Observation of expansion velocity of laser plasmas using a streak camera

M. Heya, K. Matsumoto, T. Takeshita, S. Okihara, and M. Yamanaka

The Graduate School for the Creation of New Photonics Industries, 1955-1 Kurematsu-Chou, Nishi-Ku, Hamamatsu-City, Shizuoka 431-1202, Japan

ABSTRACT

In a conventional laser shock peening (LSP), it was previously reported that an interaction efficiency from laser pulse energy to pulse pressure energy was relatively lower and was experimentally estimated to be ~20%. The purpose of this study was to establish the time-resolved observation of laser plasmas using a streak camera in order to optimize the laser conditions for an efficient LSP. We preliminarily observed the dynamics of laser plasmas using a streak camera. We estimated the dependence of the expansion velocity of the laser plasmas on the laser pulse energy. We found that the expansion velocity became higher with an increase of the laser pulse energy even when the laser pulse width was constant. Higher velocity leads to the generation of higher pulse pressure. Thus, we confirmed the usefulness of the time-resolved measurement of the plasma expansion using a streak camera for the development of an efficient LSP system.

KEY WORDS

Efficient LSP, Expansion velocity, Laser plasmas, Pulse pressure, Streak camera

INTRODUCTION

Laser shock peening (LSP) is an attractive and unique surface treatment technique, which has been successfully applied to improve fatigue performance of metallic components in heavy industries (K. Ding and L. Ye, 2006). LSP is conventionally treated by a commercial Q-switch Nd:YAG laser with a pulse width of 5-30 ns. In this case, it was previously reported by several researchers that an interaction efficiency, α, from a laser pulse energy to a pulse pressure energy was experimentally estimated to be about 20% (R. Fabbro *et al*., 1990; Y. Sano *et al*., 1997). During the interaction between a laser and a metallic surface, the total energy, E_T, from the laser source is converted into two parts. One part of the energy, αE_T, contributes to the generation of the pulse pressure, while the other part of the energy, $(1-\alpha)E_T$, is devoted to the generation and ionization of the laser plasmas. The improvement of the efficiency is essentially important for an efficient generation of the pulse pressure. This leads to a compact and low-priced LSP system.

The interaction effciency can be experimentally determined by measuring the temporal behaviors of the pulse pressure (R. Fabbro *et al*., 1990) and laser plasmas (Y. Sano *et al*., 1997). We focus on the temporal behavior of the laser plasmas, in particular, the expansion velocity of the laser plasmas, V(t), which is linearly proportional to the pulse pressure, P(t) (K. Ding and L. Ye, 2006). The use of a streak camera is suitable for the time-resolved measurement of plasma expansion, because a measuring instrument requires a higher temporal resolution. In this paper, we observe the dynamics of the expansion of the laser plasmas using a streak camera and estimate the temporal change of the expansion velocity as a function of a laser pulse energy.

METHODS

Figure 1 shows the experimental setup. The Fe targets were irradiated by a Q-switch Nd:YAG laser. The laser wavelength and the laser pulse width were 532 nm and ~7.5 ns, respectively. The laser pulse energy was varied within 5-20 mJ. The beam spot diameter was fixed and was estimated to be ~0.2 mm. We observed the dynamics of the laser plasmas by using a visible streak camera (C5680, Hamamatsu Photonics K. K.) with an observable spectral range of 200-850 nm. The estimated temporal resolution was ~8 ns. We used a combination of two relay lenses (f = 250 mm and 50 mm), resulting in the image magnification of ~5.

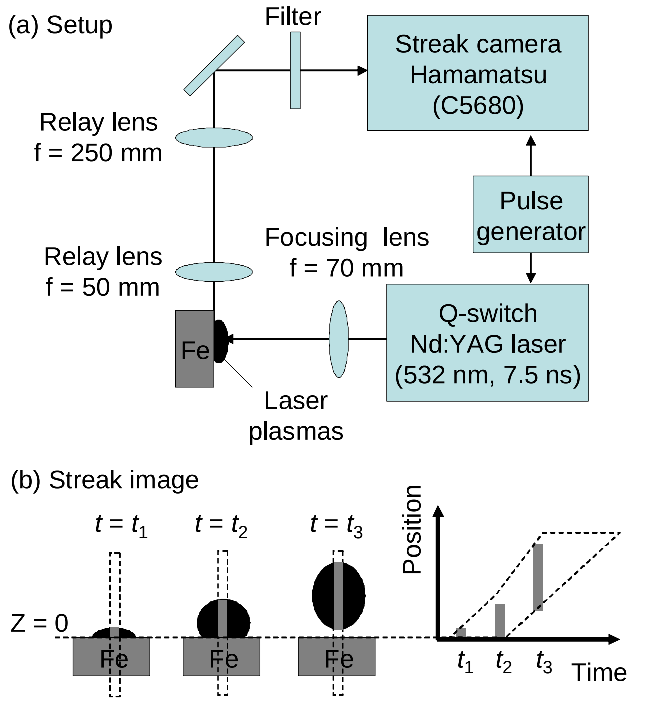

FIG. 1 (a) The drawing of the experimental setup and (b) the expected streak image

An expected streak image is shown in Fig. 1 (b). Z = 0 represents the surface of the metallic target. In this experiment, we can time-sequentially observe the information about a one-dimensional (1D) plasma emission distribution including the center of the laser plasmas. The data at $t = t_1$, t_2, and t_3 show the corresponding 1D emission distributions at the early, middle, and late parts of the plasma emission, respectively. The obtained streak image is expected to be a trapezoid-like image as shown by a dotted line in Fig. 1 (b).

RESULTS

Figure 2 represents the observed streak images at the laser pulse energies of (a) 5 mJ, (b) 10 mJ, (c) 15 mJ, and (d) 20 mJ, respectively. Figure 3 shows the 1D spatial distributions at t = 25 ns, 75 ns, 125 ns, and 165 ns, respectively.

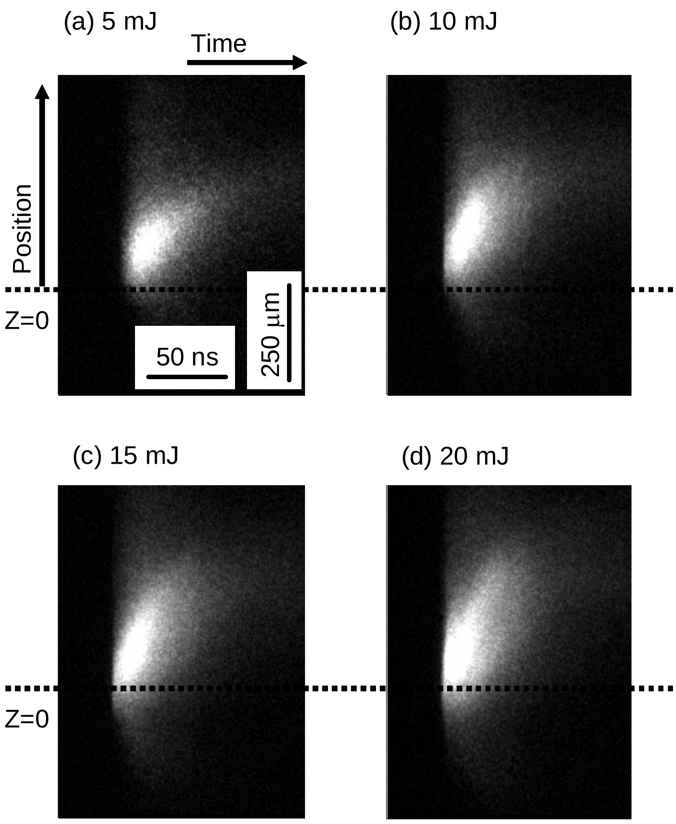

FIG. 2 The observed streak images at the laser pulse energies of (a) 5 mJ, (b) 10 mJ, (c) 15 mJ, and (d) 20 mJ. Z = 0 represents the surface of the metallic target.

The laser pulse energy was 20 mJ. We can see that the position of an emission peak gradually shifts from the left to right directions, signifying the expansion of the laser plasmas. Figure 4 shows the shift of the position of the emission peak at 5-20 mJ. In all cases, we observed the shift of the position of the plasma emission in outwards direction, that is, the expansion of the laser plasmas. Additionally, we can see a rapid expansion and a marked shift at the higher laser pulse energy range.

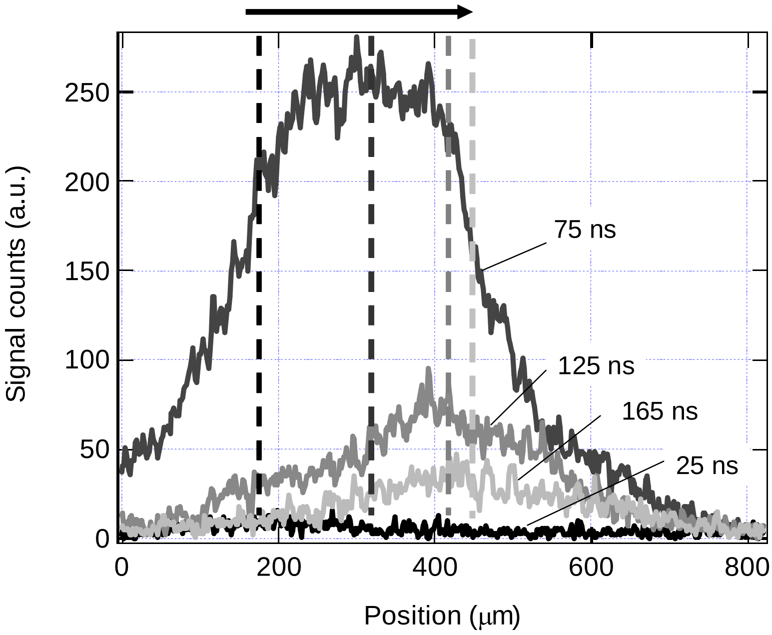

FIG. 3 The observed 1D emission distributions of the laser plasmas. The dotted lines show the positions of the emission peak.

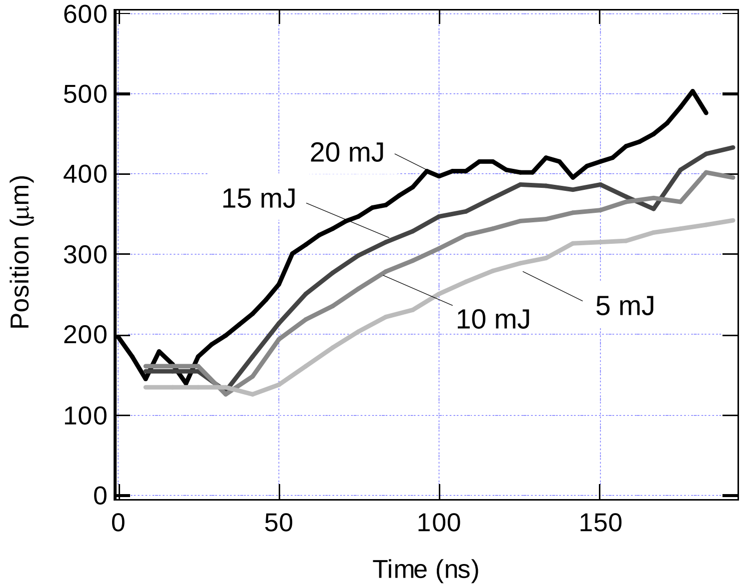

FIG. 4 Temporal behaviors of the positions of the emission peak at 5-20 mJ.

Figure 5 shows the temporal behaviors of the expansion velocity at 5-20 mJ. The expansion velocity can be obtained by time-differentiating the data indicated in Fig. 4. At 20 mJ, we recognized a pulse-like change with the duration of ~100 ns. The amplitude and duration of the expansion velocity gradually became lower and longer with a decrease of the laser pulse energy, respectively. Thus, we found that the expansion velocity strongly correlates with the laser pulse energy even when the laser pulse width was constant.

DISCUSSION

The temporal behavior of the pulse pressure, $P(t)$, would mainly determine the mechanical behavior of treated metallic components. According to the 1D model, the pulse pressure can be obtained as follows: $P(t) = (1/Z_1+1/Z_2)^{-1}V(t)$, where Z_1 and Z_2, respectively, are the acoustic impedances of a metallic target and a transparent overlay, and V(t) is the expansion velocity of laser plasmas (K. Ding and L. Ye, 2006). Z_1 and Z_2 depend on materials used, while V(t) strongly correlates with laser parameters used, such as a laser wavelength (μm), a laser pulse energy (mJ), a laser pulse width (ns), a beam spot size (cm^2), and so on. Thus, the observation of $V(t)$ can experimentally determine the optimal laser parameters for an efficient LSP.

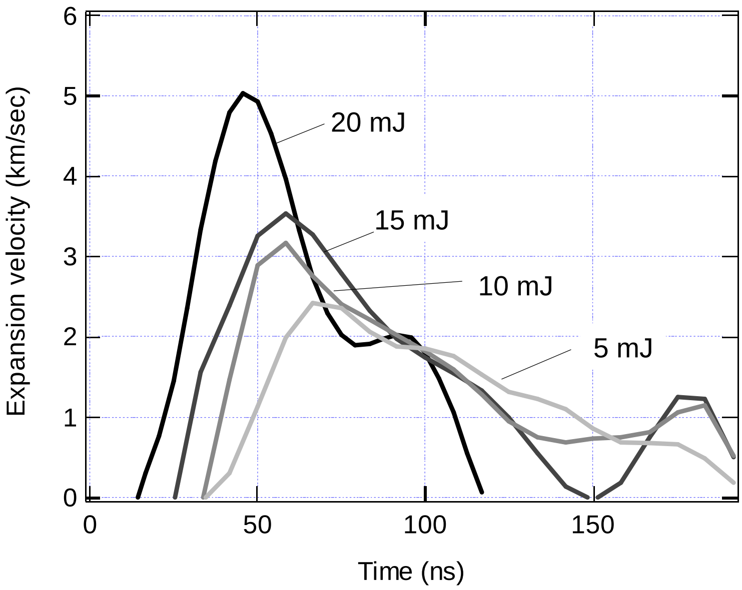

FIG. 5 Temporal behaviors of the expansion velocities at the laser pulse energies of 5-20 mJ.

The observed rise time of $V(t)$ was on the order of ~10 ns as can be seen from Fig. 5. The rise time would become more shorter less than ~1 ns when promising sub-nanosecond or picosecond pulse lasers are used for an efficient LSP. Therefore, a spatially-resolved measuring instrument with a high temporal resolution less than ~1 ns is needed in order to observe the dynamics of laser plasmas. Since a streak camera can provide us with 1D-spatially-resolved and temporally-resolved information, it is quite suitable for the observation of $V(t)$. Thus, we confirmed the usefulness of a streak camera to estimate the probable laser parameters for an efficient LSP.

CONCLUSION AND IMPLICATIONS

In order to optimize the laser parameters for an efficient LSP, we have established the time-resolved observation of laser plasmas using a streak camera. We estimated the dependence of the expansion velocity of the laser plasmas on the laser pulse energy. We found that the expansion velocity became higher with an increase of the laser pulse energy. Higher velocity leads to the generation of higher pulse pressure, which causes the effect of LSP onto a metallic surface. Thus, we confirmed the usefulness of the time-resolved measurement of the plasma expansion using a streak camera. In the near future, we will investigate the relation between laser parameters and a pulse pressure in the water confined geometry.

ACKNOWLEDGMENTS

The authors acknowledge the excellent technical supports from R. Hanayama and K. Ishii. We also thank Hamamatsu Photonics K. K. for the use of the streak camera. This study was financially supported by the grant for project research from the Graduate School for the Creation of New Photonics Industries.

REFERENCES

K. Ding and L. Ye, “Laser shock peening,” WOODHEAD PUBLISHING LIMITED, Cambridge (2006).

R. Fabbro *et al*., “Physical study of laser-produced plasma in confined geometry,” J. Appl. Phys. **68**, 775-784 (1990).

Y. Sano *et al*., “Residual stress improvement in metal surface by underwater laser irradiation,” Nucl. Instr. Meth. in Phys. Res. B **121**, 432-436 (1997).