

Adaptive Control and Repair for Lap Welds of Aluminum Alloy Sheets Based upon In-Process Monitoring[†]

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Abstract

A new procedure of in-process monitoring and adaptive control has been developed for laser micro-spot lap welding of A3003 aluminum alloy sheets. The objective is to produce sound partial- and full-penetration welds without through-holes. In partial-penetration welds, the reflected laser beam and the radiated heat from the welding area were effective as in-process monitoring signals for detecting melting and through-hole formation in the upper sheet during laser irradiation. Laser pulse duration and peak power were controlled at every 150 μ s intervals during spot welding on the basis of the heat radiation signal detecting the through-hole. In the full-penetration welds, the laser power was controlled so as to keep the value of the reflected light signal higher than the minimum and to restrict the variation of the heat radiation signal within one-third levels of the maximum increase and decrease, to prevent the formation of a through-hole. Consequently, the laser pulse peak power was properly controlled on the basis of the reflected light power and the heat radiation variation and this led to the production of sound welds at all times. The above results proved the effectiveness of in-process monitoring and the availability of adaptive control.

KEY WORDS: (Adaptive control), (In-process monitoring), (Micro laser welding), (Aluminum alloy), (Repair)

1. Introduction

Micro-spot welding with a pulsed laser beam has been widely used for mass production in electronics and electrical industries, because it is capable of micro joining with a narrow heated affected zone and high-speed joining by taking advantage of laser features. However, laser apparatuses are high-cost compared with the other welding machines such as resistance welders. Therefore, it is essential to create not only high-productivity but also high-reliability in manufacturing processes.

Aluminum alloy, which is one of the weight-saving materials in automobile and electronics industries, is difficult to weld with a laser beam, due to high heat conductivity and low absorptivity for the wavelengths of a fundamental YAG laser and a carbon dioxide laser. Moreover, deformation or distortion is easily induced in and around the welded spot due to the high linear expansion coefficient. For example, in the application for high-precision junctions of micro size, it is extremely difficult to produce stable, high quality welds, because the small changes in heat capacity or surface reflectivity are apt to cause different weld-quality results, including bad welds with through-holes. Therefore, in-process monitoring and adaptive control are important as ways of

solving the above problems in laser welding of aluminum alloys. Recently several articles have been devoted to these researches¹⁻⁵⁾. There are few papers reporting the production of sound welds with adaptive control.^{1,2)}

In this research, sound partial- and full-penetration welds of A3003 aluminum alloy sheets were produced with a pulsed fundamental YAG laser beam, and the intensities of reflected light and heat radiation during laser welding process were monitored in parallel with the observation of the molten pool and the laser-induced plume using high-speed video cameras. Moreover, in the partial-penetration weld, laser pulse duration and peak power were controlled for in-process repair of a non-bonded weld on the basis of the heat radiation signal detecting a through-hole. As for the full-penetration welds, the laser power was controlled so as to maintain both the reflected light intensity and the variation of heat radiation within the levels for the formation of normal full-penetration welds, in order to prevent through-holes.

2. Material Used and Experimental procedures

The experimental material is A3003 alloy, whose aluminum content is more than 96 % and which contains about 1.25 % manganese. The sheets were of 30 x 5 mm in size, and 0.1 mm and 1 mm in thickness for

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partially-penetrating welds. On the other hand, two 0.1 mm thick sheets were employed for fully-penetrating welds.

Micro-spot lap welding was carried out with the pulsed fundamental YAG laser of 50 W maximum output power, as shown in **Figure 1**. With respect to partial penetration welds, 0.1 mm thick sheet was put on 1 mm thick sheet, and welded in air. In full penetration welds, 0.1 mm thick lap sheets were also welded in air. These laser irradiation conditions are shown in **Table 1**. Moreover, a reflected light, heat radiation and high-speed images from the area irradiated with the YAG laser beam were monitored in process in order to clarify the phenomena during laser micro-spot lap welding. The reflected light and the heat radiation were measured coaxially with the YAG laser beam. At the same time the change of molten pool behavior was observed by the high-speed video camera at an angle of 45° to the A3003 sheet surface with the illumination light of a He-Ne laser which was set opposite to the high-speed camera. The laser-induced plume was also observed by the high-speed video camera set horizontally. The intensities of the reflected light and heat radiation were measured by PIN photo-diodes. In particular, as for the measurement of the heat radiation, the intensity of the reflected beam was reduced by OD levels of 8 or more by a notch filter and an interference filter of 1,300 nm wavelength with a half bandwidth of 10 nm. The high-speed pictures of the sheet surface during laser irradiation were taken at the frame rate of 9,000 F/s in the illumination light of a He-Ne laser.

Regarding the adaptive control in partial penetration welds, laser pulse duration and peak power of the

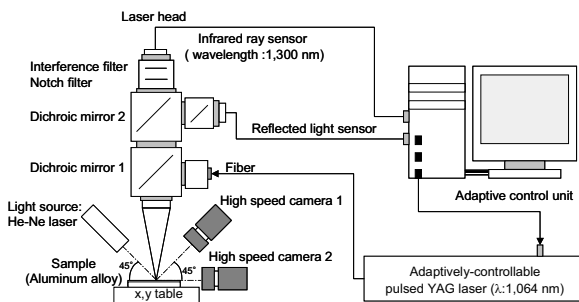


Fig. 1 Schematic drawing of experimental set-up for in-process monitoring and adaptive control.

Table 1 Laser conditions with pulsed YAG laser.

	Partial-penetration weld	Full-penetration weld
Energy	4.6 J	25.2 J
Pulse shape		
Laser focusing condition	@focus	@focus
Spot diameter	150 μm	150 μm

fundamental YAG laser were controlled at 150 μs intervals on the basis of the heat radiation measured during laser irradiation. The laser peak power was raised when detecting through-hole existence in the upper sheet, and then the pulse duration was terminated when the heat radiation predicted that the shear strength of the lap-welded joint reached a desired level. On the other hand, under an adaptive control in a full penetration weld, laser peak power was controlled at 150 μs intervals on the basis of the reflected light of the YAG laser beam and the heat radiation from the molten pool so as to suppress the rapid increase and decrease in the heat radiation power and to keep the intensity level of the reflected light higher in comparison with the case of the production of through-holes.

3. Experimental Results and Discussion

3.1 In-Process Monitoring for Partial-Penetration Welds

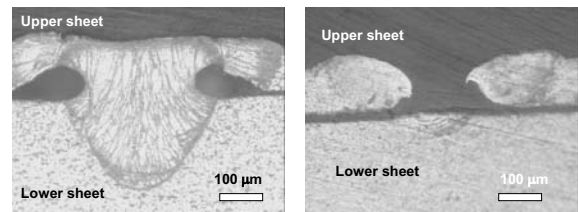
1) Laser micro-spot lap welding of A3003 aluminum alloy sheets

Twenty samples were subjected to pulsed YAG laser welding. As a result, four non-bonded welds with through-holes were produced and partial-penetration welds were obtained in the other samples. In the partially-penetrated welds as shown in **Figure 2 (a)**, the geometry of the weld fusion zone was similar to a keyhole mode of penetration rather than a heat conduction type. It was also found that a gap between upper sheet and lower sheet was formed by the deformation or distortion of the upper sheet around the lap-welded joint. On the other hand, a non-bonded welds with a through-hole is shown in Fig. 2 (b), The through-hole existed in the upper sheet and a small melted zone was formed on the upper surface of the lower sheet.

Consequently, it was found that non-bonded welds with through-holes were produced under the conventional laser conditions as shown in Table 1.

2) In-process monitoring for laser micro-spot lap welding of A3003 sheets

An example of the monitoring results of reflected light, heat radiation, and high-speed images is shown in **Figure 3**. This shows the wave shape of a YAG laser beam, reflected light and heat radiation. The vertical axis



(a) Normal partial-penetration welds

(b) Non-bonded welds with through-holes

Fig. 2 Cross sections of YAG laser spot welds in A3003 alloy sheets subjected to the same normal pulse shape.

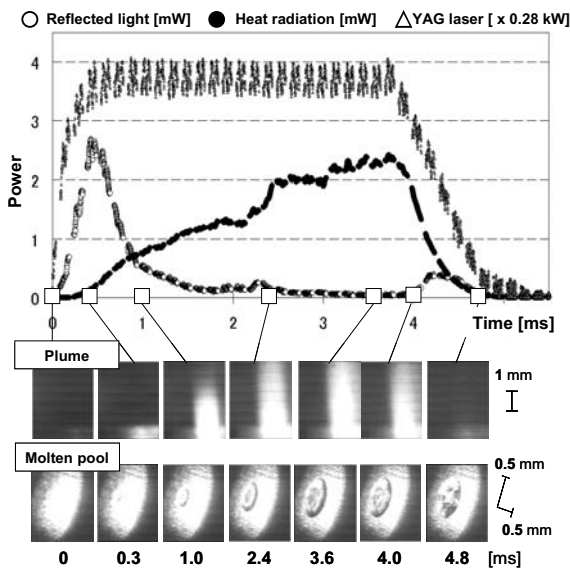


Fig. 3 Monitoring results of laser micro-spot lap welding of A3003 sheets, showing high-speed observation images, pulse shape, reflected light and heat radiation signals.

of the YAG laser, the reflected laser beam and the heat radiation are power in kW, mW and μ W, respectively. The horizontal axis is time in ms. 0 ms being the start of the YAG laser irradiation. The upper and lower photos show the laser-induced plume and the high-speed images of the surface condition during welding. The lower photos show that a small molten area was formed at 0.3 ms and grew into a molten pool while the laser irradiation continued at 1.07 kW peak power. Then, a concavity or hollow in molten pool was observed at 1.0 ms and expanded steadily. At the end of laser irradiation the melt rose inside the hollow. On the other hand, as indicated in the upper photos for 1.0 ms, the plume was observed when the hollow was in the molten pool and became higher during laser irradiation at 1.07 kW peak power. However, it disappeared as the laser peak power was lowered. According to the above-mentioned observation of the molten pool and the plume, it was considered that the hollow was a keyhole.

In respect of the reflected light, the intensity increased for 0.5 ms after the start of the laser irradiation, and then it decreased during irradiation at 1.07 kW peak power. As the peak power decreased, it increased again from 4.0 ms to 4.4 ms. This 0.4 ms period coincides with the period that the melt rose inside the hollow as shown the lower photos in Fig. 3. It was thought that a YAG laser beam was reflected by the flat surface which resulted from a closing keyhole. The wave shape of the reflected light had one peak at the start of melting and the other in closing a keyhole. As for the heat radiation, the intensity increased in proportion to the expansion of the molten area. When the laser peak power decreased, the heat radiation declined with it.

Consequently, the reflected light showed two peaks caused by melting the sample surface and by closing the

keyhole. In other words, the reflected light was characteristic of the phenomena before and after the melting process. On the contrary the heat radiation increased in proportion to the expansion of the molten area and showed the melting process clearly.

3) Relationship of monitoring signals to shear strength of A3003 lap-welded joint

Shear strengths of laser lap-welded joints were measured for twenty samples. The test results were compared with the reflected beam and heat radiation and are shown in Figure 4 (a) and (b). The vertical axis is shear strength of lap-welded joints in N. The horizontal axis of the reflected light is the period between two peaks of the monitored wave shape, gaining the information of the melting time on the sample surface. The horizontal axis of the heat radiation is the period over the power level of 1.7μ W, which was the index for distinction between partially penetrated welds and non-boned welds with through-holes in the upper sheets. The average and standard deviation of the shear strength are 10 N and 5.5 N, respectively.

In respect of the reflected light, when a through-hole was formed, the YAG laser beam was strongly reflected from the surface of the lower sheet. As a result, the period between two peaks decreased. However, a through-hole was formed just before laser irradiation was stopped. Therefore, judging from the shearing test result in Fig. 4 (a), it was difficult to make a close correlation between the reflected light and the shear strength. As for the heat radiation, the heat radiation intensity significantly decreased due to loss of the molten area corresponding to a through-hole. As a result, the intensity was much lower than 1.7μ W, therefore their periods indicate 0 ms. On the other hand, sound welds show that the shear strength increased in proportion to the period until about 12 ms, and kept almost constant for more than 12 ms in Fig. 4 (b).

It was consequently considered that heat radiation was correlated to the shear strength of a lap-welded joint. As shear strength was the important factor in laser welding, the heat radiation was selected as a real-time monitoring signal for adaptive control.

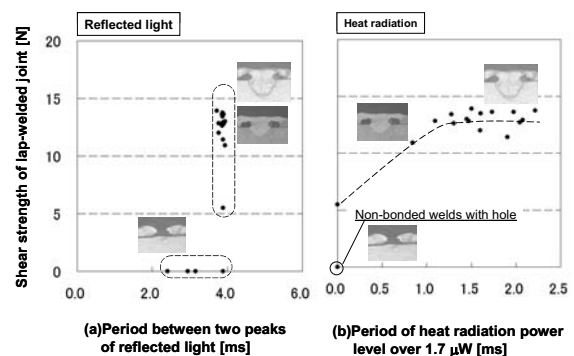


Fig. 4 Relationship of monitoring signals to shear strengths of lap-welded joints.

4) Discussion of feasible phenomena during laser micro-spot lap welding of sheets

Laser micro-spot welding is considered to be the ideal process without gap or the typical process with a gap between the upper and lower sheets, as schematically shown in **Figure 5** and **6**, respectively. (a), Fig.5 (b) and (c) show the formation of a melt surface and single reflection at the beginning of laser irradiation, the formation of a concave melt surface due to the recoil pressure of the metallic vapor and a reduced reflection beam at about two milliseconds, and the keyhole formation for the joint and high absorption due to multiple reflection, respectively. Practically, since the upper sheet is thin, the gap should form more or less due to the heat-expansion effect and the pressuring degree of a jig, as exhibited in Fig. 6. The existence of such gaps may affect the increase in the laser beam reflection and the decrease in the penetration, as exhibited in Fig. 6 (c).

Moreover, during laser micro-spot lap welding of sheets, a wide gap may be induced by significant deformation or distortion, as schematically illustrated in **Figure 7**. Aluminum alloy especially has such a high linear expansion coefficient that large deformation can be easily induced in and around the welded spot. It is therefore considered that the surface of the lower sheet will be heated from low temperatures, as shown in Fig. 7

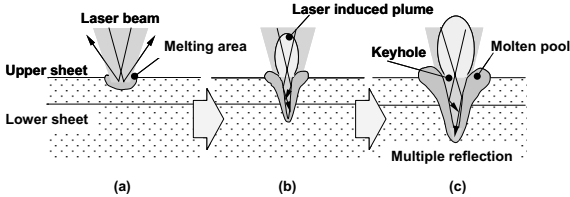


Fig. 5 Schematic drawing of ideal process of laser micro-spot lap welding.

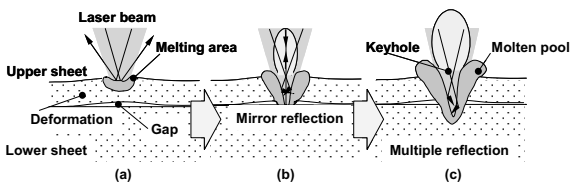


Fig. 6 Schematic drawing of typical process of laser micro-spot lap welding of sheets with narrow gap induced by small deformation.

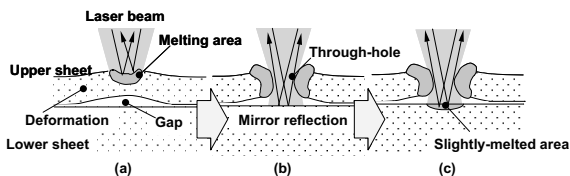


Fig. 7 Schematic drawing of typical process of non-bonded welding with through-hole in upper sheet induced by significant deformation.

(b). Consequently, a through-hole and shallow penetration may form in the upper and lower sheets, respectively.

Furthermore, in order to repair a through-hole during welding, the utilization of a higher power laser of high power density is required as shown in **Figure 8**. In the case (a) of the through-hole existence in the upper sheet, laser peak power is raised so rapidly that a larger molten pool is produced in the lower sheet, as shown in (b). Then the peripheral melt of the keyhole inlet in the lower sheet floats out to fill the peripheral through-hole in the upper sheet, resulting in the production of one large molten pool similar to that of the normal weld, as shown in (c).

From the above interpretation, it is important to suppress the gap between the upper and lower sheets. However, it is rather difficult to know and control the level of the gap during welding of the upper thin sheet. Thus the development of monitoring and adaptive control is indispensable to produce a sound lap-welded joint.

3.2 Adaptive Control For Repairing Through-Hole in Partial-Penetration Welds of A3003 Sheets

An adaptive control was implemented in twenty samples in order to produce a weld with satisfactory joint strength and/or to repair a non-bonded weld with a through-hole in the upper sheet. The flowchart of the adaptive control is shown in **Figure 9**.

Concerning the stabilization of joint strength, the target period (1.5 ms in this trial) was secured as the start time when the existence of a melt on the upper surface in

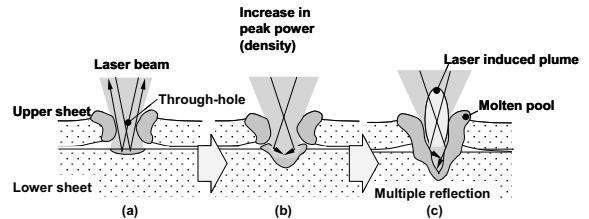


Fig. 8 Schematic drawing of typical adaptive control process for repairing non-bonded weld with through-hole in upper sheet induced by significant deformation.

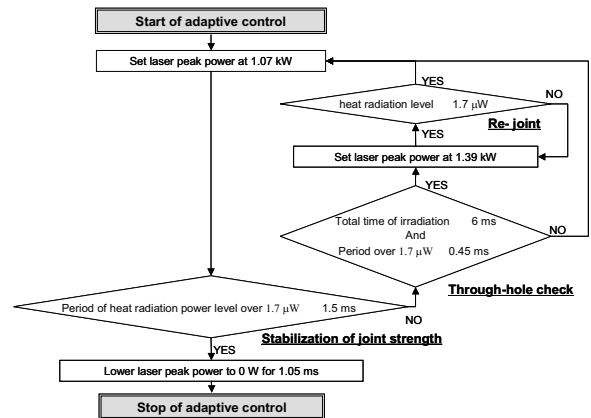


Fig. 9 Flow chart of adaptive control based upon intensity level and period of heat radiation.

the lower sheet was judged on the basis of the heat radiation intensity, in order to cancel out the difference of laser absorption among welding points. The laser pulse duration was controlled so as to obtain 1.5 ms over the heat radiation power level of 1.7 μ W. In the feasible case of no lap welding, the adaptive control unit judges the existence of the through-hole from the condition that the period of heat radiation power level 1.7 μ W could not reach 0.45 ms within 6 ms from the start of laser irradiation. With the existence of the through-hole, it makes laser peak power increase from 1.07 kW to 1.39 kW at 6 ms for melting both the area around the through-hole in upper sheet and the surface of lower sheet in order to rejoin these sheets. After the intensity of heat radiation achieved 1.7 μ W, laser peak power was lowered from 1.39 kW to 1.07 kW and then laser pulse duration was controlled for the stabilization of joint strength.

An example of the results monitored by heat radiation and high-speed image in repairing a through-hole in the upper sheet is shown in **Figure 10** as well as Fig. 3. According to the upper photos, at 3.0 ms a through-hole was formed on the surface of the upper sheet, and the light emission was observed inside the through-hole from 6.0 ms to 6.8ms. Then the melt flowed over and filled the through-hole. At 7.6 ms the keyhole was observed in the molten pool again and at 8.1 ms the melt rose inside the keyhole. On the other hand, the upper photos show that the laser-induced plume emerged at 6.0 ms again, grew up until 7.6 ms and disappeared as the laser peak power decreased.

As for the heat radiation, the intensity declined rapidly at 2.2 ms for the through-hole formation. At 6 ms the adaptive control unit recognized the existence of the through-hole and made the peak power rise from 1.07 kW to 1.39 kW. The intensity increased during laser

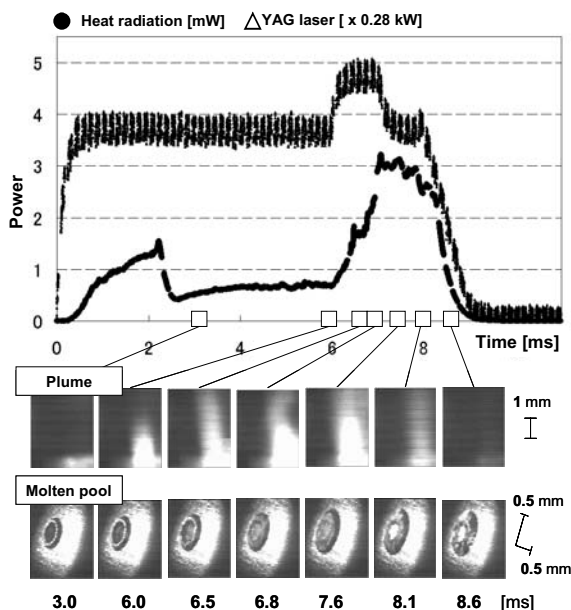


Fig. 10 Monitoring results of adaptive control, showing high-speed observation images, pulse shape and heat radiation signals.

irradiations at 1.39 kW and declined as the peak power decreased. The results of twenty samples showed that, the period of the heat radiation power level over 1.7 μ W was from 1.5 ms to 2.0 ms for the target period of 1.5ms. The main reasons were that the interval of adaptive control was 0.15ms and that the laser beam pulse had 1.05 ms of tailing shape as shown in Table 1. Accordingly it was realized that the adaptive control could be implemented to repair the non-bonded joint and moreover stabilized the joint strength as expected in real-time.

Under the experimental results of the adaptive control seven through-holes formed during laser irradiation were repaired and the A3003 sheets were jointed together. The shapes of the repaired welds were similar to the shapes of the sound partial-penetration welds as shown in Fig. 2 (a). Furthermore, the shear strength of the joint part was measured in twenty samples under the adaptive control. The test results are shown in **Figure 11**. The average and standard deviation of the shear strength are 15 N and 1.9 N, respectively.

Consequently, laser pulse duration and peak power were controlled at every 0.15 ms interval during the irradiation by a YAG laser beam, on the basis of the heat radiation signal in order to stabilize the joint strength and to repair the non-bonded weld with the through-hole in the upper sheet. All twenty samples were partially-penetrating welds, seven through-holes were formed during laser irradiation, but were repaired in process to joint together. The average and standard deviation of the improved shear strength were 1.5 times higher and 1/3 times lower than those without the adaptive control.

3.3 In-Process Monitoring for Full-Penetration Welds of A3003 Sheets

1) Laser micro-spot lap welding of aluminum alloy sheets

Fully-penetrating welded joints were produced at the laser focal point with a rectangular laser pulse of 0.9 kW peak power and 28 ms pulse width as indicated in Table 1. As a result, two through-holes were produced and sound

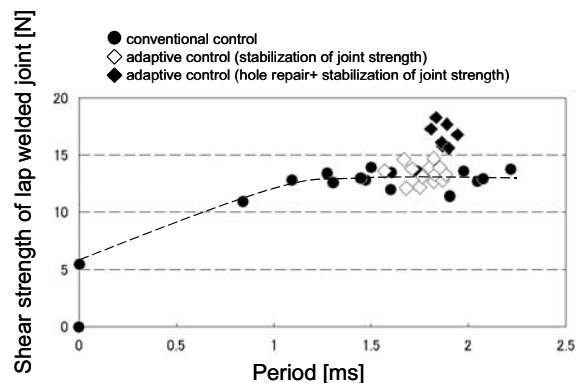


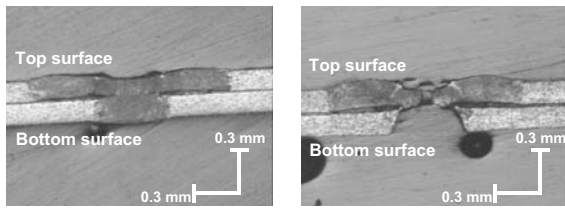
Fig. 11 Relationship between period of heat radiation power level over 1.7 μ W and shear strength of lap-welded joint made under adaptive control for hole repair in addition to data under conventional control.

full-penetration welds were obtained in the other samples. These cross sections are indicated in **Figure 12**. Fig. 12 (a) shows an example of a sound full-penetration weld with the area of lap joint weld, which was smaller than that of spot-weld fusion zone on the bottom surface. The average diameters of the fusion zones on the top and bottom surface were 0.95 mm and 0.4 mm respectively. On the contrary, in Fig. 12 (b) the through-hole was formed in the sheets. It was thought that the melt was blown off by a strong recoil pressure of the laser-induced plume.

Consequently, the welding defects of through-holes were produced under the conventional laser conditions as shown in Table 1.

2) In-process monitoring in the case of through-holes formation

Monitoring the results of sound full-penetration welds showed that the changes of reflected light and heat radiation were similar to the tendencies of monitoring signal in normal partial-penetration welds as indicated in Fig. 3. Here, an example of the monitoring results of reflected light, heat radiation, high-speed images of the molten area and the laser-induced plume is shown in **Figure 13**. The lower photos shows that melting started



(a) Normal full-penetration weld (b) Weld with through-hole in sheets

Fig. 12 Cross sections of normal full-penetration weld and bad weld with through-hole.

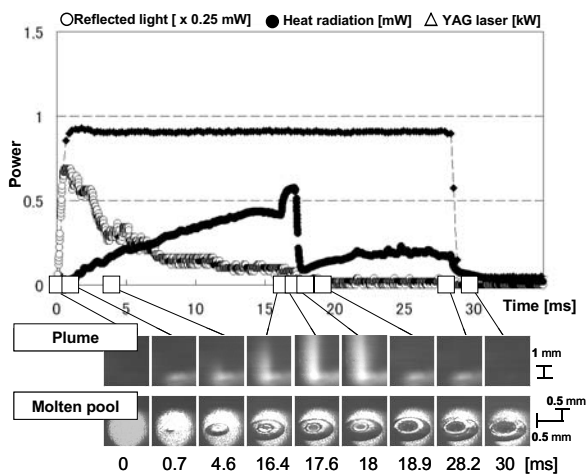


Fig. 13 Monitoring results in full-penetration A3003 weld with through-hole, showing laser pulse shape, reflected light and heat radiation signals, and high-speed observation images of plume and molten pool.

at 0.7 ms and the molten area expanded until 16.4 ms. At 17.6 ms it is observed that the laser-induced plume grew rapidly. A through-hole was formed and the plume disappeared at 18.9 ms.

In respect of the reflected light, after 18.9 ms the intensity of the reflected light fell because most of YAG laser beam passed through the through-hole. As for heat radiation, the rapid increase and decrease was observed just before the formation of the through-hole and then increased slowly. These rapid variation tendencies in monitoring signals were interpreted by considering the following laser welding phenomena.

- (i) Excessive absorption of YAG laser power took place on the concave molten pool surface due to the laser irradiation at the laser focal point.
- (ii) The intensity of heat radiation rose with the growth of the molten area.
- (iii) The easy formation of the deep hollow led to the strong absorption of the laser beam.
- (iv) The absorbed energy of laser beam caused the rapid growth of a laser-induced plume.
- (vi) The strong recoil pressure due to rapid evaporation made a through-hole in A3003 sheets.
- (vii) The heat-radiated area was reduced by the formation of the through-hole due to the loss of the molten area. On the other hand, the reflected light was hardly measured because most of a laser beam passed through the through-hole.
- (viii) The heat radiation intensity slowly increased because the molten area around the through-hole was slightly heated by the laser beam.

Consequently, the through-hole formation was characterized by the further decrease of reflected light intensity and the rapid increase and decrease of heat radiation power. These changes are useful for detecting the formation of a through-hole during welding. In particular, the heat radiation signal clearly represents the rapid change of the molten pool before and after the formation of the through-hole.

3) Relationship between in-process monitoring signals and laser lap welding results

The heat radiation and reflected light signals of the mentioned monitoring samples were compared with the spot weld fusion zones on the bottom surfaces. The results of reflected light and heat radiation are shown in **Figure 14** and **15**, respectively. These vertical axes are the reflected light intensity measured right before laser irradiation was stopped at 28 ms and the maximum increase and decrease of heat radiation power within every 0.1 ms monitoring period, respectively. The horizontal axes are the diameter of a spot weld fusion zone on the bottom surface. In the case of the generation of a through-hole, however, the diameters of through-holes were plotted as substitutes for the diameters of spot weld fusion zones. With respect to the reflected light, the intensity of a sound full-penetration

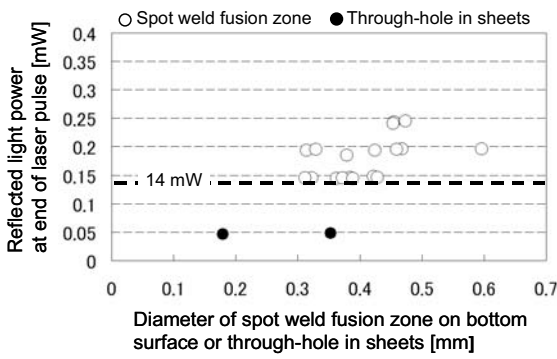


Fig. 14 Relationship between spot weld fusion zone diameter on bottom surface and reflected light.

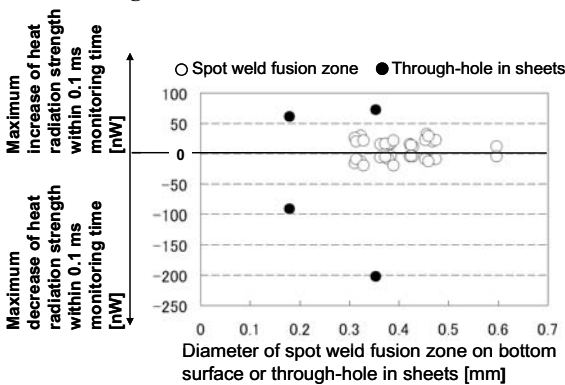


Fig. 15 Relationship between spot weld fusion zone diameter on bottom surface and heat radiation.

weld was over 14 mW and three times higher than that of the welds with through-holes as shown in Fig. 14. As for the heat radiation, the sound full-penetration welds were plotted between 61 nW and -91 nW. However, the maximum increase and decrease for the welding defects were two times higher than those in the full-penetration welds. The generation of the through-hole caused the great change of the heat radiation signal and was effective for monitoring the laser welding results.

Consequently, there was a large difference in both the reflected light and heat radiation signals between sound and bad full-penetration welds with and without through-holes, respectively. These were not only useful as in-process monitoring signals but also for the evaluation of the laser micro-spot lap welding result.

3.4 Adaptive Control for Prevention of Though-Hole in Full-Penetration Weld

The typical process of the generation of a through-hole in laser micro-spot lap welding is schematically shown in Figure 16. In some situations the normal welding process has the excessive absorption of a laser beam due to the slight differences of surface conditions and so on, as shown in Fig. 16 (a) and (b). The excessive absorption of a laser beam causes such a rapid growth of the laser-induced plume that the recoil pressure

of the plume blows off the melt as spatter in Fig. 16 (c). Therefore, the laser power was adaptively controlled with the utilization of an in-process monitoring signal in order to prevent the through-holes, as exhibited in Figure 17. The laser beam power was lowered until the current condition returns to the normal welding process, according to the reflected light decrease or the heat radiation increase, as shown in Fig. 17 (b) and (c). However, it is difficult to control laser power in response to the high-speed change from the level of a sound full-penetration weld to the level of the formation of a through-hole, because 100 μs response time of this adaptively-controllable pulsed YAG laser is late for the speed stratified with the adaptive control.

In this research, the aim of the adaptive control is to maintain both the level of the reflected light and the variation of heat radiation within the range of the monitoring data measured in the case of normal fully-penetrated welds. The adaptive control was implemented in twenty samples according to the flow chart as illustrated in Figure 18. The laser irradiation period was fixed at 28 ms. Firstly laser peak power is lowered to 0.88 kW in order to limit rapid growth of the molten area or a laser-induced plume, when the reflected light intensity was below 14 mW. Secondly, as long as the reflected light intensity is over 14 mW, the laser peak power was dropped to 0.88 kW when the increase of heat radiation exceeded 11 nW, or the laser peak power was raised up to 0.92 kW when the decrease of heat radiation was below -9 nW. These threshold values were one third of the maximum decrease and increase in Fig. 15. Except for the mentioned conditions, the laser peak power was held at 0.9 kW.

An example of the experimental results under the adaptive control is shown in Figure 19. The lower photos indicate that the small molten area was formed at 0.6 ms and grew up during the laser irradiation. The

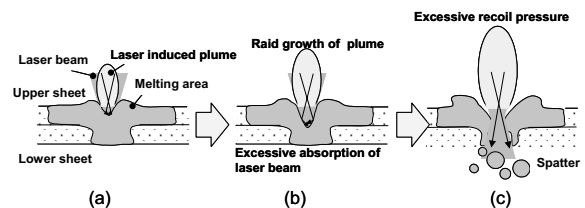


Fig. 16 Schematic drawing of typical process of generation of a through-hole in laser micro-spot lap welding of sheets.

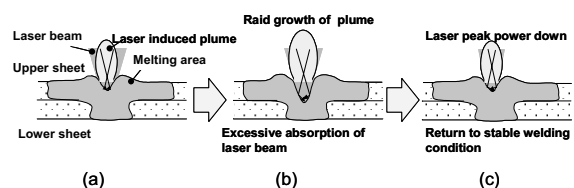


Fig. 17 Schematic drawing of typical adaptive control process for preventing a through-hole defect.

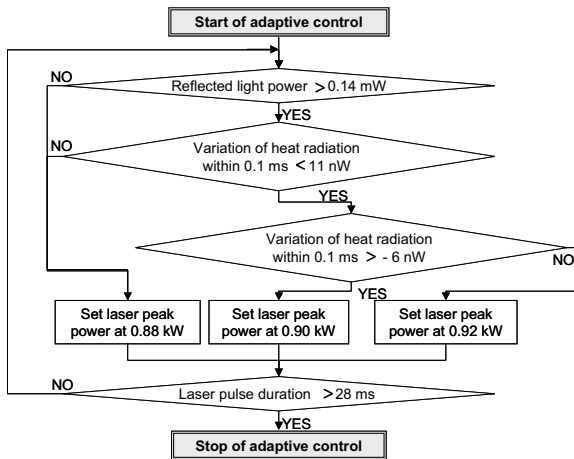


Fig. 18 Flow chart of adaptive control based upon reflected light and heat radiation.

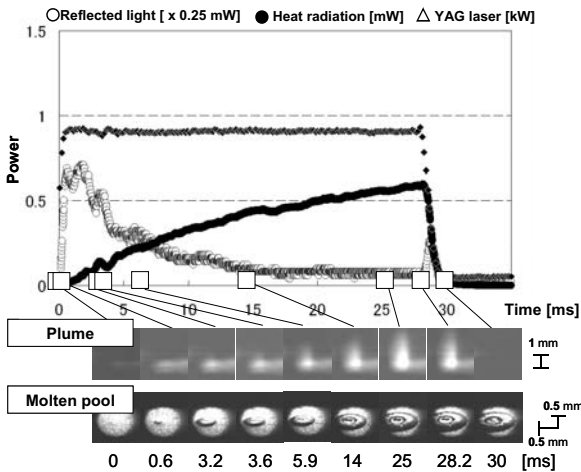


Fig. 19 Monitoring results of typical full-penetration weld of A3003 sheets, showing laser pulse shape, reflected light and heat radiation signals, and high-speed observation images of plume and molten pool under adaptive control condition.

laser-induced plume was observed at 5.9 ms and continued to exist until the laser irradiation was stopped. In respect of the reflected light, the intensity increased until 0.6 ms and then decreased during laser irradiation. As for heat radiation, the intensity increased in proportion to the expansion of the molten pool. However, the laser power was rapidly changed at some points by the adaptive control. The remarkable points existed within the period between 2.4 ms and 3.8 ms as shown in Figure 20. It shows that the wave shape of the laser power was changed in the opposite direction to the wave shape of the heat radiation power. This change of the laser power was considered to suppress the rapid increase of heat radiation power. The laser power was not controlled on the basis of the reflected light under the adaptive control, because the behavior of the molten surface seemed to keep stable owing to the stable growth of a molten pool and a laser-induced plume under the adaptive control on the

basis of a heat radiation signal.

The heat radiation and reflected light signals were compared to the spot weld fusion zones on the bottom surfaces among twenty samples under the adaptive control. As a result of the adaptive control, all the twenty samples have no through hole. The intensities of the reflected light were over 14 mW and the maximum increase and decrease of the heat radiation were 32 nW and -31 nW, respectively. Although the heat radiation signals exceeded the designed threshold value of the maximum decrease, no through-holes were formed among twenty samples under this adaptive control. Therefore these designed thresholds of in-process monitoring signals were effective for preventing the generation of through-holes.

The diameters of the spot weld fusion zone on the bottom surface under the adaptive control as shown in Figure 21 and contrasted with the conventional laser conditions. All the twenty samples under adaptive control have no through-holes. The average diameters of the spot weld fusion zones on the top surface or the bottom surface were 1.00 mm and 0.37 mm, respectively. However, the minimum value of the spot weld fusion

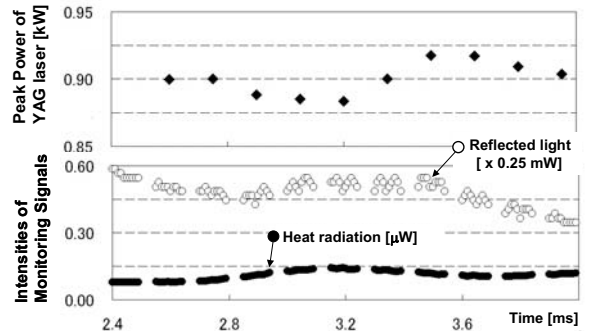


Fig. 20 Typical monitoring results under adaptive control during short period, showing laser peak power, reflected light and heat radiation signals.

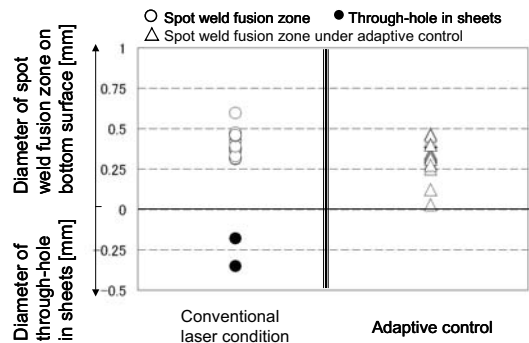


Fig. 21 Bottom surface diameter of spot weld fusion zone made under conventional conditions and under adaptive control for preventing through-holes in addition to data under conventional conditions.

zone on the bottom surface was about 30 μm . The small diameter seems to be caused by the restriction of laser power during welding.

Consequently, all the twenty samples under the adaptive control have full-penetration welds and the generation of through-holes was prevented by the adaptive control on the basis of the reflected light and heat radiation. Therefore, the stable growth of the molten area was significantly effective for preventing the generation of a through hole. It confirms clear availability of the adaptive control for the prevention of a through-hole in producing a sound full-penetration weld of A3003 sheets.

4. Conclusion

In-process monitoring and adaptive control has been developed for laser micro-spot lap welding of A3003 aluminum alloy sheets. The effectiveness of in-process monitoring and the applicability of adaptive control for sound partial- and full-penetration welds was confirmed. The results obtained are as follows:

1) Concerning in-process monitoring for partial-penetration welds

- (i) The reflected beam had two peaks caused by high-reflection of the sample solid-state surface and from the flat surface during closing the keyhole. It was characteristic of the phenomena before and after the laser welding process. The heat radiation increased in proportion to the expansion of the molten area and showed the laser welding process clearly.
- (ii) The heat radiation was considered to contain the information of the shear strength of lap-welded joint. It was suitable for the real-time monitoring signal for adaptive control of stabilizing the joint strength.

2) Concerning adaptive control for repairing through-hole in partial-penetration welds

- (i) Laser pulse duration and peak power were controlled at every 150 μs interval during the irradiation of a YAG laser beam, on the basis of the heat radiation signal in order to stabilize joint strength and to repair a non-bonded weld. In twenty partially-penetrated welds, seven through-holes formed in process were repaired.
- (ii) The shear strength of the joint part was measured in twenty samples under the adaptive control. The average and standard deviation of the shear strengths were 1.5 times higher and 1/3 times lower than those without the adaptive control.

3) Concerning In-process monitoring for full-penetration welds

- (i) The reflected light intensity decreased by the generation of a through-hole. As for the heat radiation, the rapid increase and decrease in the intensity were observed just before the formation of the through-hole was completed.
 - (ii) Both the reflected light and the heat radiation were useful as in-process monitoring signals for discrimination of normal fully-penetrated welds from bad welds with through-hole defects.
- 4) Concerning adaptive control for prevention of through-hole in full-penetration welds**
- (i) All the twenty samples have full-penetration welds and the generation of through-holes was prevented by the adaptive control on the basis of the reflected light and heat radiation during 28 ms laser irradiation.
 - (ii) This adaptive control indicated the clear possibility of the prevention of a through-hole. Therefore, the heat radiation was the prospective real-time monitoring signal for the adaptive control in preventing through-holes in sheets.

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