

Adaptive Gap Control in Butt Welding with a Pulsed YAG Laser[†]

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Abstract

The gap is one of the most important issues to be solved in laser welding of a micro butt joint, because the gap leads to welding defects such as underfilling or a non-bonded joint. In-process monitoring and adaptive control has been suggested as one of the useful procedures for the stable production of sound laser welds without defects. The objective of this research is to evaluate the availability of in-process monitoring and adaptive control in micro butt-welding of pure titanium rods with a pulsed Neodymium: Yttrium Aluminum Garnet (Nd:YAG) laser beam with a 150 μm spot diameter. It was revealed that a 45 μm-narrow gap was characterized by a remarkable jump in the reflected light intensity due to the formation of the molten pool which can bridge the gap. Heat radiation signal levels increased in proportion to the sizes of molten pools or penetration depths for the respective laser powers. As for adaptive control, the laser peak power was controlled on the basis of the reflected light or the heat radiation signals to produce sound deeply penetrated welds with reduced underfilling. In the case of a 100 μm gap, the underfilling was greatly reduced to half those made with a conventional rectangular pulse shape in seam welding as well as spot welding with a pulsed Nd:YAG laser beam. Consequently, the adaptive control of the laser peak power on the basis of in-process monitoring could reduce the harmful effects due to gaps in micro butt laser welding with a pulsed laser beam.

KEY WORDS: (Activating fluxes) (Electron Beam) (Welding)

1. Introduction

Micro butt-welding with a pulsed laser has been often used for sealing batteries in automobile and electronics industries^{1,2)}. A gap in such laser welding is one of the most important manufacturing problems, because the gaps may cause fatal welding defects such as shallow penetrations with underfilling or non-bonded joints.

In-process monitoring and adaptive control has been proposed as one of the useful procedures to stably produce sound penetration welds without welding defects. Recently, some articles have been devoted to the researches of in-process monitoring and advanced adaptive control technology in laser welding³⁻⁹⁾. The authors³⁻⁵⁾ have shown that the heat radiation signal levels increased in proportion to the molten pool diameters and accordingly the shear strengths of lap welds in thin A3003 aluminum alloy sheets, and demonstrated that adaptive control on the basis of the heat radiation signal could stably produce sound welds or on-site repaired welds.

In this research, micro butt welding of pure titanium was used with a pulsed fundamental Nd:YAG laser beam, and the reflected light and the heat radiation from the laser-irradiated area were measured as in-process

monitoring signals. These in-process monitoring signals were evaluated by the correlation with the spot diameter of a molten pool, the penetration depth or the gap. Moreover, the laser peak power was controlled on the basis of both the reflected light and the heat radiation detecting the gap and the spot diameter of a molten pool in order to suppress underfilling and small spot diameters for, not only spot welding, but also seam welding with the pulsed laser.

2. Materials and Experimental Procedures

The material used was commercially available pure titanium of more than 98 % in purity. The samples were 3 mm thick and 1 mm wide as shown in **Fig. 1**.

Micro butt welding was carried out with the pulsed fundamental Nd:YAG laser in 40-l/min Argon shielding gas. The beam was focused into a ϕ 150 μm spot diameter as shown in Fig. 1. The laser oscillator has the noteworthy feature of 50 W maximum average output power, with peak power changeable within 5 kW at intervals of 100 μs according to the external voltage signal. The reflected light and heat radiation from the laser irradiated area were monitored coaxially with the Nd:YAG laser beam. The in-process monitoring signals were measured by pin photo diode sensors. High-speed

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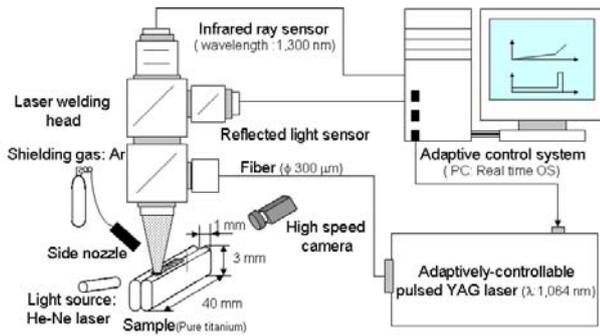


Fig. 1 Schematic experimental set-up of in-process monitoring and adaptive gap control in micro butt laser welding.

pictures of the molten area during laser irradiation were taken at the frame rate of 20,000 f/s from the angle of 45 degrees under the illumination light of a 22-mW He-Ne laser. As for adaptive control, the laser peak power was controlled at 150 μ s intervals during irradiation according to the reflected light or heat radiation to produce designed-size spot diameters with suppression of underfilling. The 150 μ s-rapid adaptive control loop consists of 100 μ s monitoring periods and 50 μ s for the estimation of laser welding conditions on the basis of in-process monitoring signals and the change in the laser peak power.

3. Experimental Results and Discussion

3.1 Laser micro-spot welding results of butt joint with wide gaps

Micro butt welds of titanium were produced with three kinds of rectangular Nd:YAG laser pulses for several gap below 110 μ m. The laser pulse durations were 15, 5 and 2 ms at the peak powers of 0.4, 0.8 and 1.6 kW, respectively. **Figure 2** shows the typical surface appearances and cross sections of the micro butt laser welds. Moreover, spot widths, underfills and penetrations are summarized as function of gap sizes in **Fig. 3**. The wider gaps caused the spot to become smaller, and this was enhanced by higher laser peak power. The spot width was reduced by about 45 % to 0.47 mm at 1.6 kW laser power for a 106 μ m gap. The penetration increased in proportion to the gap size at each laser peak power. However, deeply concave underfills were obtained at 0.8 or 1.6 kW in the case of 100 μ m-wide gaps. The maximum depth of the concavity reached 0.4 mm. On the other hand, it was found that the underfills were suppressed below 50 μ m at the laser peak power of 0.4 kW even when the gap was 98 μ m-wide.

Consequently, wider gaps resulted in the formation of more deeply-concaved underfills and small spots, which was enhanced by laser peak power in the micro butt welding. A 0.4 mm-deep underfilling weld with 45% reduced width was obtained at 1.6 kW for a 106 μ m gap. It was also found that the underfills were

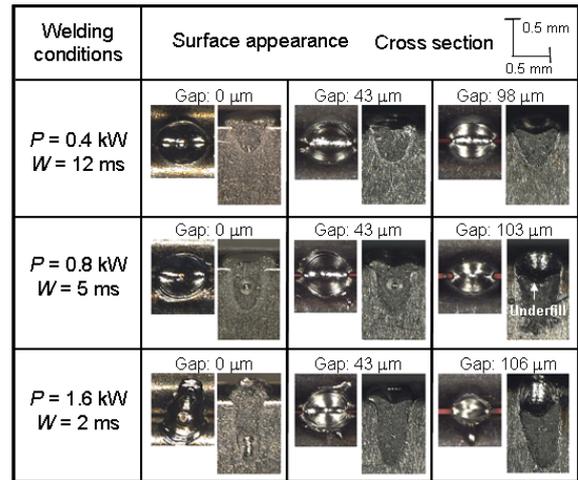


Fig. 2 Surface appearances and cross sections of micro butt laser welds made with pulsed Nd:YAG laser beam under different gap conditions.

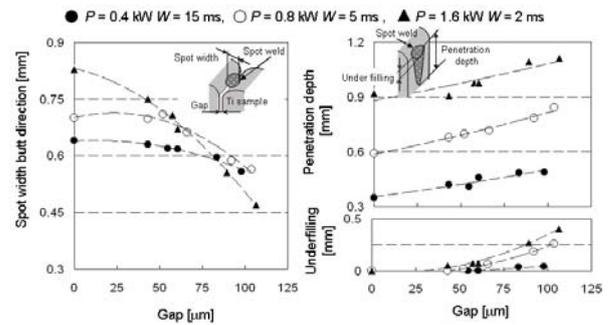


Fig. 3 Features of welding results produced by each gap sizes.

suppressed below 50 μ m by using 0.4 kW laser peak power even when the gap was 98 μ m-wide.

3.2 In-process monitoring results in laser micro welding of butt joint without gaps

An example of typical monitoring results of reflected light, heat radiation and high-speed video pictures during laser spot welding of a butt joint without a gap at 0.4 kW power is shown in **Fig. 4**. The horizontal axis is time, and the vertical axis indicates measured values of laser power and monitoring signals. The pictures show that melting started at 0.4 ms and the molten pool expanded gradually during the following laser irradiation. According to the series of pictures from 5.75 to 5.85 ms, the molten pool surface oscillated rapidly in 100 μ s short periods. The molten pool grew continuously during the laser irradiation. As for the reflected light, the intensity increased until the molten area was formed at 0.4 ms, and then it became almost constant during laser irradiation. On the other hand, the

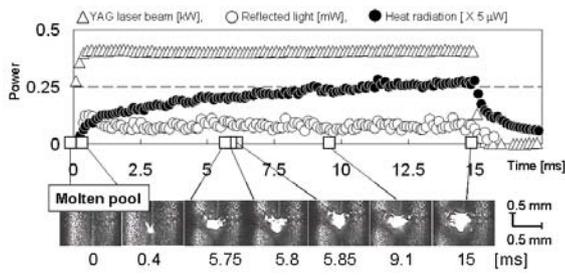


Fig. 4 Monitoring results of typical butt welding, showing laser pulse shape, reflected light, heat radiation and high-speed observation images of the spot molten pool under non-gap conditions.

intensity of heat radiation increased continuously from the start of the laser irradiation. Compared with the molten pool in the high-speed video pictures, it was found that the increase in the heat radiation was in proportion to the growth of the molten pool.

The surface molten pool diameter is plotted as a function of the reflected light or the heat radiation at each laser power in **Fig. 5**. However, the diameters were measured by using the high-speed video observation images showing the clear profiles of molten pools as seen at 9.1 ms and 15 ms in Fig. 4, since the heat radiation sampling cycle corresponded to the frame rate of the high speed camera. It was difficult to find a correlation between the molten pool diameter and the reflected light at each laser peak power. On the other hand, the heat radiation intensity was proportional to the molten pool diameter and the proportion depended upon the laser peak power. Higher heat radiation was obtained at higher laser peak power in comparison with the same diameter of the molten pool, because higher input energy heated the molten pool to higher temperature. Furthermore, **Figure 6** shows the relationship between the penetration depth and the heat radiation intensity. At each laser power, the heat radiation was proportional to the penetration depth as well as the molten pool diameter. The reason was attributed to the phenomenon that the molten pool depth and diameter are determined roughly

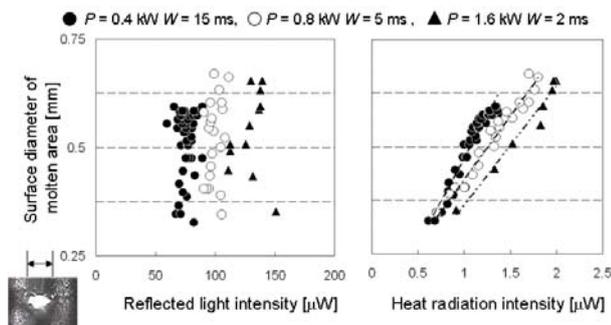


Fig. 5 Relationship between surface diameters of molten area and in-process monitoring signals.

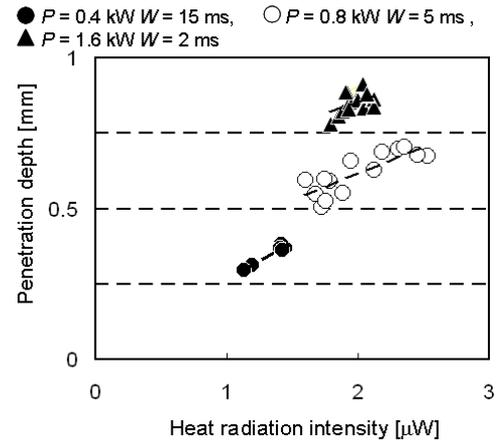


Fig. 6 Relationship between penetration depth and heat radiation signal for each laser peak power.

by laser peak power and input energy in the micro spot laser welding.

Consequently, the heat radiation values had clear correlation with molten pool sizes or penetration depths for respective laser peak powers in the laser welding of a micro butt joint. It was concluded that the heat radiation was significantly useful as an in-process monitoring signal for detecting a molten pool diameter or penetration depth during laser irradiation as long as the laser peak power was monitored.

3.3 In-process monitoring results during laser micro welding of butt joints with wide gaps

Monitoring results of reflected light and heat radiation, high-speed video pictures and 0.4 kW laser welding results of a joint with an 84 μm gap are shown in **Fig. 7**. The lower pictures show the cross sections of butt welds made when the laser irradiations were stopped at the times shown at the bottom. The split molten pool images in the upper pictures at 3 ms or 4.9 ms indicated that molten pools could not bridge the gaps, and it was confirmed by the existence of the gaps. At 5 ms the lower picture showed that the weld fusion zone bridged the wide gap and the upper picture demonstrated one molten pool. As for the reflected light, the intensity became almost constant when the molten bridge was formed at 4.9 ms. At 5 ms a rapid increase over 80 μW occurred and then became almost constant again during the subsequent laser irradiation. On the other hand, the heat radiation intensity increased continuously from the start of the laser irradiation to 4.9 ms. At 5 ms it rose so sharply that the gradient was over 0.3 mW/s within 50 μs, and then increased gradually until the termination of the laser welding.

The correlations between gap sizes and the in-process monitoring signals are shown in **Fig. 8**. The reflected light increased in proportion to the gap from 43 μm to 98 μm, owing to the sensitivity of the reflected light to the change of molten pool surface. On the other hand, the heat radiation intensities were almost constant

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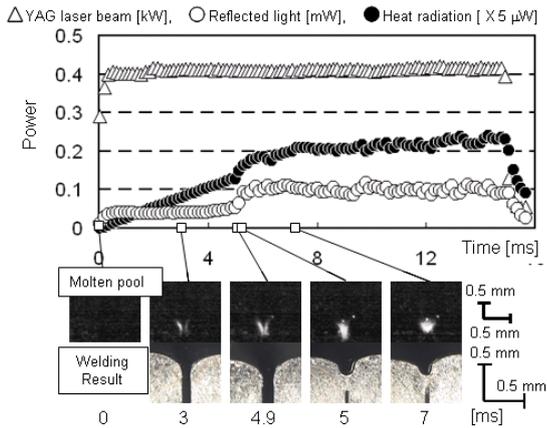


Fig. 7 Monitoring results showing laser pulse shape, reflected light, heat radiation, high-speed observation images of spot molten pool and cross sections of Ti joints with 84 μm gap.

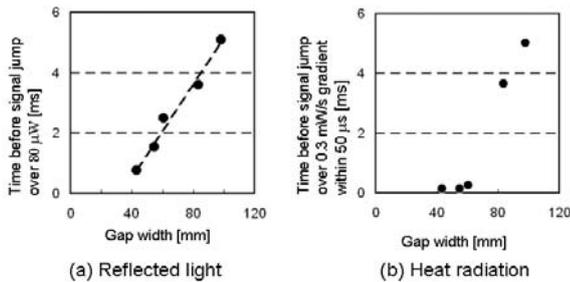


Fig. 8 Relationship between gap sizes and in-process monitoring signals at 0.4 kW laser peak power.

among gaps below 60 μm , which was not suitable for narrow gap monitoring. However, the heat radiation intensities increased greatly in the case of gaps over 80 μm . Here the laser welding processes before and after the formation of the molten pool which bridged a gap are illustrated in **Fig. 9**. The most part of the laser beam passed through the gap before the bridged molten pool was formed as shown in Fig. 9 (a). Therefore, the laser beam was hardly reflected and weak heat radiation was emitted from the small molten area produced by part of the laser beam. After the large molten pool bridging the gap, all the parts of laser beam were reflected except the absorbed laser beam on the laser-irradiated surface. The heat radiation intensity also increased drastically owing to the rapid raise in the absorbed laser beam. The monitored signals of the reflected laser beam and the heat radiation were fully interpreted in connection with the characteristic processes during laser micro welding of butt joints with gaps, and they can be utilized as good signals for adaptive control.

Lastly, the high-speed images before and after the formations of the molten pools which bridged about 85 μm -wide gaps at 0.4 kW, 0.8 kW and 1.6 kW laser peak

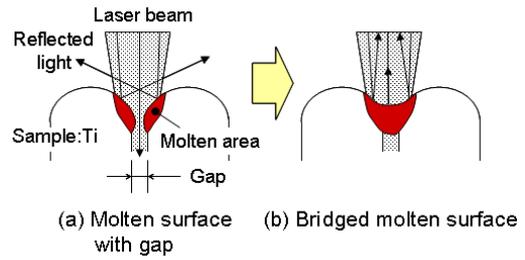


Fig. 9 Schematic drawing of micro butt welding process when molten pool bridged gap.

Laser welding Conditions	High-speed observation images	
Laser power: 0.4 kW Gap: 84 μm	4.9 ms	5 ms
Laser power: 0.8 kW Gap: 84 μm	1 ms	1.1 ms
Laser power: 1.6 kW Gap: 87 μm	0.4 ms	0.6 ms

Fig. 10 High-speed observation images showing formation of bridged molten pool over gaps.

power are shown in **Fig. 10**. It was found that the higher laser peak power caused the melt to flow into the deeper part of the gap and the molten area filled up the gap to more deeply-concaved surface. The depth of the gap-induced underfills thereby depended upon laser peak power. On the other hand, it was expected that underfilling was suppressed using 0.4 kW-low peak power until the molten pool bridged the gap.

Consequently, it was found that a reflected light and heat radiation provided in-process monitoring signals for gap size in micro butt laser welding with a pulsed Nd:YAG laser beam. The reflected light signal represented 45 μm -narrow gap size, owing to the sensitivity of the reflected light to the change of molten pool surface. Moreover, it was expected that underfills were suppressed by using 0.4 kW-low peak power until the molten pool bridged the gap.

3.4 Adaptive control for defect reduction in laser spot and seam welding of butt joints

In order to produce the designed spots with reduction in deeply-concaved underfills or smaller spots, the laser peak power was controlled according to the flow chart as shown in **Fig. 11**. The 0.4 kW laser peak was changed to 1.6 kW on the basis of the reflected light over

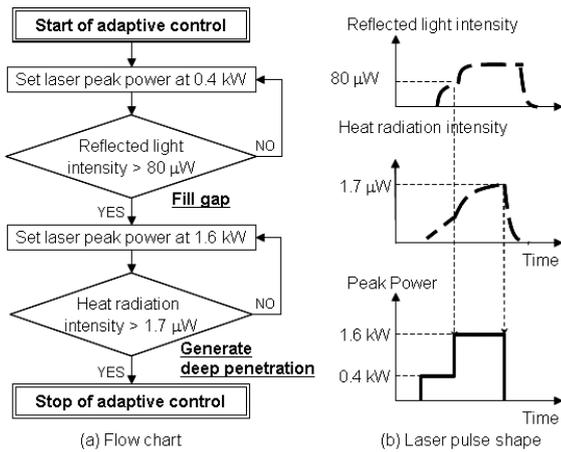


Fig. 11 Flow chart of adaptive control for narrow spot and underfilling.

80 μW indicating that a molten pool bridged a gap. The laser irradiation was terminated according to the heat radiation over 1.7 μW which predicted that the spot size reached the designed size of 0.6 mm. The in-process monitoring results are demonstrated in Fig. 12. A molten pool was observed to bridge the gap at 5.4 ms when the reflected light intensity was over 80 μW . Then the laser irradiation was continued until the heat radiation reached 1.7 μW . Therefore, it was confirmed that the adequate adaptive control was achieved on the basis of the reflected light and the heat radiation.

Figure 13 shows typical surface appearances and cross sections produced by the adaptive control for the joints with the gaps of 60 μm and 106 μm , and as a reference the ones on the right were made with conventional rectangular pulses of 1.6 kW and 2 ms. The spot width, underfills and penetrations produced by the adaptive control for the joints with several gaps are

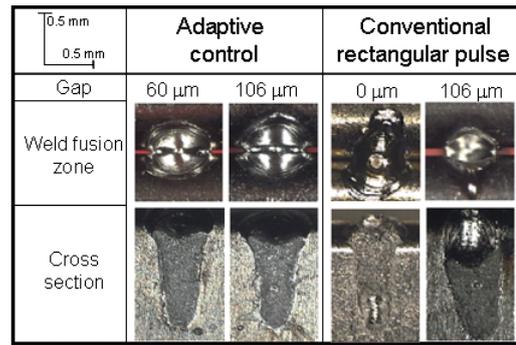


Fig. 13 Surface appearances and cross sections under adaptive control for several sizes of gap.

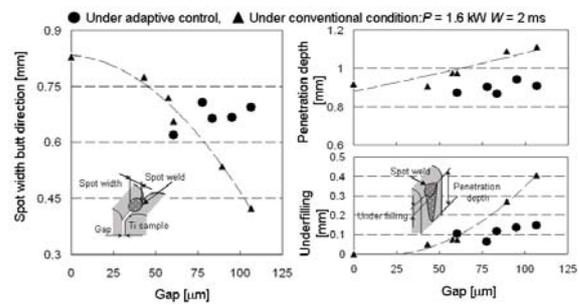


Fig. 14 Features of welding results produced by each gap under adaptive control.

summarized as a function of gap sizes in Fig. 14. The minimum spot width was improved from 0.4 mm to more than 0.6 mm, and the underfills were also reduced from 0.4 mm to 0.15 mm as a result of the adaptive control. Moreover, the penetration depths were kept constant at all the gap sizes.

Furthermore, the adaptive control was applied to the laser seam welding of butt joints with a 100 μm gap. The surface appearances and cross sections under the adaptive control or with the conventional rectangle laser pulse are demonstrated in Fig. 15. However, the rectangle pulse had 2 ms pulse duration and 1.6 kW laser peak power. The minimum bead width increased from 0.4 mm to 0.6 mm and the maximum depth of underfills was reduced from 0.32 mm to 0.16 mm. Therefore, the bead surface appearances and underfills were improved greatly in comparison with those with the conventional rectangle laser pulse. Moreover, it was found that the adaptive control was more effective with the underfills or the smaller spots in more early laser shots, because the gap size was reduced by solidification shrinkages generated in the previous laser welds.

Consequently, the laser peak power adaptively controlled on the basis of in-process monitoring had a beneficial effect for gaps in micro butt-welding with a pulsed laser. In spot welding, the minimum spot width was improved from 0.4 mm to more than 0.6 mm and the maximum depth of underfills was also reduced widely from 0.4 mm to 0.15 mm. As for seam welding, the

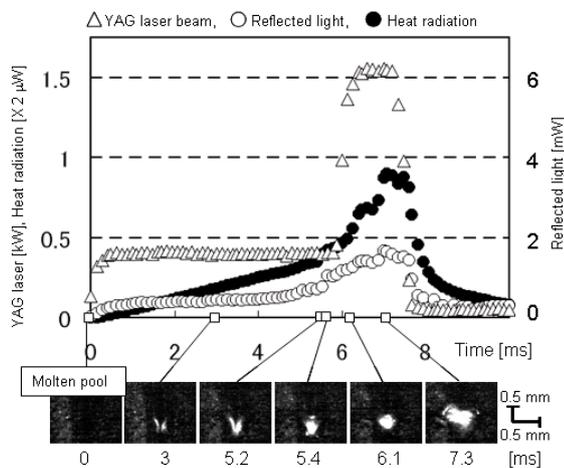


Fig. 12 Monitoring results under adaptive control for narrow spot and underfilling.

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	Adaptive control	Conventional rectangular pulse
Minimum bead width	0.6 mm	0.4 mm
Maximum underfilling	0.16 mm	0.32 mm
Surface appearance		
Cross section		

Fig. 15 Surface appearances and cross sections under the adaptive control in seam welding with Pulsed YAG laser beam.

minimum bead width was improved as well as the adaptively controlled spot diameter in welding and the maximum underfill was reduced to be half size.

5. Conclusions

In-process monitoring and adaptive control for the reduction of harmful effect of gaps has been developed in micro butt welding of pure titanium with a pulsed Nd:YAG laser. The availability of in-process monitoring for the spot diameter of a molten pool, penetration or a gap, and the effectiveness of adaptive control on the improvement in underfills and small spots were evaluated. The results obtained are as follows:

Concerning laser micro-spot welding of butt joints with a wide gap

- (1) Wider gaps resulted in more deeply concave underfills or smaller spots, which were enhanced by laser peak power in the micro butt-welding. A 0.4 mm-deep underfill and 45 %-reduced spot width were obtained in the joint with a 106 μm gap size at 1.6 kW laser power.
- (2) It was found that the underfilling levels were suppressed below 50 μm by using 0.4 kW laser peak power even when the gap was 98 μm -wide.
- (3) It was revealed that the higher laser peak power caused that the melt to flow into the deeper part of the gap and then the molten area filled up the gap to more deeply concave surface.

Concerning in-process monitoring in laser micro butt welding

- (1) The intensity of heat radiation showed clear correlation with the molten pool size or penetration depth for respective laser peak powers in the laser micro butt-welding. The heat radiation was thereby useful as an in-process monitoring signal for detecting a molten pool diameter or penetration depth

during laser irradiation as long as the laser peak power was monitored.

- (2) It was found that a reflected light and heat radiation were available as in-process monitoring signals for gap sizes in micro butt welding with a pulsed Nd:YAG laser beam. The reflected light signal could detect a 45 μm -narrow gap, owing to the high sensitivity of the reflected light to the change in the molten pool surface.

Concerning adaptive control for the reduction of welding defects in laser spot and seam welding

- (1) In spot welding, the minimum spot diameter was improved from 0.4 mm to more than 0.6 mm and the maximum depth of underfills was also reduced widely from 0.4 mm to 0.15 mm. As for laser seam welding, the minimum bead width was improved as well as the adaptively controlled spot diameter in spot welding and the maximum underfilling level was reduced to be half size.
- (2) The laser peak power adaptively-controlled on the basis of the reflected light and the heat radiation had a beneficial effect for the reduction in underfills and for the improvement of small spots in micro butt welding with a pulsed Nd:YAG laser beam.

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