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Micro-welding of Copper Plate by Frequency Doubled Diode Pumped Pulsed Nd:YAG Laser

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Abstract

A pulsed laser of 532 nm wavelength with ms range pulse duration was newly developed by second harmonic generation of diode pumped pulsed Nd:YAG laser. High electro-optical conversion efficiency more than 13% could be achieved, and 1.5 kW peak power green laser pulse was put in optical fiber of 100 µm in diameter. In micro-welding of 1.0 mm thickness copper plate, a keyhole welding was successfully performed by 1.0 kW peak power at spot diameter less than 200 µm. The frequency doubled pulsed laser improved the processing efficiency of copper welding, and narrow and deep weld bead was stably obtained.

Keywords: copper; laser welding; absorption; pulsed Nd:YAG laser; SHG; green laser

1. Introduction

Recently, all-electric home and electric car became popular by development of electronic technologies, and copper is widely used as a wiring material in electric and electronics industries because of its high electrical conductivity [1]. However, it is difficult to perform the effective and stable laser welding for copper material by Nd:YAG laser of 1,064 nm in wavelength because of its high thermal conductivity and low absorptivity around 1,000 nm in wavelength [2]. The light absorptivity by copper material increases with decreasing the wavelength, and it increases drastically below 600 nm in wavelength. In order to apply this spectral characteristic, the green CW Yb:YAG disc laser was developed, and it was reported

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that the processing efficiency could be increased with green laser beam compared with IR laser [3]. However, in order to obtain the deeper penetration depth, the high laser power is required, and it would accompany the risk of distortion in micro-welding according to continuous high energy input. On the other hand, the similar approach was applied to the lamp-pumped pulsed Nd:YAG laser, and the high peak power up to 1.5 kW was obtained [4]. However, the ratio of processing energy to pumping one is low, since it is difficult to achieve the efficient pumping and high-quality beam by using a flash lamp. Therefore, the pulsed laser of 532 nm in wavelength was developed by second harmonic generation of diode pumped pulsed Nd:YAG laser. In this study fundamental investigation of newly developed pulsed green laser oscillator and its welding characteristics of copper were discussed.

2. Pulsed Green Laser

Fig. 1 shows the schematic illustration and specifications of newly developed pulsed green Nd:YAG laser. The green laser of 532 nm in wavelength was obtained by frequency doubling of pulsed Nd:YAG laser of 1,064 nm in wavelength with nonlinear optical crystal (NLO). A quasi CW diode lasers were used as the pumping source, and the NLO was arranged as an intra-cavity design to perform the high wavelength conversion efficiency. This optical setup led to the high beam quality, which allows that the laser beam was coupled into the optical fiber of 100 μm in diameter. The axis of green laser beam was inclined by 5 degrees to avoid the back reflection of laser beam from the surface of workpiece to the optical fiber.

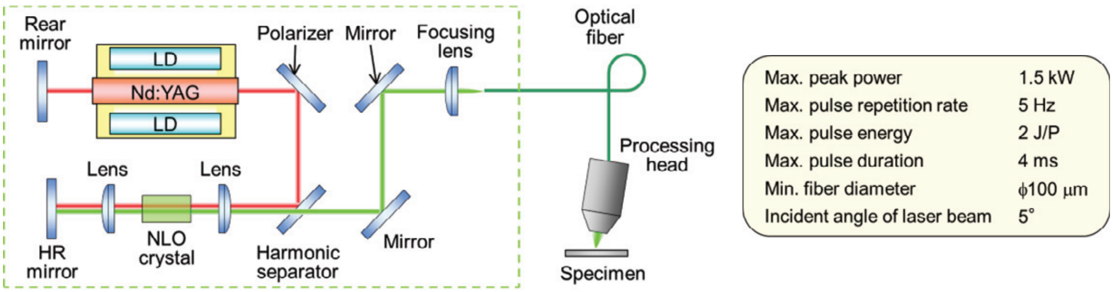

Fig. 1. Schematic illustration and specifications of pulsed green Nd:YAG laser

Fig. 2 shows the characteristics of newly developed pulsed green laser. As shown in Fig.2 (a), the electro-optical conversion efficiency to obtain green laser increased with increasing the pumping current of diode lasers under the higher output power condition. High electro-optical conversion efficiency more than 13% could be achieved at pumping current 90 A. Fig. 2 (b) shows the variation of peak power with pumping current of diode lasers. The peak power increased proportionally to the pumping current of diode lasers, and 1.5 kW peak power could be accomplished at pumping current 90 A. Diode laser pumping method could perform the high-quality beam due to the reduction of thermal lens effect, hence the high conversion efficiency could be achieve in frequency doubled pulsed Nd:YAG laser. Moreover, the pulse waveform could be varied easily only by controlling the pumping current of diode laser as shown in Fig.2 (c).

Fig. 3 (a) shows the result of 10 hours lifetime test of pulsed green laser under the oscillation conditions, where the peak power, the pulse duration (rectangular pulse) and the pulse repetition rate were 1.4 kW, 0.48 ms and 5 Hz, respectively. Here, the laser oscillation was stopped for about 10 hours at the night time every day in order to assume the practical use. The initial average power was defined as 100 %, and the ratio of measured average power to initial one was plotted as the output power. As shown in the figure, the output power was very stable during the measurement time period, and the initial output power could be kept more than 200 hours operating time. The stability of output power kept within 0.5 %rms for both one day and whole measurement time period, which would indicate the sufficient for the practical use. Fig. 3 (b) shows the long-term lifetime test results for the fundamental wavelength of pulsed Nd:YAG laser pumped by the same pumping source as the green pulsed laser [5]. As shown in the figure, since it was confirmed the lifetime of pulsed Nd:YAG laser to keep more than 95% of initial output power was longer than 20,000 hours, the long lifetime also could be expected for the green pulsed laser generated by frequency doubling of this fundamental laser.

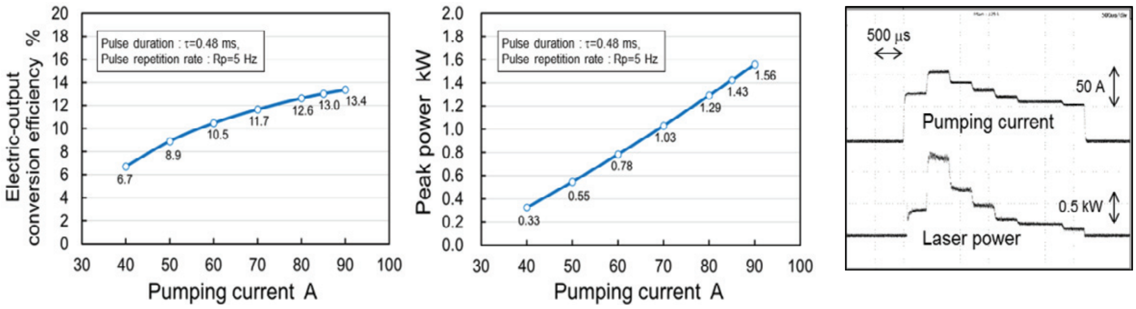

Fig. 2. (a) electro-optical conversion efficiency to obtain green laser power; (b) relationship of peak power and current curve; (c) pulse waveform of pumping current and actual output power

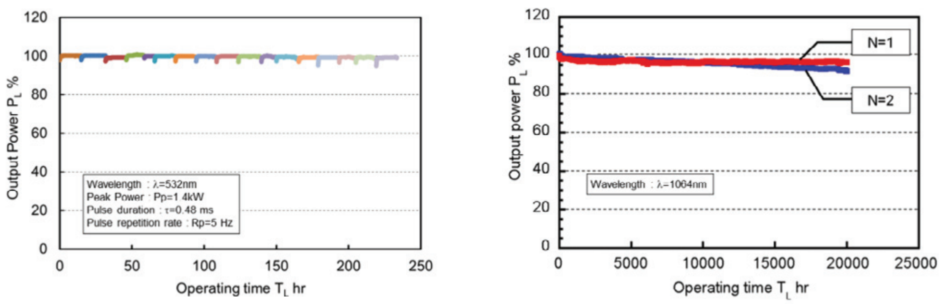

Fig. 3. (a) life test result of pulsed green Nd:YAG laser; (b) life test results of pulsed LD pumped Nd:YAG laser

3. Welding Results and Discussion

1.0 mm thickness oxygen-free copper plate C1020 (in JIS specification) of 99.96% purity was used as a specimen, and its physical properties are summarized in Table 1. C1020 is widely used as a wiring material, heat sink because of its high electrical and thermal conductivity. The content of oxygen in this copper material was extremely small, which would indicate the relative good weldability.

Pulsed green laser beam was delivered to the processing head through an optical fiber of 100 μm in diameter with NA 0.2, and focused on the specimen with various diameters from 100 μm to 300 μm by arranging the collimation and the focusing lenses. Nitrogen was used as a shielding gas. In order to compare the processing characteristics, the same experiment conditions were used for 1,064 nm pulsed Nd:YAG laser.

Table 1. Physical properties of copper C1020 [6]

Melting temperature	1356 K
Thermal conductivity	391.1 W/(m•K)
Coefficient of thermal expansion	17.6×10^{-6} (1/K)
Density	8.94 (g/cm^3)
Electrical resistivity	17.1 nΩ•m
Electric conductivity	59.1 (MS/m)

Fig. 4 (a) shows irradiated surfaces and cross sections by the single laser shot of 1,064 nm and 532 nm in wavelength with 1.0 kW peak power and 1.2 ms pulse duration (rectangular pulse) for various spot diameters. As shown in the figure, there is no remarkable melting spot in the case of 1,064 nm, while an obvious melting spot could be observed on the irradiated surface by pulsed green laser. It was clear that the processing efficiency was drastically improved by frequency doubling of pulsed Nd:YAG laser. Fig. 4 (b) shows variations of penetration depth with pulse duration from 0.48 ms to 1.2 ms and spot diameters from 100 μm to 300 μm by the single laser shot. In the case of pulsed green laser, the penetration depth was greatly increased at the spot diameter less than 200 μm. Judging from variations of penetration depth with spot diameter, it is considered that a keyhole would be generated at the spot diameter less than 200 μm. The penetration depth was also increased with increasing of pulse duration. In the case of absorptivity 35.6%, the calculated power density to generate keyhole is about 1.25×10^6 W/cm^2, and it agrees with the commonly required minimum power density from 10^5 to 10^6 W/cm^2 for the keyhole welding [7].

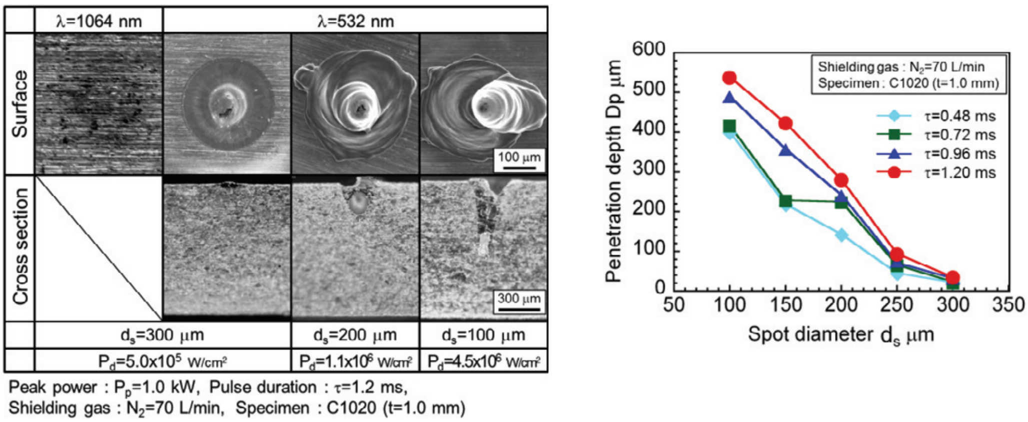

Fig. 4. (a) irradiated surfaces and cross sections by 1,064 nm and 532 nm for various spot diameters; (b) penetration depth for various spot diameters and pulse durations by pulsed green laser

As shown in Fig. 4, relative large-scale porosity was formed in the molten area at the spot diameter less than 200 μm, in which the keyhole would be generated. Copper is a material with high thermal conductivity. The heat generated by laser absorption would diffuse rapidly from molten pool to the surrounding area, hence the molten pool would be solidified in a short time. During the closing time of keyhole, bubbles of evaporated material and assist gas could not go out from molten pool, and the captured material was remained as porosity due to the rapid cooling down. In addition, Heider et al. reported that the modulation of laser power was effective to reduce spatter and stabilize processing at the seam welding of copper with CW fiber laser [8]. Therefore, the pulse waveform of laser beam was investigated to decrease the porosity and improve the welding stability.

The pulse waveforms, top surfaces and cross sections by single laser short of 100 μm spot are shown in Fig. 5 (a). Three types of pules waveforms were used with the same peak power 1.2 kW, pulse duration 2.4 ms and pulse energy 2 J/P. One was the early P.p., in which the maximum peak power was set at the early period during pulse duration. The others are middle and later P.p. with peak power at middle and late time during pulse duration, respectively. The middle and later P.p. had large size porosity at the deeper part of molten area. On the other hand, the small size porosity was observed at the relative shallower location in the case of early P.p. compared with other pulse waveforms. It is considered that the longer time duration after the maximum peak power would lead to the sufficient time to push up the bubbles from the bottom of keyhole. Fig. 5 (b) shows the variations of penetration depth in 5 experiments by three types of pulse waveform. The average of penetration depth increased with moving the peak power toward the later part during pulse duration. However, the difference between minimum and maximum value of penetration depth became smaller with moving the peak power toward the early part during pulse duration. Heider et al. also reported that undesired spike of penetration depth appeared without modulation of laser power [7]. Therefore, it is considered that the absorption of laser beam became unstable at the later part due to the large change of temperature, and the penetration depth became deeper at a certain condition.

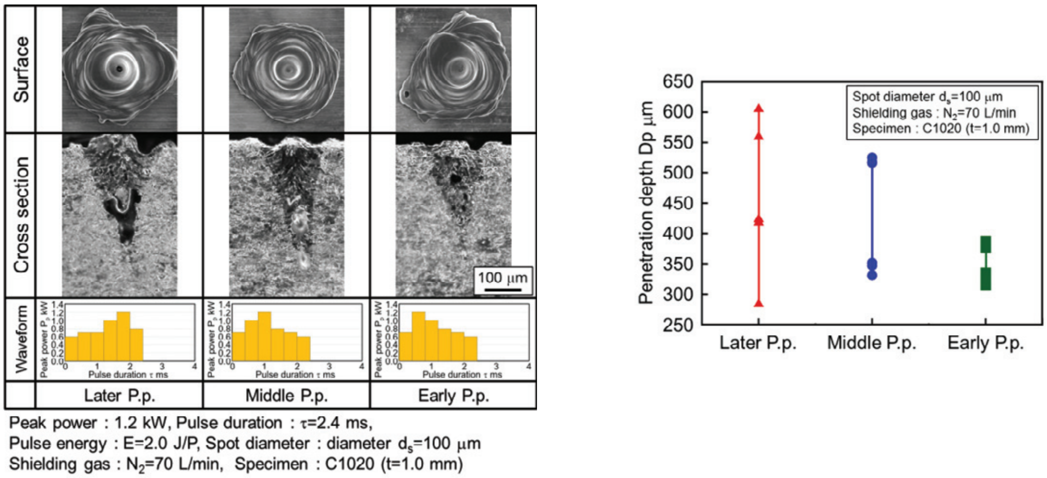

Fig. 5. (a) irradiated surfaces and cross sections for various waveforms; (b) penetration depth for various waveforms by the same peak power 1.2 kW, pulse duration 2.4ms and pulse energy 2 J/P

In order to discuss welding results as shown in Fig.5, the regular reflection of laser beam from the processing point was measured. The intensity of regular reflection was detected by the photo detector, which was set at axial symmetry position of green laser beam by 25 degrees incident angle as shown in Fig. 6. The same spot diameter of 100 μm was used, and the irradiated area was shielded by nitrogen gas.

Measurement of reflection intensity was carried out 10 times of single shot, and the 10 measurement results of reflection waveform were overlaid as shown in Fig. 7. The intensities of regular reflection were stable under every condition, and the stable absorption of laser beam would be expected by irradiation of green laser beam.

As shown in Fig. 7, the intensity of regular reflection light took a maximum immediately at the beginning of laser pulse, and its intensity was decreased rapidly from 0.1 ms to 0.2 ms. The intensity of regular reflection kept almost constant value until the end of laser irradiation. The time period τ_f, when the intensity of regular reflection became smaller from the maximum value to the second level, became shorter with pulse waveform of Early P.p.. The low intensity at the early time period would indicate superior absorption of laser beam. On the other hand, the regular reflection from 0.5 ms to 2.4 ms after the start of laser pulse became unstable in order of later P.p., middle P.p. and early P.p.. The dispersion of regular reflection indicated that unstable absorption of laser beam would lead to the unstable processing. Therefore, it is considered that the dispersion of penetration depth was smallest by using Early P.p., and stable welding with little porosity could be performed as shown in Fig.5.

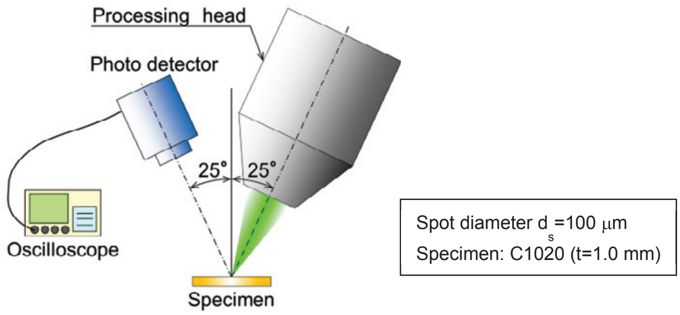

Fig. 6. Setup for measurement of regular reflection from processing point

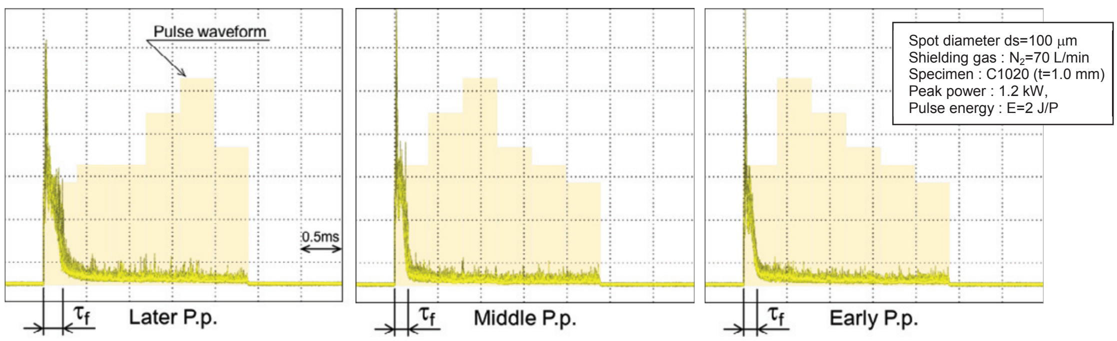

Fig. 7. Intensity of regular reflection during laser irradiation for various waveforms

Effects of pulse duration were investigated under the same pulse energy of 2 J/P. Fig. 8 (a) shows the irradiated surfaces and cross sections by the single laser shot for various pulse durations, and variations of penetration depth in 5 experiments are shown in Fig. 8 (b). The maximum peak power was limited to less than 1.0 kW at waveform with pulse duration longer than 3.2 ms, and the peak power was set to the highest value under every pulse duration condition. The waveform with peak power at early time period during pulse duration made it possible to reduce porosity under every pulse duration conditions, and the porosity could not be observed at pulse duration longer than 3.2 ms. The penetration depth of pulse duration 4.0 ms was shallow due to the low peak power of 0.8 kW, while there was little difference in the penetration depth and its dispersion by the other pulse duration conditions. The peak power would relate to the penetration depth, and the peak power more than 1.0 kW at spot diameter of 200 μm could obtain the deeper penetration depth. In addition, the longer pulse duration would lead to the reduction of porosity.

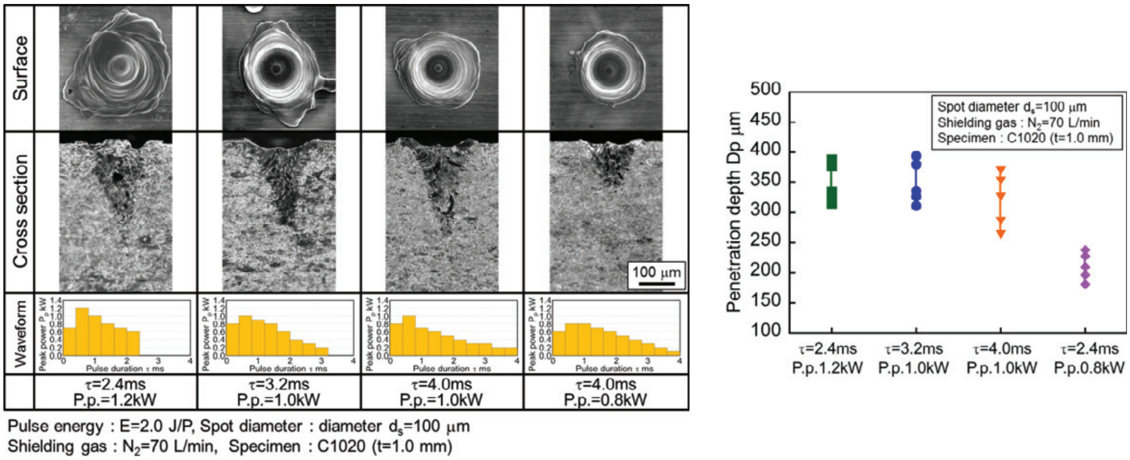

Fig. 8. (a) Irradiated surfaces and cross sections for various pulse width and peak powers; (b) penetration depth for various pulse width and peak powers by the same pulse energy 2 J/P

4. Conclusions

Pulsed green laser of 532 nm in wavelength was newly developed by frequency doubling of diode pumped Nd:YAG laser, and its welding characteristics of high-purity copper was experimentally investigated. Main conclusions obtained in this study are as follows:

(1) The ms range pulsed green laser with 1.5 kW peak power could be obtained by frequency doubling of Nd:YAG laser pumped by diode laser, and electro-optical conversion efficiency more than 13% could be achieved.
(2) Keyhole welding of 1.0mm thickness high-purity copper was successfully performed by 1.0 kW peak power at spot diameter less than 200 μm.
(3) The generation of porosity could be reduced by controlling the pulse waveform, and the longer pulse duration was also effective to remove the remaining porosity.
(4) The pulse waveform with maximum peak at the early period could lead to the stabilization of penetration depth.

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