In-process Monitoring and Adaptive Control for Laser Spot and Seam Welding of Pure Titanium

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Abstract

In-process monitoring and adaptive control is increasingly expected for the decisive detection of laser welding defects and for the stable formation of sound welds since laser welding has been applied in several industries. The objective of this research is to obtain a fundamental knowledge of in-process monitoring and availability of adaptive control for laser spot and seam welding of pure titanium with a pulsed Nd:YAG laser beam. The reflected light and heat radiation from the laser-irradiated area were monitored in synchronism with 20,000 F/s high-speed video observation of a molten pool. With respect to in-process monitoring, it was found that the reflected light was sensitive to the molten area formation and the heat radiation had clear correlation to the molten pool sizes for respective laser powers. Moreover, the heat radiation intesity had a quick response to the rapid change of laser peak power, and then the correlation between the heat radiation and the molten pool size was maitained in the designed laser power. As for adaptive control, spatters and pores were drastically reduced by controlling laser peak power and pulse duration according to the obtained features of the heat radiation-monitoring signal.

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Keywords: In-process monitoring, Adaptive control, Spot and seam welding, Spatters, Porosity

1. Introduction

It is indispensable to industrial application of laser welding to develop in-process monitoring for the decisive detection of welding defects and adaptive control for the stable formation of sound welds as well as to develop a high-brightness, high-performance and high-quality laser apparatus. Recently, several articles have been devoted to the researches on in-process monitoring and advanced adaptive control technology in laser welding [1)-9)]. The authors [1)-5)] clarified the correlation of the heat radiation signal levels to the molten pool diameters and shear strengths of lap welds in aluminum alloy A3003, and demonstrated the stable production of sound welds or repairing non-boned welds with through holes in real time under the adaptive controls.

In this research, in-process monitoring and adaptive control were applied in spot and seam welding of commercially available pure titanium. The intensities of reflected light and heat radiation from the molten area during laser welding were measured, and the molten pool behavior was synchronously observed in order to understand welding phenomena. On the basis of the obtained relationship between in-process monitoring signals and the welding results, a feasibility of adaptive control of laser peak power and pulse duration was investigated for the reduction in spattering or porosity.

2. Materials and experimental procedures

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

Micro-spot welding was carried out in 40-*l*/min Ar shielding gas with the pulsed fundamental Nd:YAG laser beam which was focused into ϕ 150 μm spot diameter, as shown in Fig. 1. The reflected light and heat radiation were monitored coaxially with the YAG laser beam, and high-speed pictures of a molten pool were taken at the angle of 45 degrees, in order to clarify the rapid phenomena of laser micro-spot welding and seam welding. The reflected light and the heat radiation were directed by pin photo diode sensors. In measuring the heat radiation, the reflected light intensity was reduced by optical density (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 molten area during laser welding were taken at the frame rate of 20,000 F/s under the illumination light of a 22-mW He-Ne laser.

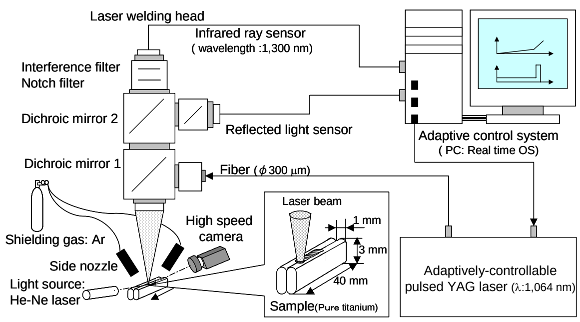

Fig. 1 Schematic experimental set-up of in-process monitoring and laser adaptive control system.

3. Experimental results and discussion

3.1 In-process monitoring for laser micro-spot butt-welding of pure titanium

Butt welding of titanium was exploited with rectangular laser pulse shape. The peak power was in the range from 0.4 to 1.6 kW at the focal position. The surfaces and cross sections of the laser spot welds are shown in **Fig. 2**. The penetration shapes seem to be a keyhole type of laser welds and the penetration depth of 0.8 mm was achieved at 1.6 kW.

An example of the monitoring results of a reflected light, heat radiation and high-speed video images at 0.4 kW laser power is shown in **Fig. 3**. The photos demonstrated that melting started at 0.4 ms and the molten pool expanded gradually during the following laser irradiation. In the short period from 5.75 to 5.85 ms, the molten pool surface was observed to wave violently. As for the reflected light, the intensity increased until the molten area was formed at 0.4 ms. Then the reflected light became almost constant during laser irradiation. This is attributed to such round corners of titanium samples that an incident laser beam did not reflect but scattered as shown in **Fig. 4 (a)**. However, the laser beam reflected vertically when the flat molten area was formed as shown in Fig. 4 (b). This means that the reflected light signal is indicative of the information of remarkable change in the surface. On the other hand, the heat radiation intensity increased gradually from the start of the laser irradiation. The high-speed pictures show that the intensity of heat radiation was proportional to the size of the molten area. Therefore, it was found that the molten pool size could be predicted by measuring the heat radiation intensity.

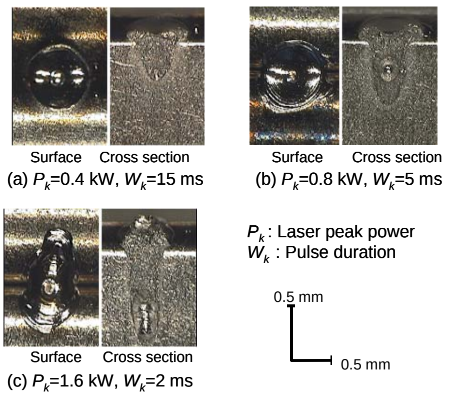

Fig. 2 Surfaces and cross sections of micro butt welding of pure titanium with pulsed Nd:YAG laser beam.

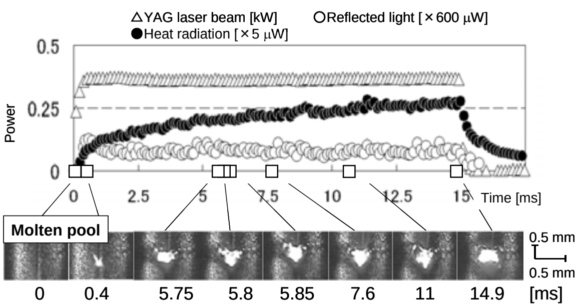

Fig. 3 Monitoring results of typical butt weld of pure titanium, showing laser pulse shape, reflected light and heat radiation signals, and high-speed observation images of spot weld molten pool.

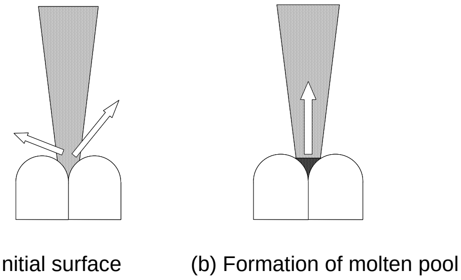

Fig. 4 Schematic drawing of laser beam reflection from titanium parts.

Here, the relationship between the heat radiation and the surface molten pool diameter at each laser power is shown in **Fig. 5**. The heat radiation was proportional to the molten pool diameter, and high laser peak power had stronger heat radiation in comparison with the same diameter. This means that the molten area heated to higher temperature by high peak power if the molten pool size is the same.

Moreover, the relationship between the penetration depth and heat radiation intensity during at each laser power is shown in **Fig. 6**. The heat radiation was proportional to penetration depth. The penetration depth became deep with an increase in the laser power. Therefore, it was considered that the penetration depended upon laser peak power.

Consequently, it was found that the heat radiation had

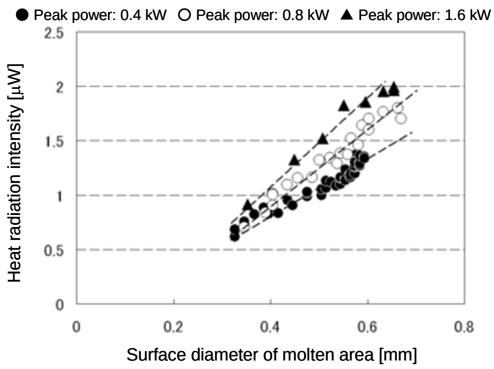

Fig. 5 Relationship between diameter of surface molten area and heat radiation at each laser peak power.

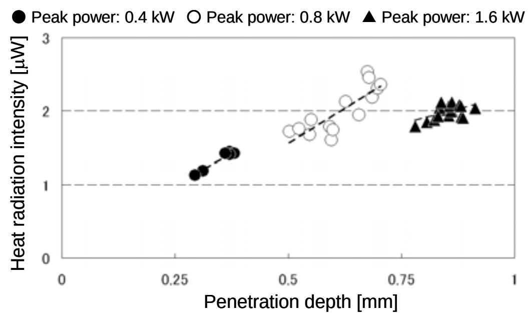

Fig. 6 Relationship between penetration depth and heat radiation at each laser peak power.

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clear correlation to the molten pool size or the penetration for respective laser peak powers. It was significantly useful as an in-process monitoring signal for detecting the surface molten pool diameter and penetration depth.

3.2 Behavior of heat radiation signal according to rapid laser power change during YAG laser irradiation

It was found that the diameter of surface molten area and the penetration depth were predicted by monitoring heat radiation. Here, the change in heat radiation was investigated by changing the peak power from 0.4 to 0.8 kW, from 0.4 to 1.6 kW or from 0.8 to 1.6 kW during laser irradiation. The results are illustrated in **Fig. 7**. An example of the monitoring results of a laser pulse shape, heat radiation and diameter of the molten pool with the typical high-speed observation images is shown in **Fig. 8**, when the laser power was increased from 0.8 to 1.6 kW. The intensity of heat radiation increased at the start of laser irradiation, and showed a sharp rise again when the peak power rose at 1.2 ms. However, the molten pool diameter was almost the same value regardless of the laser power increase. Then, it was increasing gradually during laser irradiation at 1.6 kW laser power. The relationship between heat radiation and surface molten pool diameter is plotted in **Fig. 9**. Three lines indicate the relationships between the molten pool diameter and the heat radiation at different powers as shown in Fig. 5. It was found that the molten pool growth was not sensitive to the rapid increase of the laser power, but the heat radiation intensity increased according to the laser power. Moreover, it was revealed that after the rapid increase, the heat radiation and the molten pool increased again depending upon the relationship of Fig. 5. The behavior of heat radiation has not been fully understood so far, and was the point to notice in using heat radiation as a monitoring signal.

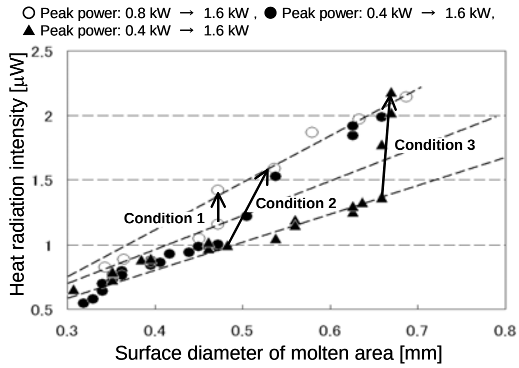

Fig. 9 Relationship between surface diameter of molten area and heat radiation with respect to laser power increase.

At last, the change in heat radiation was investigated by decreasing the laser power from 1.6 to 0.8 kW, from 0.8 to 0.4 kW or from 1.6 to 0.4 kW during laser irradiation as indicated in **Fig. 10**. An example of the monitoring results is shown in **Fig. 11**, when the laser power was decreased from 1.6 to 0.8 kW. The heat radiation intensity decreased slightly when the laser peak power dropped down at 1 ms. Then the molten pool diameter was almost constant regardless of the rapid decrease. The relationship between the heat radiation and the surface molten pool diameter is plotted in **Fig. 12**. It was found that the behavior of heat radiation signal had the tendency contrary to that in the rapid increase of laser peak power. However, the sensitivity of the heat radiation to the laser power or the

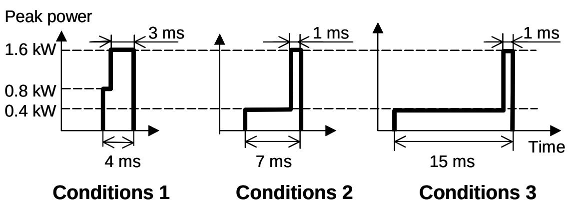

Fig. 7 Three welding conditions used, showing different laser peak power in pulsed YAG laser welding.

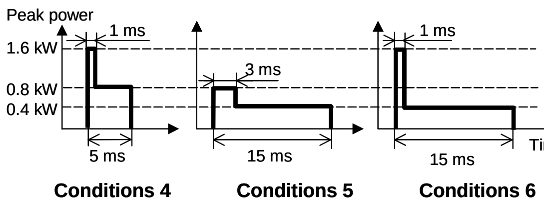

Fig. 10 Decrease welding conditions of laser peak power in pulsed YAG laser.

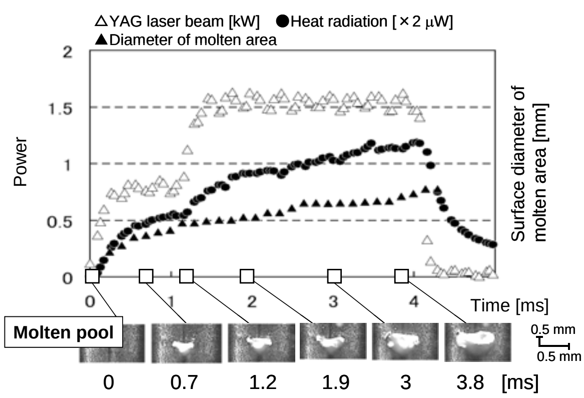

Fig. 8 Monitoring results of typical welding process caused by rapid increase of laser peak power, showing laser pulse shape, reflected light and heat radiation signals, and high-speed observation images of molten pool.

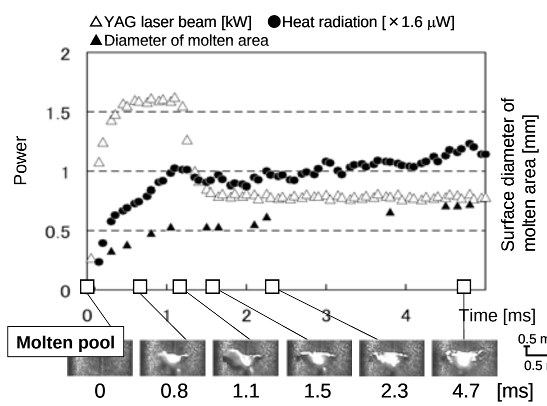

Fig. 11 Monitoring results of typical welding process caused by rapid decrease of laser peak power, showing laser pulse shape, reflected light and heat radiation signals, and high-speed observation images of molten pool.

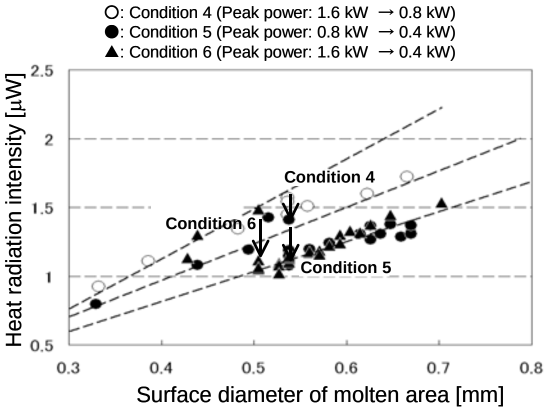

Fig. 12 Relationship between surface diameter of molten area and heat radiation with respect to laser power increase.

molten pool diameter was reduced due to slow ambient heat release in comparison with laser beam heating.

Consequently, it was found that the heat radiation was not sensitive to the molten pool diameter but to the laser power, when the laser power was changed rapidly. Moreover, it was revealed that the correlation between the heat radiation and the molten pool at the designed laser power was maintained before and after the rapid laser power change.

3.3 Adaptive control for spatter reduction in seam welding

Spatters are generated easily when a high laser peak power is used for the formation of a deeply penetrated weld. Therefore, it is difficult to make deep penetration without spattering. The spatters are often generated by rectangular laser pulse with kW-class-high peak power, because a small molten pool has less accommodation for the abrupt growth of a keyhole, as shown in **Fig. 13 (a)**. It is important to make a large molten pool sufficient to reduce spattering, as seen in Fig. 13 (b). Here, laser pulse shape should be modified by controlling peak power and pulse duration for the reduction of spattering as shown in flow chart of **Fig. 14**. The laser peak power was maintained at 0.4 kW until the molten area grew up into the target size which was expected to prevent spattering. Here the target size was 0.6 mm and was represented by 1.3 μW heat radiation intensity according to the correlation in Fig. 5. Then the peak power was rapidly increased to 1.6 kW and the laser irradiation was stopped when the intensity of the heat radiation was

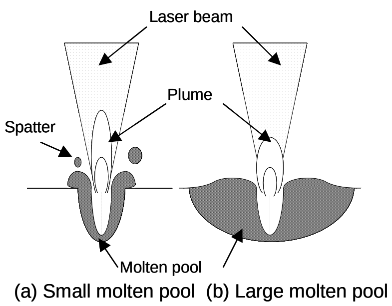

Fig. 13 Schematic drawing of easier generation of spatters from small molten pool but area.

over 2 μW, which represented 0.8 mm penetration depth according to the correlation in Fig. 6. Seam welding was implemented with 10 laser shots under the adaptive control for spattering reduction. The overlapped ratio and the laser pulse frequency were 0.5 and 1 Hz, respectively. An example of the monitoring results under the adaptive control for spattering reduction is shown in **Fig. 15**. The heat radiation intensity increased slowly at the beginning of laser irradiation. When the heat radiation was over 13 μW at 13ms, the laser power increased from 0.4 to 1.6 kW. Then the heat radiation was over 2 μW at 13.5 ms and the laser irradiation was stopped. Therefore, the laser power change indicated the proper function of the adaptive control for spattering reduction. At last, the bead surfaces with and without the adaptive control are shown in **Fig. 16.** The upper and lower photos show the surface appearances under the adaptive control and with 1.6 kW rectangular laser pulse shape with 2 ms pulse duration, respectively. It was found that the adaptive control improved drastically the bead surface appearance by removing large spatters, in comparison with the appearance under the conventional laser conditions. The adaptively-controlled bead width and penetration depth were 0.7 mm and 0.8 mm, respectively.

Consequently, it was found that adaptively-controlled low peak power in the initial stage of a laser pulse was beneficial to the reduction in large spatters. The heat radaiton was an effective input siganl for the adaptive control to reduce spattering.

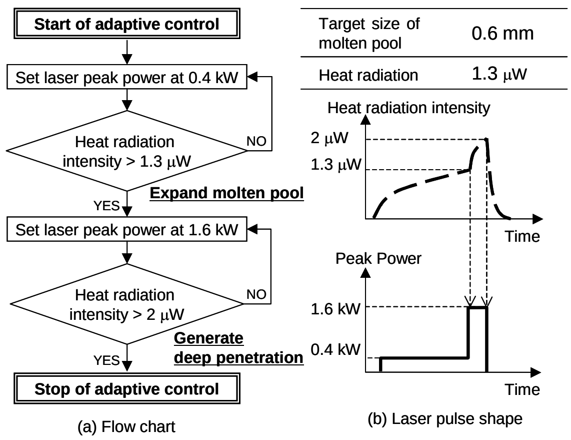

Fig. 14 Flow chart of adaptive control for reduction of spatters.

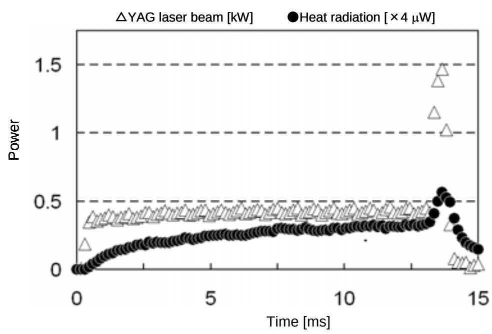

Fig. 15 Monitoring results of laser pulse shape and heat radiation signals under the adaptive control for reduction of spattering.

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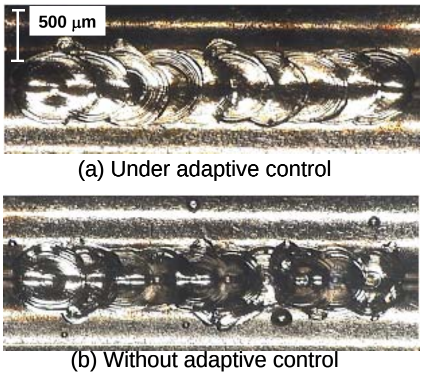

Fig. 16 Surface appearances of laser seam weld without adaptive control and under adaptive control for spattering reduction.

3.4 Adaptive control for porosity reduction in seam welding

The longitudinal section of butt weld joint under the adaptive control for reduction of spattering is shown in **Fig. 17**. Although the surface appearance was drastically improved, porosity was formed at the bottom or near the center of weld fusion zones. Two kinds of porosity formation mechanisms were clearly observed in the report [10]: One is present all over the weld fusion zone, and the other is at the root of the spot weld. These respective porosity formation situations are schematically illustrated in **Fig 18** (a) and (b). Both were formed from part of a keyhole. The former was generated due to the enclosure the upper part of a keyhole, while the latter was produced because of rapid laser power termination just after the formation of a deep keyhole. It was essential to render the keyhole shallow gradually by filing liquid in the lower part.

Fig. 17 Porosity in the cross section of weld bead under adaptive control for reduction of spattering.

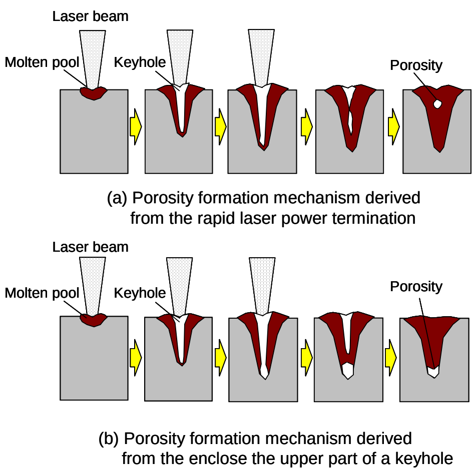

Fig. 18 Schematic drawing of porosity formation mechanism.

Therefore, the laser pulse tailing shape was modified by two-steps decease in laser power as shown in **Fig. 19**. However, the laser pulse shape except for the tailing was the laser pulse adaptively-controlled for reduction of spattering. Here the overlapped ratio was increased from 1/2 to 7/8 in order to remove porosity by remelting. An example of the cross sections of seam welding is shown in **Fig. 20**. The right-side and left-side photos are the cross sections with and without laser pulse tailing, respectively. The right-side photo showed that the porosity was not completely removed by the increase of overlapped ratio from 1/2 to 7/8. In the left-side photo, the tailing power was so effective that the last laser irradiation only produced the porosity above the root of spot weld. This means that the laser pulse tailing could reduce the porosity formed by the rapid laser power termination.

Moreover, the period of the second step tried to be adaptively controlled on the basis of the heat radiation in order to enclose the upper part of a keyhole during laser irradiation. The laser irradiation was stopped when the variation of the heat radiation intensity achieved less than 45 nW during 450 μs. However, the adaptively-controlled period was limited within 8 ms according to the restriction of the adaptive control system. The adaptive control was implemented for five seam welds. An example of the monitoring results is shown in **Fig. 21** as well as Fig. 15. The variation of the heat radiation intensity achieved 38 nW in the last 0.45-ms period of the laser pulse tailing, and then the laser irradiation was terminated. Therefore, the adaptive control was identified to exert the designed work.

At last, one of the experimental examples is shown in **Fig. 22**. It is found that the size or the number of porosity was reduced drastically by the adaptive control. All the five seam welds had no porosity. Therefore, it was considered that the heat radiation stabilization was useful for the reduction of porosity.

Consequently, laser pulse tailing and increase of overlapped ratio was useful for the prevention or removal of porosity. Moreover, the porosity was reduced drastically by the termination of laser irradiation controlled adaptively on the basis of monitoring the stable variation of heat radiation intensity.

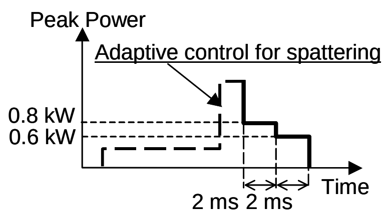

Fig. 19 Two-steps laser pulse tailing for prevention of porosity.

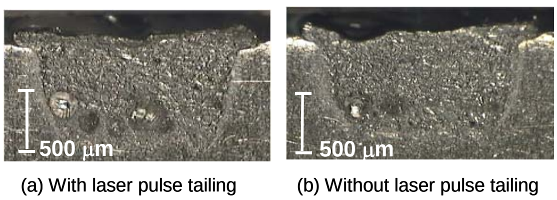

Fig. 20 Cross section of weld bead with or with laser pulse tailing in seam welding of 7/8 overlapped rate.

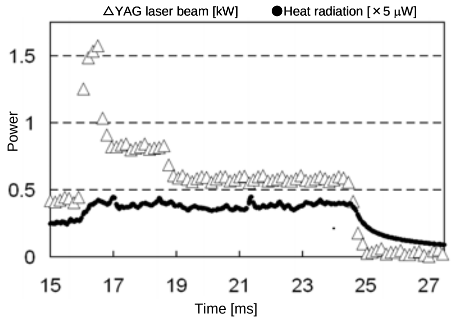

Fig. 21 Monitoring results of laser pulse shape and heat radiation signals under adaptive control for reduction of porosity.

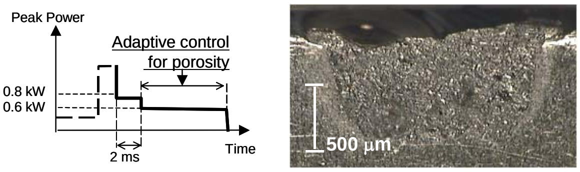

Fig. 22 Cross section of weld bead produced by laser with adaptively-controlled laser pulse tailing.

4. Conclusions

In-process monitoring and adaptive control has been developed for laser micro-spot butt and seam welding of pure titanium. The effectiveness of in-process monitoring for molten pool size or penetration depth, and the applicability of adaptive control for the reduction of spatters or porosity was evaluated. The results obtained are as follows:

1) Concerning in-process monitoring for laser micro-spot butt-welding of pure titanium

1. The reflected light signal was indicative of the information of remarkable change in the surface such as formation of a molten pool.
2. As for the heat radiation, the intensity had clear correlation to the molten pool size or the penetration for respective laser peak powers. It was significantly useful as an in-process monitoring signal for detecting the surface molten pool diameter and penetration depth.
3. It was found that heat radiation was not sensitive to the molten pool diameter but to the laser peak power, when the peak power was changed rapidly. Moreover, the correlation between the heat radiation and the molten pool at the designed laser peak power was maintained before and after the rapid change.

2) Concerning adaptive control for reduction of spatters and porosity in seam welding

1. Adaptively-controlled low peak power in the initial stage of a laser pulse was beneficial to the reduction in large spatters, which led to the deiserable bead surface appearance.
2. Laser pulse tailing and increase of overlapped ratio was useful for the prevention or removal of porosity. Moreover, the porosity was reduced drastically by the termination of laser irradiation controlled adaptively on the basis of monitoring the stable variation of heat radiation intensity.
3. The heat radaiton was an effective input siganl of the adaptive control for reduction of spatters and porosity in seam welding of pure titanium with a pulsed Nd:YAG laser beam.

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