q-switching. The average width of sub-pulses is ca. 400 ns, and the interval between the sub pulses are 3-7 μs. This data was taken without averaging. Because of the timing jitter and fluctuation of the relative intensity of sub-pulses, averaging over at least 16 iterations was required to obtain the data shown in Fig. 4b.

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