Influence of Pulse Duration on Effective Energy on Material Removal in Micro-processing of Mild Steel by Several Hundred Nanoseconds Pulsed Laser

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Abstract

A little longer pulse duration more than several hundred nanoseconds is the middle region between ablation and melting removal of material, and effective removal of material can be expected. However, influence of these phenomena on material removal characteristics has not been clarified sufficiently. Therefore, influence of pulse duration and laser intensity on plasma was investigated by measurements of transmittance of laser energy through the plasma. Finally, effective energy to material removal characteristics was discussed with calculated laser energy relating to removal volume of mild steel as a commonly used steel by using several hundred nanoseconds pulsed laser. Transmittance ratio of laser energy was high at long pulse duration in several hundred nanoseconds range under the same pulse energy condition, because there was low reduction rate of laser energy by laser induced plasma. A little long pulse duration could perform efficient processing of mild steel under the same pulse energy condition by using several hundred nanoseconds pulsed laser.

Key words: nanosecond pulsed laser, pulse duration, plasma, effective energy, removal volume

1. INTRODUCTION

In general, short pulsed lasers are useful to reduce the thermal influence to material in micro-machining process. The difference of pulse duration affects characterization of processing such as removal volume and surface state. Moreover, laser induced plasma is generated around laser irradiation point, when laser energy is sufficient to evaporate materials at laser irradiation point. The laser induced plasma has an influence on the transmittance of laser energy and removal characteristics, since it is considered that the difference of pulse duration changes plasma absorption and/or reflection. There are some reports to discuss the influence of plasma on transmittance and/or reflection of laser beam in short pulse duration less than a few ten nanoseconds, and it is suggested that shorter pulse is effective to avoid the reduction of laser energy due to existing laser induced plasma. On the other hand, a little longer pulse duration more than several hundred nanoseconds is the boundary region between ablation and melting removal process of material, and effective removal of material with small heat influence can be expected. However, influence of these phenomena on material removal characteristics has not been clarified sufficiently. Therefore, in this study, effective input energy to materials was evaluated by the measurements of plasma size and transmittance of laser energy through laser induced plasma, and the effect of pulse duration on energy to material removal characteristics were experimentally investigated by using several hundred nanoseconds pulsed laser in micro-processing of mild steel as a commonly used steel.

2. LASER INDUCED PLASMA AND TRANSMITTANCE RATIO OF LASER ENERGY

The whole laser beam for the measurement of transmittance ratio have to pass through the laser induced plasma in order to measure transmitted laser energy. In other words, the spot size of laser beam for the measurement must be smaller than the size of laser induced plasma. Firstly, laser induced plasma was observed to confirm that its size is much larger than the spot size of laser beam for the measurement of transmitted laser energy. Then, effect of pulse duration on transmittance ratio of laser energy was discussed.

2.1 Observation of Laser Induced Plasma

Figure 1 shows the experimental setup for the observation of laser induced plasma generated on the specimen, which is mild steel of 10 mm thickness. The specimen was set in the box, which can control the pressure, but the box is not used as a vacuum chamber. This box is used to avoid the influence of air flow on plasma behavior, and the pressure is a normal atmospheric one. The laser induced plasma was observed in the micro-processing of mild steel by using ns pulsed fiber laser of 1086 nm wavelength with various pulse durations. Three pulse durations of 430 ns, 510 ns and 610 ns were used in this study. The laser beam of 2.8 mm diameter for processing was expanded by 3 times, it was focused on the
surface of specimen by a lens of 80 mm in focal length. Pulse energy was set to 500 µJ for every pulse duration, and laser fluence \( F \) is 217 J/cm\(^2\). High-speed shutter camera was temporarily controlled by using a pulse generator to observe the variations of laser induced plasma \(^{11}\), and its exposure time was set to 50 ns.

Figure 2 shows pulse waveforms as laser optical intensity variation for various pulse durations under the same pulse energy condition. All pulse waveforms show similar tail width, but FWHM (Full width at half maximum) values are different in pulse durations. Laser optical intensity decreased with increasing the pulse duration, and it is considered that plasma size would be affected by the pulse duration under the same pulse energy condition.

Figure 3 shows photographs of laser induced plasma generated from 50 ns to 450 ns for various pulse durations. Figure 4 illustrates the definition of the height and width of laser induced plasma. Plasma height and width are determined by their sizes in the directions of laser irradiation axis and specimen surface, respectively. Plasma size was measured 5 times every 50 ns, its average was recorded as the measurement results of laser induced plasma size.

2.2 Effect of Pulse Duration on Transmittance Ratio of Laser Energy

Figure 6 shows the experimental setup for measurement of transmitted laser energy. Q-switched Nd:YAG laser of 5 ns pulse duration and 532 nm wavelength was used as a laser beam for the measurement. Although the wavelength of measurement is different from that of processing, the similar transmittance tendency of both wavelengths can indicate their relative transmittance characteristics\(^{12}\). The different laser wavelength can contribute to avoid the influence of processing laser beam on measurement results of laser intensity by the phot detector located after laser irradiation point.
The diameter of laser beam was expanded by 3 times, and it was focused into the laser induced plasma by a lens of 60 mm in focal length. The spot diameter is 50 µm at the focusing point. The intensity of laser beam before and after laser induced plasma was measured using the combination of a photodiode and an oscilloscope, and the transmittance ratio $T_r$ was calculated by using Eq. (1).

$$T_r = \left( \frac{I_T}{I_{Tr}} \right) \left( \frac{I_{N}}{I_{Nr}} \right)$$

where $I_T$ and $I_N$ are measured intensity of laser beam with and without the laser induced plasma after passing through above the specimen, respectively. $I_{Tr}$ and $I_{Nr}$ are measured intensity of reference laser beam for both cases when laser induced plasma is generated or not. $I_N$ is measured by the photodetector located after laser irradiation point, when laser induce plasma is not generated. Laser energy might fluctuate, and the reference value is useful to avoid the influence of its fluctuation on transmittance ratio. Therefore, $I_{Nr}$ is measured as a reference value of $I_T$ without laser induced plasma by the photodetector located after the laser oscillator for transmittance measurement. Both $I_N$ and $I_{Nr}$ are measured, when laser induced plasma is not generated. On the other hand, both $I_T$ and $I_{Tr}$ are measured, when laser induced plasma is generated. $I_T$ is measurement value by the photodetector located after laser irradiation point, while $I_{Tr}$ is measured as a reference value of $I_T$. The reference values $I_{Tr}$ and $I_{Nr}$ can avoid the influence of fluctuation of laser pulse energy on measurement results. In this setup, the measurement results include both influence of absorption and reflection caused by plasma.

Figure 7 shows the measurement results of transmittance ratio of laser energy from 50 ns to 950 ns after laser induced plasma is generated on the specimen. Judging from Figs. 5 and 7, the transmittance ratio of laser intensity increases slightly before the peak power for each pulse duration. The lowest transmittance was reported at the peak power of pulse waveform in short pulse duration less than a few ten nanoseconds [13], but the plasma size increases widely with the time in the case of several nanoseconds pulsed laser. It is considered that electron density is not the highest at the peak power due to the increase of plasma size, and the increasing tendency of transmittance ratio becomes lower around the peak power. The
transmittance ratio increases suddenly after the peak power. Because input peak power decreases with the time, and the size of plasma slightly increases. It is considered that electron density is affected by intensity of laser beam, and the transmittance ratio of laser energy is changed by the reflection of laser beam due to the existence of laser induced plasma. Therefore, it becomes clear that pulse duration and pulse waveform affect the transmittance ratio of laser energy, and longer pulse duration 610 ns indicates higher transmittance because of its low intensity. Shorter pulse duration 430 ns shows higher transmittance than middle pulse duration 510 ns, because the sudden decrease of laser intensity at 430 ns as shown in Fig. 2. These phenomena would result in variation of material removal characteristics by using several hundred nanoseconds pulsed laser.

3. TOTAL INPUT ENERGY RATIO

In order to investigate the influence of pulse duration on material removal characteristics, the reaching ratio of laser energy to the specimen was discussed. Firstly, the energy $E(t)$ during time $t$ is calculated by integrating the laser power $P(t)$, as shown in Eq. (2).

$$E(t) = \int P(t)dt$$  \hspace{1cm} (2)

The time of pulse duration is divided into 10 parts for every pulse duration to correspond to the measurement results of transmittance ratio. $E$ is the total value of $E(t)$ by the sum of 10 measurement points, and it is the pulse energy from the laser oscillator. $P'(t)$ is laser power reaching to the specimen at time $t$, which is defined by Eq. (3).

$$P'(t) = P(t) \cdot T_r(t)$$  \hspace{1cm} (3)

where $T_r(t)$ is the transmittance ratio at time $t$.

$E'(t)$ is laser energy reaching to the specimen during time $t$, which is calculated by integrating laser intensity after laser beam passes through the laser induced plasma during time $t$ as shown in Eq. (4).

$$E'(t) = \int P'(t)dt$$  \hspace{1cm} (4)

$E'$ is the sum of $E'(t)$ at 10 measurement points, and it is reaching energy to the specimen. Finally, total input energy ratio $T_i$ is calculated by Eq. (5).

$$T_i = \frac{E'}{E}$$  \hspace{1cm} (5)

Total input energy ratio $T_i$ is the ratio of reaching energy to the specimen to pulse energy from the oscillator.

4. REMOVAL VOLUME FOR VARIOUS PULSE DURATIONS

Figure 8 shows schematic diagram of laser irradiation system to determine the removal volume of material. Individual irradiation spot was obtained by controlling the scanning speed of laser beam with Galvano scanner. Maximum pulse repetition rate is 100 kHz at pulse duration of 610 ns, and maximum diameter of drilled hole was less than 50 μm. The scanning speed was set at 7 m/s to obtain an individual irradiation spot. The laser beam of 2.8 mm was expanded by 2 times, and the focusing conditions were arranged to obtain the same spot size of 17 μm as the measurement of transmittance ratio by controlling the defocused distance. The removal process was carried out under the same condition as the observation of laser induced plasma and measurement of transmitted laser energy.

Figure 9 shows the photographs of surface and cross section of drilled hole under the same pulse energy of 500 µJ for various pulse durations, and the diameter $D_i$ and removal depth $D_R$ of drilled hole were determined as shown in Fig. 10. Firstly, diameter $D_i$ and removal depth $D_R$ of drilled hole were measured for various pulse durations. The removal volume $V_R$ was calculated by using Eq. (6),

$$V_R = \int D_i \cdot D_R$$
since it was confirmed that all drilled holes were similar to spherical segment judging from the observation of cross section.

\[ V_R = \pi D_R / 6 + \left\{ 3(D_i/2)^2 + D_R^2 \right\} \]  \hspace{1cm} (6)

Figure 11 shows the calculated total input energy ratio \( T_i \) and removal volume \( V_R \) for various pulse durations. Total input energy ratio increased with increasing the pulse duration, although removal volume had no correlation with pulse duration. It is necessary to investigate other factors in order to consider laser energy to removal materials. Then, the contribution ratio of laser energy to material removal is calculated.

5. CONTRIBUTION RATIO OF LASER ENERGY TO MATERIAL REMOVAL

Effect of pulse duration on transmitted laser energy and removal volume were investigated under the same pulse energy condition. Since the peak power changed with the pulse duration under the same pulse energy condition, the contribution of laser peak power to material removal was considered. The specimen was processed at the same pulse duration of 510 ns to investigate the effect of laser peak power on material removal, when the standard peak power was set to 819 W, which was the same value used for the measurement of transmitted laser energy and discussion of removal volume. The laser irradiation experiments were carried out at the power range from 0.3 times to 1.0 times of standard peak power, and actual removal volume \( V_R \) was measured. In previous discussion, it was assumed that removal volume was proportional to peak power, and the total input energy ratio was calculated under this relationship between estimated removal volumes \( V_E \) and peak power \( P_P \). However, actual measured removal volume \( V_R \) increased exponentially with increasing the peak power, as shown in Fig. 12. Thus, it revealed that the contribution ratio of laser energy to material removal was larger at high peak power. Other pulse durations also indicated the similar tendency to 510 ns. Therefore, contribution ratio of laser energy to material removal \( C_r \) was calculated by using Eq. (7).

\[ C_r = V_R / V_E \]  \hspace{1cm} (7)

6. TOTAL REMOVAL ENERGY RATIO

In order to include the effect of peak power on material removal, the total removal energy ratio \( T_e \) was considered by introducing the contribution ratio of laser energy to material removal \( C_r \) into laser power reaching to the specimen \( P'(t) \). The product of \( P'(t) \) and \( C_r(t) \) is expressed by \( P''(t) \) as shown in Eq. (8), and it is contributed laser power at time \( t \) depending on the peak power.

\[ P''(t) = P'(t) \cdot C_r(t) \]  \hspace{1cm} (8)

\( E_s(t) \) is the contributed laser energy reaching to the specimen during time \( t \), and it is calculated by integrating \( P''(t) \) at time \( t \) as shown in Eq. (9).

\[ E_s(t) = \int P''(t) \, dt \]  \hspace{1cm} (9)

\( E_s \) is the sum of \( E_s(t) \) at 10 measurement points, and it is the total energy reaching to the specimen. Finally, total removal energy ratio \( T_e \) is calculated by using Eq. (10).
\[ T_e = \frac{E_r}{E} \quad (9) \]

Figure 13 shows the relationship between total removal energy ratio and removal volume for various pulse durations. The consideration of peak power in material removal leads to good correlation between total removal energy ratio and removal volume. Removal volume at the pulse duration of 430 ns is larger than that at 510 ns, because peak power at 430 ns is higher than 510 ns. On the other hand, removal volume at 610 ns is larger than 430 ns, although the peak power at 610 ns is lower than 430 ns. In addition, total removal energy ratio at 610 ns is the largest. It is considered that lower peak power results in larger transmitted laser energy on material, because the influence of laser induced plasma on transmittance of laser energy became lower. Therefore, it can be concluded that a little long pulse duration under the same pulse energy condition can perform efficient processing of mild steel by using several hundred nanoseconds pulsed laser.

7. CONCLUSIONS

In this study, effective laser energy to material removal was discussed in micro-processing of mild steel by several hundred nanoseconds pulsed laser. The main conclusions are as follows:

1) Transmittance ratio of laser energy was high at long pulse duration in several hundred nanoseconds range under the same pulse energy condition, because there was low reduction rate of laser energy by laser induced plasma.

2) High peak power led to larger contribution ratio of laser energy to material removal, when removal volume was calculated at the same pulse duration.

3) The consideration of peak power in material removal indicated good correlation between the removal volume and the total removal energy ratio.

(4) A little long pulse duration could perform efficient processing of mild steel by using several hundred nanoseconds pulsed laser under the same pulse energy condition.

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