In-Process Monitoring and Adaptive Control during Pulsed YAG Laser Spot Welding of Aluminum Alloy Thin Sheets

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Recently aluminum alloys have been often used as weight saving materials in automobile and electronics industries. It is difficult to stably produce high quality welds in aluminum alloys because of high heat conductivity/diffusivity and low laser absorptance. Moreover, the deformation is easily induced around the welded spot due to high linear expansion coefficient. Therefore, in-process monitoring and adaptive control are important as one of the ways to solve the problems in laser welding of aluminum alloys. In this study, a new procedure of in-process monitoring and adaptive control has been developed for laser micro-spot lap welding of A3003 aluminum alloy sheets of 0.1 mm and 1mm in thickness. It was revealed that the reflected laser light and the radiated heat from the welding area were effective as in-process monitoring signals in detecting melting, keyhole generation and though-hole formation in the upper sheet during laser irradiation. Laser pulse duration and peak power and were controlled at every 0.15 ms interval during the laser spot welding on the basis of the heat radiation signal detecting the though-hole. Upon investigation of 20 samples, 4 non-bonded welds with holes were formed under conventionally used conditions. However, good laser lap spot welds could be always produced by utilizing newly developed in-process monitoring and adaptive control system.

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Keywords: laser welding, in-process monitoring, adaptive control, micro-spot lap welding, aluminum alloy, heat radiation, reflected light

1. Introduction

Recently aluminum alloy has been often used as weight saving material in automobile and electronics industries. Aluminum alloy is difficult to be welded with a laser beam, because of high heat conductivity and low absorptance for the wavelengths of a fundamental YAG laser and a carbon dioxide laser. Moreover, the deformation is easily induced in and around the welded spot due to high linear expansion coefficient. For example, in the application for high-precision junctions of micro size in small electric devices, it is extremely difficult to stably produce high quality welds, because the small changes in heat capacity or surface reflectivity are apt to cause different weld-quality results, including non-bonded welds with holes. Therefore, in-process monitoring and adaptive control are important as one of the ways to solve the above problems in laser welding of aluminum alloys. Recently several articles have been devoted to these researches [1–5].

In this research, micro-spot lap welding of A3003 aluminum alloy sheets of 0.1 mm and 1mm in thickness was performed with a pulsed fundamental YAG laser beam, and the intensities of reflected light and heat radiation during laser welding were measured in parallel with the behavior observation of a molten pool and a laser-induced plume using the high-speed video cameras. Compared with both the observed laser processing phenomena and the welding results, the reflected light and the heat radiation were evaluated in terms of the usefulness as an in-process monitoring signal in detecting keyhole generation and through-hole formation in the upper sheet in real-time, or in estimating the shear strengths of lap-welded joints. On the basis of the monitoring signal, laser pulse duration and laser power were controlled at every 0.15 ms interval during laser irradiation in order to stably produce sound lap spot welds without non-bonded welds with holes

2. Material used and experimental procedures

The material used is A3003 alloy, whose aluminum purity is more than 96 % containing about 1.25 % manganese. The sheets are 0.1 mm and 1mm in thickness.

Micro-spot lap welding was carried out with the pulsed fundamental YAG laser of about 50 W maximum output power, as shown in Fig. 1. 0.1 mm thick sheet was put on 1 mm thick sheet, and was welded in air. The laser irritation conditions are shown in Table 1. The area

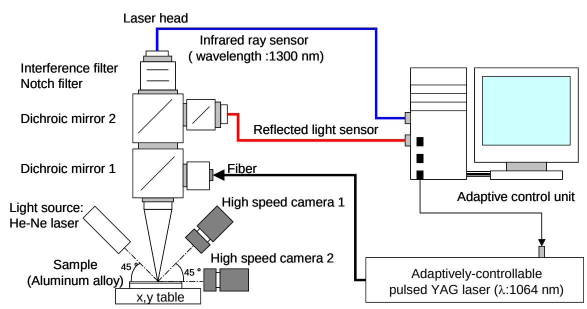
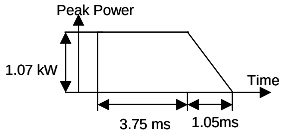


Fig. 1 Schematic drawing of experimental set-up of in-process monitoring and adaptive control.

Table 1 Laser conditions with pulsed YAG laser.

Power	4.6 J
Pulse shape	
Laser focusing condition	Focus
Spot diameter	150 μm

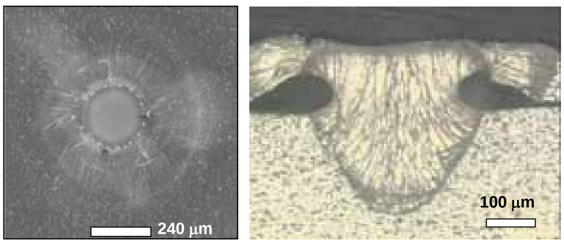
irradiated with the YAG laser beam was monitored in process by a reflected light, heat radiation and high-speed images in order to clarify the phenomena during laser micro-spot lap welding of aluminum alloy. The reflected light and the heat radiation were measured coaxially with the YAG laser beam. At the same time the change of molten pool behavior was observed by the high-speed video camera at the 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.

3. Experimental results and discussion

3.1 Laser micro-spot lap welding of aluminum alloy sheets in different thicknesses

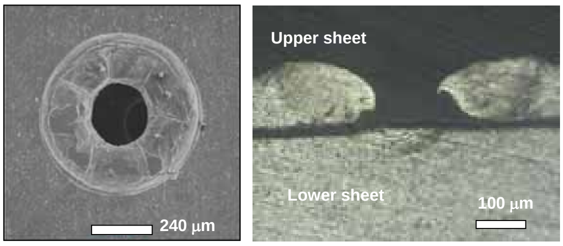
20 samples were subjected to pulsed YAG laser welding. As a result, 4 non-bonded welds with holes were produced and partial-penetration welds were obtained in the other samples. In the partially-penetrated welds as shown in Fig. 2, the average and standard deviation of the fusion zone diameters of spot welds were 650 μm and 32 μm, respectively, and 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 the gap between upper sheet and lower sheet was formed by the deformation of the upper sheet around lap-welded joint. On the other hand, in non-bonded welds with holes as shown in Fig. 3, the average and standard deviation of the diameters of spot weld fusion zones were 565 μm and 28 μm respectively, which were smaller than those of the partial-penetration welds. The through-hole existed in the upper sheet of 0.1mm in thickness, and the small melted zone was found on the upper surface of the lower sheet.

Consequently, it was found that non-boned welds with



(a) Surface of upper sheet (b) Cross section

Fig. 2 Surface and cross section of a laser micro-spot weld in A3003 alloy.



(a) upper sheet (b) Cross section

Fig. 3 Top surface of upper sheet and cross section of a non-bonded A3003 weld with a hole.

holes were produced under this conventional laser conditions as shown in Table 1.

3.2 In-process monitoring for laser micro-spot lap welding of aluminum alloy

1) In-process monitoring in partially-penetrated welds of A3003 sheets

An example of the monitoring results of a reflected light, heat radiation, and high-speed images is shown in Fig. 4. It shows the wave shape of a YAG laser beam, a reflected light and heat radiation. The vertical axis of the YAG laser, the reflected light and the heat radiation are power in kW, mW and μW, respectively. The horizontal axis is time in ms. 0 ms is the start of the YAG laser irradiation. The upper and lower photos show the high-speed images of the laser-induced plume and the surface condition during welding. The lower photos show that the small molten area was formed at 0.3 ms and grew into molten pool while the laser irradiation continued at 1.07 kW peak power. Then, the 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 of 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

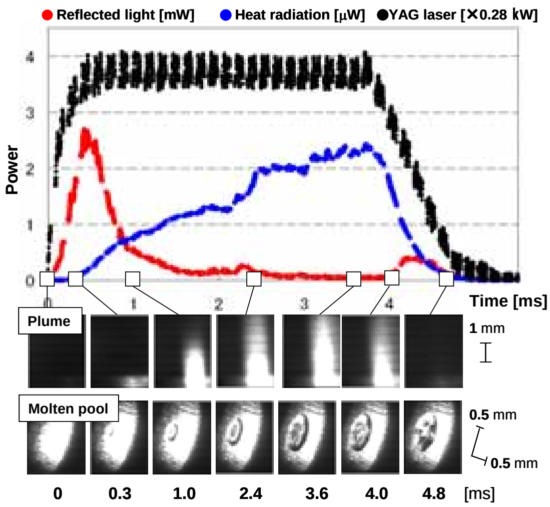


Fig. 4 Monitoring results of laser micro-spot lap welding of A3003 sheets, showing high-speed observation images, pulse shape, reflected light and heat radiation signals.

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. 4. It was thought that a YAG laser beam was reflected by a 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 together.

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 joining process. To the contrary the heat radiation increased in proportion to the expansion of the molten area and showed the joining process clearly.

2) In-process monitoring in non-bonded welds of A3003 sheets with holes

An example of the monitoring results of a reflected light, heat radiation, and high-speed images in producing non-bonded welds is shown in Fig. 5. The lower photos show that melting started at 0.4 ms and the molten area expanded until 2.7 ms. This tendency was similar to that in the case of sound partial-penetration welds. At 2.8 ms the surface of the molten pool was too rough to observe the keyhole in the molten pool. After 0.2 ms a through-hole was observed on the surface of the upper sheet. Then spattering was not observed. Considering the cross section of a non-bonded weld with a hole as shown in Fig. 3 (b), the through-hole appeared to be caused by running away of the melt from the keyhole rather than by blowing off the melt as a spatter. Similarly the upper photos show that, although the plume initiated at 1.0 ms and grew up until 2.7 ms, the plume disappeared with the formation of the through-hole at 3.0 ms.

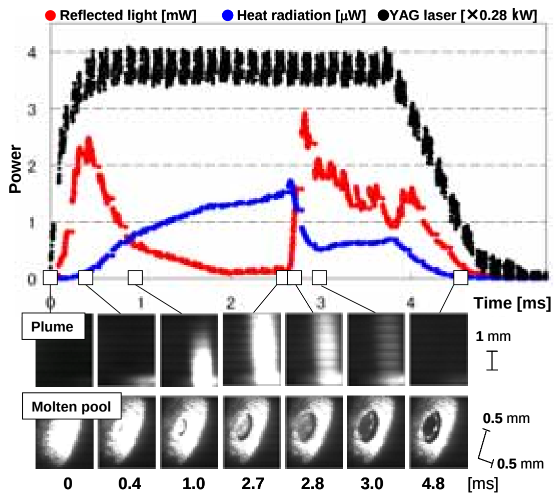


Fig. 5 Monitoring results of non-bonded welds with holes, showing high-speed observation images, pulse shape, reflected light and heat radiation signals.

In respect of the reflected light, the wave shape was almost equal to that in the case of partially-penetrated welds from the start of laser irradiation to 2.7 ms. But the reflected light intensity increased rapidly from 2.8 ms to 3.0ms. It seems to be reflected from the surface of the lower sheet, as shown in Fig. 3. That is to say, the rapid increase should be caused by the mirror reflection from the flat surface of the small molten area without the melt and a keyhole helping to increase absorption. As for the heat radiation, the tendency was almost equal to that in the partial-penetration welds until the intensity of heat radiation reached 1.7 μW at 2.7 ms. Then the heat radiation intensity fell right down to the level less than half that at 2.7 ms and from 3.0 ms slowly increased during laser irradiation at 1.07 kW peak power. It was found, from the observation of the laser-induced plume, that the near-infrared light measured in the wavelength of 1300 nm came mainly not from the plume but from the heat radiation of the molten area.

Consequently, the reflected light was useful as an in-process monitoring signal for detecting the start of melting, keyhole disappearance and through-hole formation of the upper sheet in real-time. The heat radiation monitored not only the expansion of the molten area but also the through-hole formation of the upper sheet.

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

Shear strengths of laser lap-welded joints were measured for 20 samples. The test results were compared with the reflected light and heat radiation and are shown in Fig. 6 (a) and (b). The vertical axis is shear strength of lap-welded joint in N. The horizontal axis of the reflected light is the period between two peaks in 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 1.7 μW, 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.

Judging from the shearing test result in Fig. 6 (a), it

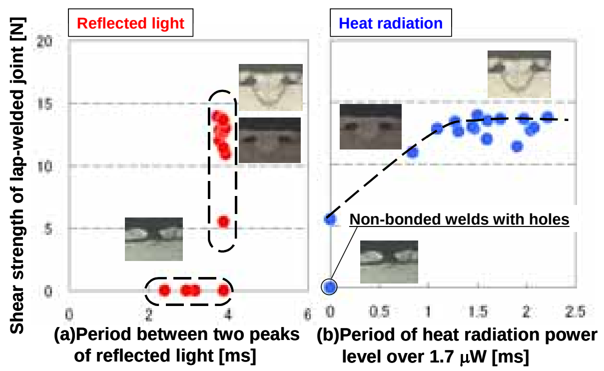


Fig. 6 Relationship of between monitoring signals to shear strength of lap-welded joint.

was difficult to make a close correlation between the reflected light and the shear strength. As for the heat radiation in Fig. 6 (b), the shear strength increased in proportion to the period until about 12 ms, and kept almost constant more than 12 ms.

It was consequently considered that heat radiation was correlated to the shear strength of 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.

3.3 Adaptive control for partial-penetration welds of A3003 sheets

An adaptive control was implemented in 20 samples in order to produce stably 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 Fig. 7.

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 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. Concretely speaking, the laser pulse duration was controlled so as to obtain 1.5 ms over the heat radiation power level of 1.7 μW.

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 μW 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 to1.39 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 μW, laser peak power was lowered from 1.39 kW to1.07 kW and then laser pulse duration was controlled for the stabilization of joint strength.

The experimental results of the adaptive control are shown in Fig. 8. It shows that all the samples were the partially-penetrated welds. 7 through-holes formed during laser irradiation were repaired and the A3003 sheets were jointed together. In the adaptive control only by stabilizing the joint strength, the average and standard deviation of the fusion zone diameters of spot welds were 675 μm and 20 μm, respectively. In the adaptive control by repairing a through-hole in the upper sheet, the average and standard deviation of the fusion zone diameters of spot welds were 765 μm and 45 μm, respectively. The average diameter of weld fusion zone expanded 1.1 times as long as that made under the normal adaptive control. However, it was also found in Fig. 8 that the gap between sheets was formed by the deformation of the upper sheet around the joint part.

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 Fig. 9. According to the lower 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 rose and filled the through-hole hardly. 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

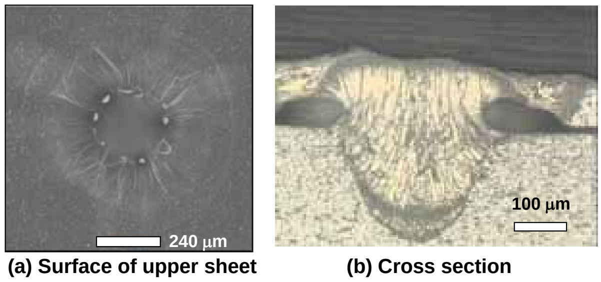


Fig. 8 Surface and cross section of laser micro-spot weld produced in A3003 alloy under the adaptive control for the through-hole repair in the upper sheet.

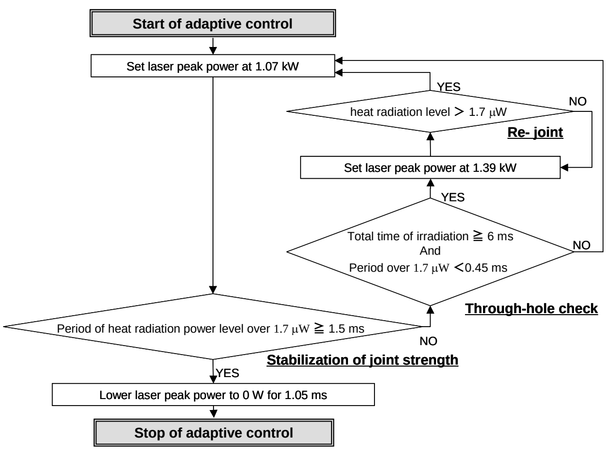


Fig. 7 Flow chart of adaptive control based upon intensity level and period of heat radiation.

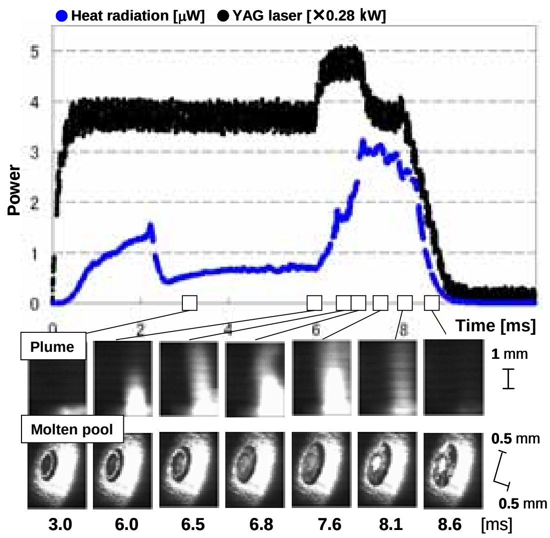


Fig. 9 Monitoring results of the adaptive control, showing high-speed observation images, pulse shape and heat radiation signals.

laser peak power decreased.

As for the heat radiation, the intensity declined rapidly at 2.2 ms for the through-hole formation. At 6ms 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 irradiations at 1.39 kW and declined as the peak power decreased. As the result among 20 samples, the period of the heat radiation power level over 1.7 μW was from 1.5 ms to 2.0 ms for the target period of 1.5ms. The main reason was that the interval of adaptive control is 0.15ms and that the laser beam pulse had 1.05 ms 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.

Furthermore, the shear strength of the joint part was measured in 20 samples under the adaptive control. The test results are shown in Fig. 10. 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 of 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 20 samples were partially-penetrated welds. 7 through-holes were formed during laser irradiation, but were repaired in process to joint together. These average and standard deviation of the improved shear strength were 1.5 times higher than and 1/3 times lower than these without the adaptive control.

Moreover, the authors decreased the gap between the upper and the lower sheets formed by the deformation of the upper sheet around lap-welded joint, by utilizing improved long tailing laser pulse shape. After the lap-welded joint was made under the above-mentioned adaptive control, laser peak power was changed to 1.39 kW during 0.9 ms period in order to increase the melt to reduce the gap. The laser peak decreased to 0.53 kW for 1.05 ms and then was terminated slowly for 4.5 ms, as shown in Table 2. The improved laser pulse could produce the

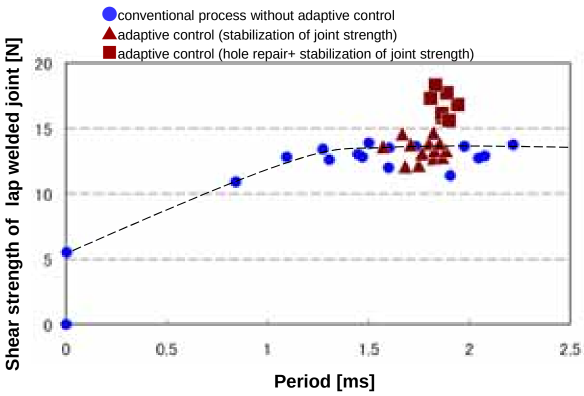
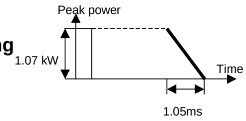
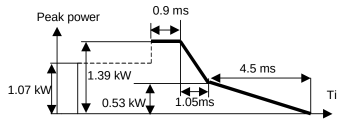


Fig. 10 Relationship between period of heat radiation power level over 1.7 μW and shear strength of lap-welded joint made under adaptive control for hole repair in addition to data under conventional control.

Table 2 Improved tailing shape of laser pulse for repair of gap between sheets, showing characteristics of long period of power decrease in comparison of conventional pulse.

	Tailing shape of laser pulse
Conventional short tailing	
Improved long tailing	

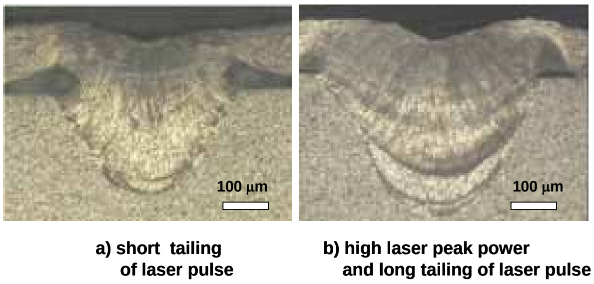


Fig. 11 Cross sections of laser micro-spot welds, showing effect of improved long tailing on gap formation between sheets.

partially-penetrated welds with a smaller gap as shown in Fig. 11.

4. Conclusions

In-process monitoring and adaptive control has been developed for laser micro-spot lap welding of A3003 aluminum alloy sheets of 0.1 mm and 1 mm in thickness. The effectiveness of in-process monitoring and the applicability of adaptive control for stabilizing the joint strength and for repairing a non-bonded weld with a hole were evaluated. The results obtained are as follows:

Concerning laser micro-spot lap welding of aluminum alloy sheets in different thicknesses;

(1) Some good lap welds or some non-bonded welds with through-holes in the upper sheets were produced under the conventional laser conditions.

(2) Welding phenomena for the formation of good and bad welds were interpreted from the high-speed video observation and welding results.

Concerning in-process monitoring for laser micro-spot lap welding of aluminum alloy;

(1) The reflected light had two peaks caused by high-reflection of the sample surface and in 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.

(2) The reflected light was useful as in-process monitoring signal for detecting the start of melting,

keyhole disappear and through-hole formation of the upper sheet during laser irradiation. The heat radiation monitored not only expansion of the molten area but also the through-hole formation of the upper sheet.

(3) 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 joint strength.

Concerning adaptive control for the partial-penetration welds in A3003

(1) Laser pulse duration and peak power were controlled at every 0.15 ms 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 20 partially-penetrated welds, 7 through-holes formed in process were repaired to joint together. The average and standard deviation of the shear strengths were 1.5 times higher than and 1/3 times lower than those without the adaptive control.

(2) The gap between upper and lower sheet formed by the deformation of the upper sheet around lap-welded joint was reduced by using the improved long tailing laser pulse shape.

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