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MICRO-WELDING OF ALUMINUM ALLOY BY SUPERPOSITION OF PULSED Nd:YAG LASER AND CONTINUOUS DIODE LASER

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The combination of a pulsed Nd:YAG laser and a continuous diode laser could perform the high-performance micro-welding of aluminum alloy. A pulsed Nd:YAG laser was absorbed effectively from the beginning of laser scanning by pre-heating Nd:YAG laser pulse with the superposition of continuous LD, and wide and deep weld bead could be obtained with better surface integrity. 6 Ref., 2 Tabls, 8 Figures.

Key words: pulsed Nd:YAG laser, aluminum alloy, micro-welding

Introduction

Mobile products such as PDA, Notebook PC and mobile phone have been widely used in the fields of information and communication technology. In the automobile industry, hybrid vehicle and electric vehicle attract customers because of their low energy consumption, and they are expected as the key products of next generation. In order to accomplish highly performance of these products, lightweight and high specific strength materials are required. Aluminum alloys have been widely used to achieve lightweight and miniaturization in these fields, hence high-performance welding has been required. A pulsed Nd:YAG laser of 1064 nm in wavelength has been applied to the micro-welding of aluminum alloy [1]. However, the absorption rate of a Nd:YAG laser by aluminum alloys is only 5 % at room temperature, as shown in Figure 1 [2, 3]. Since the absorbed laser energy is very low, high peak power laser system must be used to achieve sufficient penetration depth and acceptable bead width. High peak power is useful to increase the penetration depth and the bead width, but the excessive heat input leads to the deterioration of surface quality and integrity due to the spatter and the porosity [4].

On the other hand, the aluminum alloy shows the high absorption rate around 810 nm as shown in Figure 1. The wavelength 808 nm of diode laser (hereafter LD) is useful to increase the absorption of laser energy, and its absorption rate is 3 times higher than that of Nd:YAG laser of 1064 nm. In addition, low cost and high power LD is available by the recent development of semiconductor technology, and the high brightness LD is also expected. Therefore, the micro-welding technology of aluminum alloy by the combination of a pulsed Nd:YAG laser and a continuous LD was proposed, and efficient absorption of Nd:YAG laser was expected [5, 6].

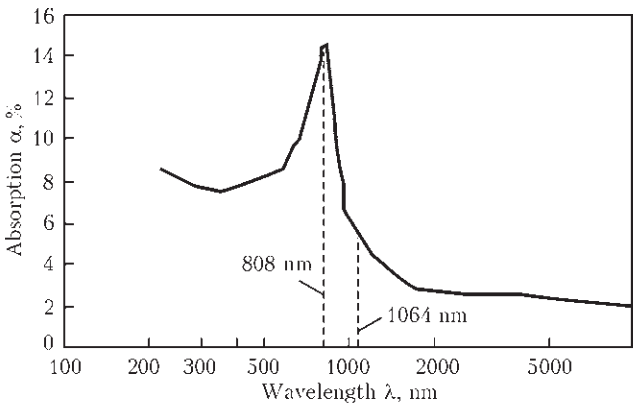


Figure 1. Absorption rate of aluminum alloy A3003 at room temperature

However, it is difficult to perform the sufficient deep penetration depth with good surface integrity at the beginning of laser scanning. The higher peak power could become the penetration depth deeper, while the deterioration of surface integrity might be noticed. The deeper penetration depth from the beginning of laser scanning with the better surface integrity is very useful for the industrial application. From the viewpoints mentioned above, the effects of superposed continuous LD on micro-welding of aluminum alloy by a pulsed Nd:YAG laser were investigated, and the pre-pulse method was discussed in order to improve the penetration depth even at the beginning of laser scanning by pre-heating Nd:YAG laser pulse.

Experimental procedures

Figure 2 shows the schematic diagram of laser irradiation system. Table 1 shows the specifications of a pulsed Nd:YAG laser and a continuous LD used in this study. A pulsed Nd:YAG laser of 1064 nm in wavelength and continuous LD of 808 nm in wavelength were superposed on the same beam axis by a dichroic mirror, and the superposed laser beam of two wavelengths were delivered to a processing head through an optical fiber of 300 μm diameter with SI

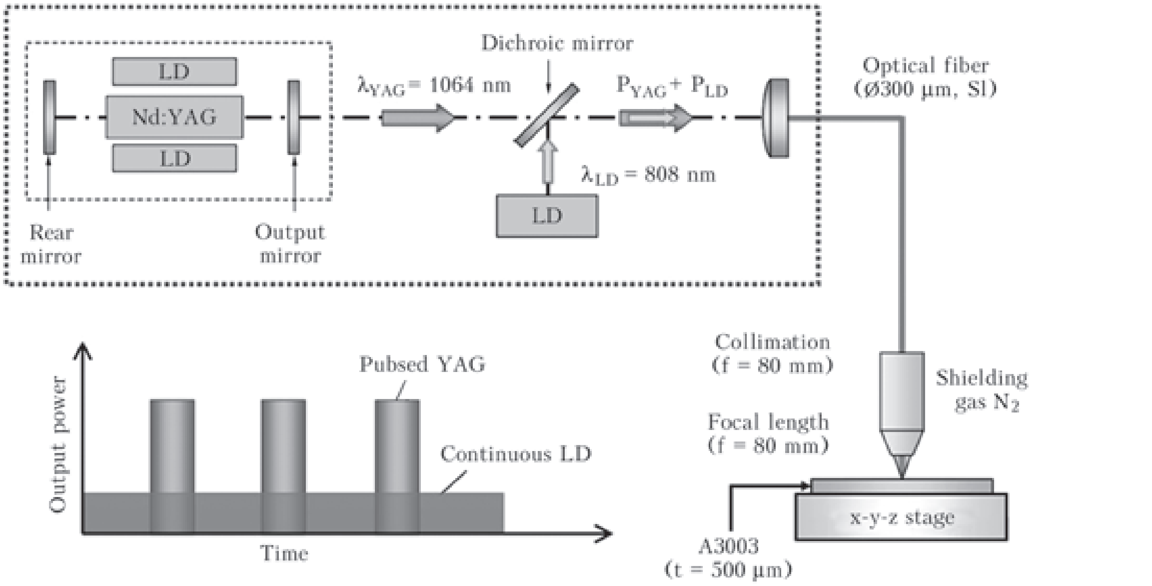


Figure 2. Schematic diagram of laser irradiation system with superposition of pulsed Nd:YAG laser and continuous diode laser

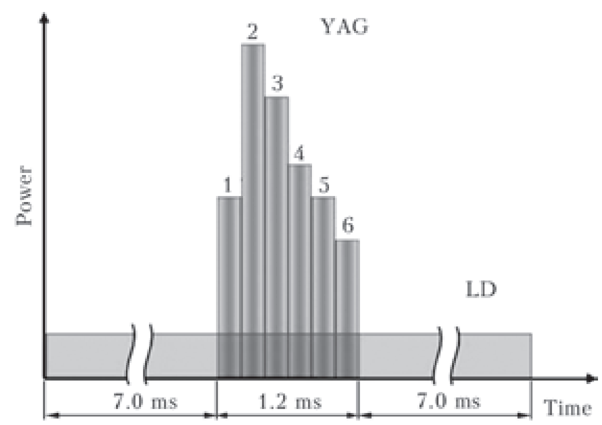
Table 1. Specifications of pulsed Nd:YAG laser and continuous diode laser

	Nd:YAG laser	Diode laser
Max. average power Pa	250 W	65 W
Max. peak power Pp	2.5 kW	-
Wavelength λ	1064 nm	808 nm
Pulse repetition rate Rp	1 - 500 Hz	CW
Pulse duration τ	0.08 - 1.2 ms	CW

Table 2. Physical properties of aluminum A3003

Specific heat	900 J/(kg·K)
Thermal conductivity	237 W/(m·K)
Density	2.73 g/cm^2
Poisson's ratio	0.33
Young's modulus	70 kN/mm^2
Coefficient of thermal expansion	2.4 × 10^{-6}/K

type. These laser beams were collimated and focused by lenses of 80 mm in the focal length. The welding experiment was carried out by controlling a scanning velocity of stage at the focusing point with N_2 shielding gas of flow rate 57 l/min. The aluminum alloy A3003 of 0.5 mm thickness was used as a specimen



Section		P_{YAG}
1	0-0.2 ms	1306
2	9.2m-0.4 ms	2375
3	0.4m-0.6 ms	2019
4	0.6m-0.8 ms	1544
5	0.8m-1.0 ms	1306
6	1.0m-1.2 ms	950

Figure 3. Irradiation waveform of pulsed Nd:YAG laser and continuous LD

except for welding experiments of battery case, and its physical properties are shown in Table 2.

The irradiation waveforms of Nd:YAG laser pulse and continuous LD are shown in Figure 3. The power of pulsed Nd:YAG laser can be controlled every 0.2 ms. In general, the sharp heating up and cooling down might lead to the welding defects such as blow holes and cracks. Therefore, the main pulse of Nd:YAG laser for the processing was controlled with a gradual increment and decrement of laser power during the pulse duration 1.2 ms. In the case of superposition of two laser beams, the irradiation of continuous LD started before the main Nd:YAG pulse as shown in Figure 3.

Effect of superposed continuous diode laser on welding results

Figure 4 shows the surfaces and cross sections of weld bead for aluminum alloy A3003 of 0.5 mm thickness with and without the superposition of continuous LD under the same peak power of Nd:YAG laser. Although the power of continuous LD is approximately 1.2 % against the peak power of pulsed Nd: YAG laser, the superposition of continuous LD made it possible to increase the bead width by 15 % and the weld depth by 150 % compared with welding results without continuous LD. It means that the energy of pulsed Nd:YAG laser could be absorbed effectively to the aluminum alloy by superposition of con-

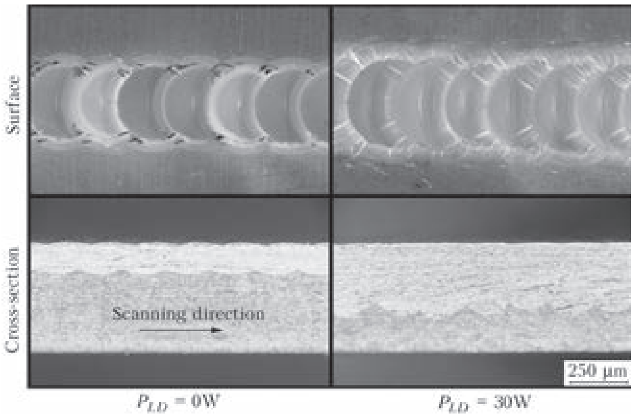
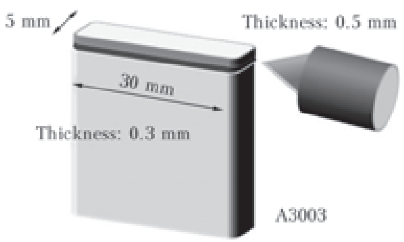


Figure 4. Surface and cross section of weld bead in bead-on-plate irradiation at scanning velocity v = 30 mm/s, pulse duration of Nd:YAG laser τ = 1.2 ms, pulse repetition rate of Nd:YAG laser R_p = 120 Hz, peak power of Nd:YAG laser P_{YAG} = 2375 W and average power of LD P_{LD} = 30 W

tinuous LD. In general, the absorption rate increases with increasing the temperature of material. Thus, it is considered that the continuous LD could become the surface temperature higher compared with the case without continuous LD [5], hence the high efficient absorption of laser energy made it possible to increase the penetration depth and bead width.



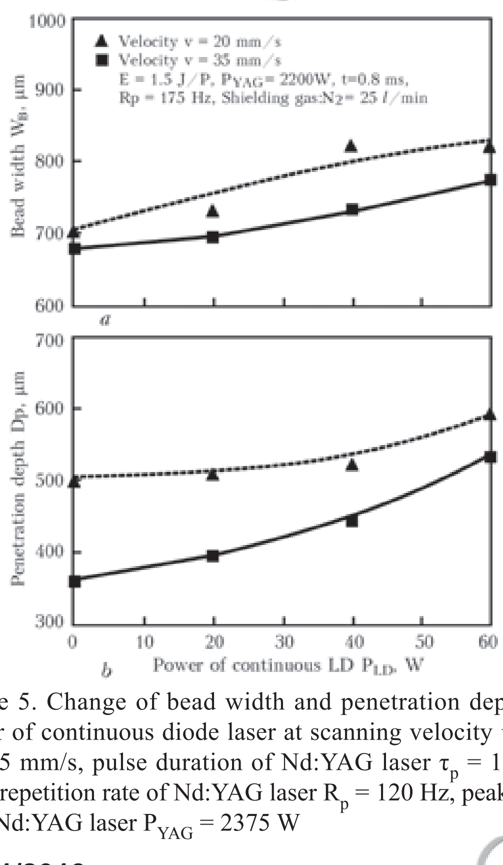


Figure 5. Change of bead width and penetration depth for power of continuous diode laser at scanning velocity v = 20 and 35 mm/s, pulse duration of Nd:YAG laser τ_p = 1.2 ms, pulse repetition rate of Nd:YAG laser R_p = 120 Hz, peak power of Nd:YAG laser P_{YAG} = 2375 W

Figure 5 shows the variations of bead width and penetration depth at scanning speed 20 mm/s and 35 mm/s in welding experiments of aluminum alloy battery case. The size of battery case is 30 mm-width x 5 mm-length x 0.3 mm-thickness. The top cover plate of 0.5 mm thickness was fitted and pressed into the inside of battery case. The bead width and penetration depth increased with increasing the continuous LD power at both scanning speeds. The penetration depth without continuous LD at scanning velocity 20 mm/s is approximately 500 µm, and the equivalent penetration depth could be obtained even at higher scanning velocity 35 mm/s by the superposition of continuous LD 50 W. When the average power of continuous LD is 60 W, the penetration depth was approximately 1.5 times larger than that without continuous LD. The bead width at scanning velocity 35 mm/s with continuous LD was also higher than that at scanning velocity 20 mm/s without continuous LD. Moreover, good quality weld beads could be obtained as shown in Figure 3.

It is confirmed that the effect of continuous LD on the penetration depth was remarkable at the faster processing speed. The high throughput and quality micro-welding by using pulsed Nd:YAG laser could be expected by superposition of continuous LD.

Effect of pre-Nd:YAG laser pulse on penetration depth at the beginning of scanning

In order to achieve the high absorption of Nd:YAG laser even at the beginning of laser scanning, pre-heating Nd:YAG laser pulse was investigated in the bead-on-plate experiment as shown in Figure 6. It was expected to keep the high surface temperature before the irradiation of main Nd:YAG laser pulse with the irradiation of continuous LD. As shown in Figure 6 (*a*), firstly, a continuous LD was irradiated on the specimen surface. Secondly, the pre-Nd:YAG laser pulse was irradiated as a rectangular pulse waveform to increase the surface temperature at the beginning of laser scanning. After the pre-Nd:YAG laser pulse, the main Nd:YAG laser pulses were irradiated.

Since the surface condition has greatly influence on the absorption state, the peak power of pre-Nd:YAG laser pulse on the surface condition was investigated. Figure 6 (b) shows microphotographs of irradiated surface for various peak powers by the single laser shot. For more than peak power 500W, the specimen surface was molten and became glossy, and the glossiness of specimen surface might reflect a main Nd:YAG laser pulse. On the other hand, the specimen surface was not glossy in the case of peak power 400 W, even the surface temperature increased. Therefore, the peak power 400 W was used for the pre-Nd:YAG laser pulse at pulse width 1.2 ms for 300 µm spot diameter.

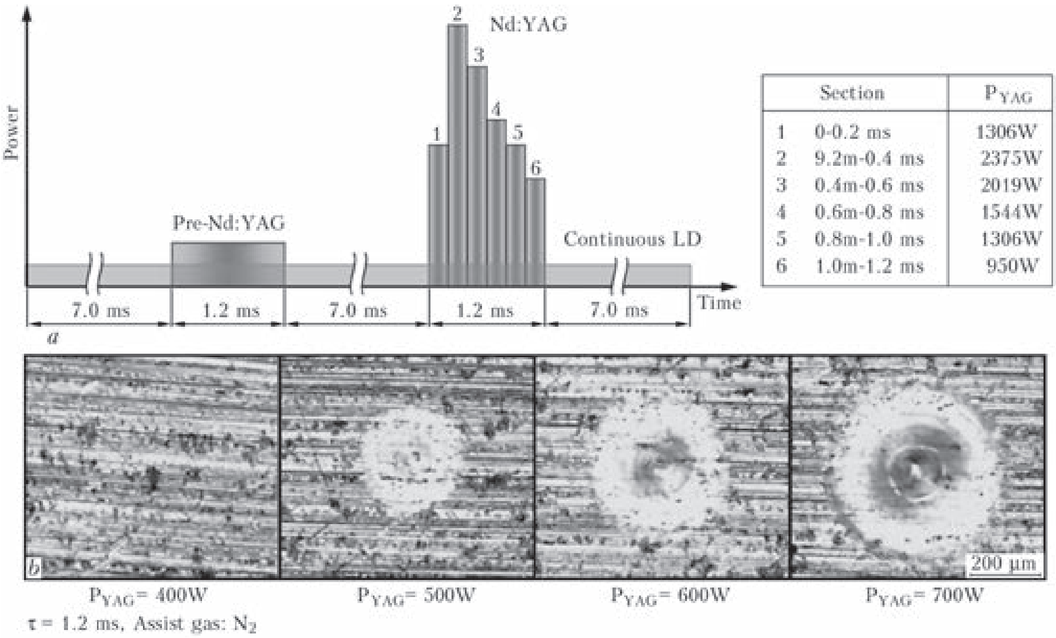


Figure 6. Irradiation waveform and irradiated surface state at pulse duration of Nd:YAG laser τ = 1.2ms without continuous LD in pre-heating method: (a) Irradiation waveform of pre-heating and main Nd:YAG lase pulse; (b) Irradiated surface for various peak powers of pre-heating pulse by single shot

Figure 7 shows the surfaces and cross sections of weld bead at the beginning of laser scanning. Here, the power density of pulsed Nd:YAG laser was set in the transitional region between heat conduction welding and key-hole welding. In the case of only main Nd: YAG laser pulse without the pre- Nd:YAG laser pulse, the penetration depth gradually increased in the scanning direction regardless of superposition of continuous LD (B, D). The penetration depth was unstable in the case of pre-Nd:YAG laser pulse without the superposition of continuous LD (A). It is considered that the absorption rate of pulsed Nd:YAG laser was unstable at low specimen surface temperature, since the power density is the transition condition between the heat conduction welding and the key-hole welding. On the other hand, in the case of pre-Nd:YAG laser pulse with the superposition of continuous LD (C), it was obvious that the penetration depth became larger from the beginning of laser scanning by stable higher absorption of laser energy. Moreover, the stable welding process could be performed with steady bead width and penetration depth. It indicated that not only the use of pre-Nd:YAG laser pulse but also the combination of pre-Nd:YAG laser pulse and the superposition of continuous LD made it possible to increase the molten volume at the beginning of laser scanning.

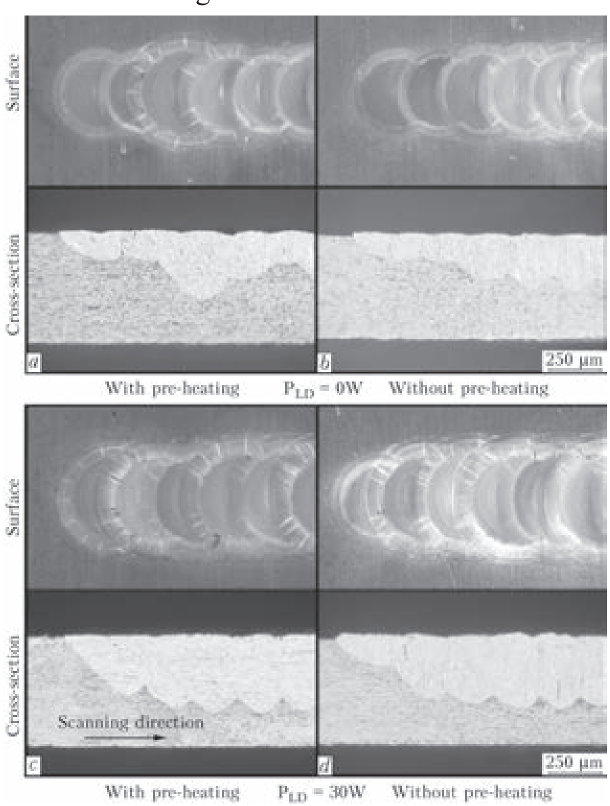


Figure 7. Welding results at the beginning of laser scanning with and without pre-Nd:YAG laser pulse at scanning velocity v = = 30 mm/s, pulse duration of Nd:YAG laser τ = 1.2 ms, pulse repetition rate of Nd:YAG laser R_p = 120 Hz, peak power of Nd:YAG laser P_{YAG} = 2375 W, peak power of pre-Nd:YAG laser pulse P_{pre} = 400 W and average power of LD P_{LD} = 0, 30 W. (a) P_{LD} = 0 W; (b) PLD = 30 W

The temperature change of specimen surface was investigated by the numerical calculation in order to discuss the welding phenomenon with and without the pre-heating pulse. The general finite element program 'ANSYS Rev.11.0', in which the unsteady calculation is possible, was used for the numerical analysis by using the analytical model as shown in Figure 8 (*a*). In the case of superposition of continuous LD, the key-hole effect was assumed. Internal heat generation by the heating element of shape mixed column and hemisphere was considered as a heat source as shown in Figure 8 (*b*). The total power of a pulsed Nd:YAG laser and a continuous LD was irradiated as an internal heat generation. A continuous LD was irradiated on the specimen surface except for pulsed Nd:YAG laser shot. The absorption rate of pulsed Nd:YAG laser was defined as 15 % for a heat flux and 30 % for an internal heat generation, and 30 W continuous LD was given by temperature dependent absorption rate, which were determined by the former investigation [5, 6]. The pulse waveform of main Nd:YAG laser was the same as shown Figure 6 (a). Pre-Nd:YAG laser pulse and a main Nd:YAG laser pulse without the superposition of continuous LD were given as a heat flux of absorption rate 15 % as shown in Figure 8 (c). A pulse of Nd:YAG laser of 300 μm spot diameter was irradiated at the pulse repetition rate 120 Hz and the scanning speed 30 mm/s. The convective heat transfer condition of air was considered after the set time of laser irradiation. Except for the laser beam irradiated area, the convective heat transfer condition of air was also considered. The pure aluminum thermo physical properties of specimen were used for this analysis. Coefficient of heat transfer and the initial temperature were 35 W/(m^2·K) and 296 K, respectively.

Figure 8 (d) shows the calculated surface temperature of spot center before the irradiation of main Nd:YAG laser pulse. In the case of only Nd:YAG laser pulse, the surface temperature was the same as an initial temperature before the first main Nd:YAG laser pulse, since there was no energy input. Only continuous LD irradiation increased the surface temperature by 40 K. By using both pre-heating pulse and continuous LD, the surface temperature increased approximately 200 K higher than that of main Nd:YAG laser pulse without pre-heating pulse. The absorption rate of Nd:YAG laser to aluminum alloy increases drastically more than 900 K, melting point of aluminum

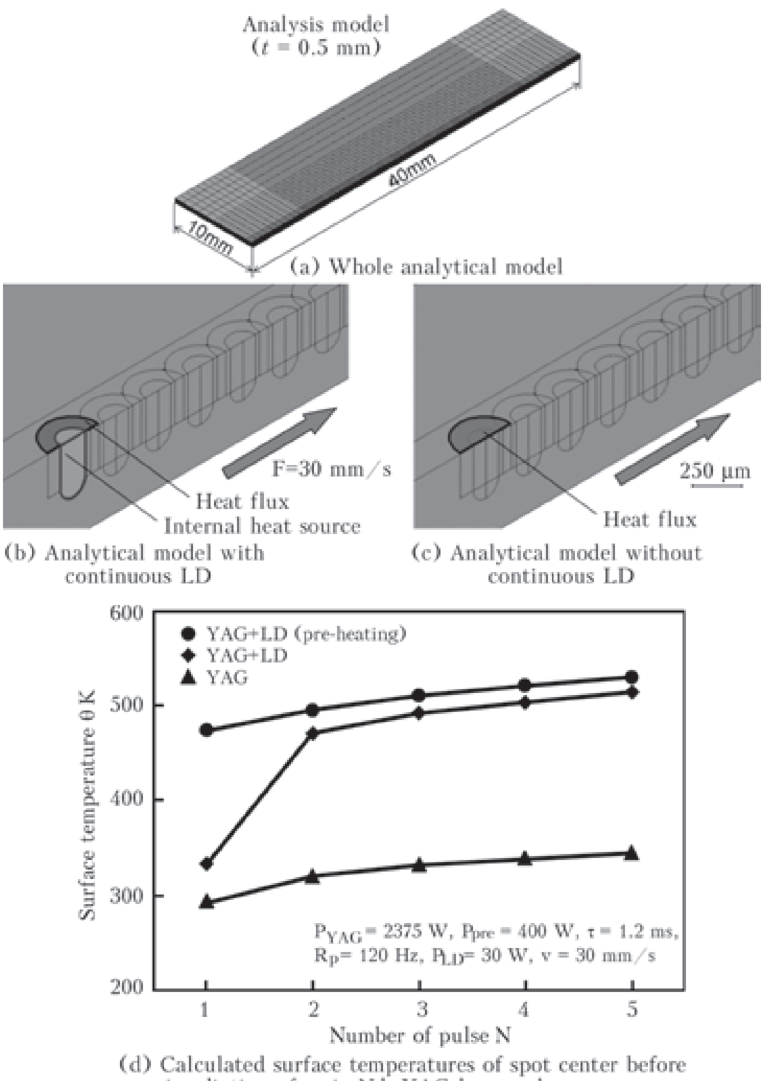


Figure 8. Analytical model and calculated surface temperatures of spot center before irradiation of main Nd:YAG laser pulse with and without pre-Nd:YAG laser pulse at scanning velocity v = 30 mm/s, pulse duration of Nd:YAG laser τ = 1.2 ms, pulse repetition rate of Nd:YAG laser R_p = 120 Hz, peak power of Nd:YAG laser P_{YAG} = 2375 W, peak power of pre-Nd:YAG laser pulse P_{pre} = 400 W and average power of LD P_{LD} = 0, 30 W

alloy. Without pre-heating pulse and continuous LD, a pulsed Nd:YAG laser was irradiated on the specimen surface at low temperature firstly, which led to the unstable absorption of a pulsed Nd:YAG laser beam. On the other hand, it is easy to reach the melting point in the case with pre-heating pulse and continuous LD compared with the case of only Nd:YAG laser irradiation. Therefore, it was considered that the energy of pulsed Nd:YAG laser could be absorbed effectively and stably to the specimen surface because of its higher surface temperature even at the beginning of laser scanning with pre-heating pulse and continuous LD.

Conclusions

The effects of superposed continuous LD on micro-welding of aluminum alloy by a pulsed Nd:YAG laser were investigated, and the pre-pulse method was also discussed in order to improve the penetration depth even at the beginning of laser scanning by pre-heating Nd:YAG laser pulse. Main conclusions obtained in this study are as follows.

(1) The energy of pulsed Nd:YAG laser could be absorbed to the aluminum alloy effectively, since the surface temperature of specimen was kept higher by the superposition of continuous LD during the interval time of Nd:YAG laser pulse.

(2) The high-efficiency and high-quality welding for aluminum battery case could be performed by the superposition of pulsed Nd:YAG laser and continuous diode laser. 15 % increase in bead width and 150 % increase in penetration depth were obtained by the superposition of continuous LD.

(3)A pulsed Nd:YAG laser was absorbed effectively from the beginning of laser scanning by pre-heating Nd:YAG laser pulse with the superposition of continuous LD due to the high surface temperature of specimen. The combination of pre-heating Nd:YAG laser pulse and continuous LD made it possible to perform the stable welding state from the beginning of laser scanning by stable absorption of pulsed Nd:YAG laser.

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