In-process Monitoring and Adaptive Control during Micro Welding with CW Fiber Laser

Yousuke KAWAHITO*, Masaharu KAWASAKI* and Seiji KATAYAMA*

Osaka University, Joining and Welding Research Institute
11-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan
E-mail: kawahito@jwri.osaka-u.ac.jp

Abstract

A fiber laser has excellent beam quality enough to be applied for micro welding of electronics or automobile parts, and thus is regarded as a promising heat source for adaptive control since the laser peak power can be changed within sub-micro-second period. Laser micro welding of sheets can be influenced by the surrounding heat transfer conditions. This study was therefore undertaken with the objective of developing a new laser system with in-process monitoring and adaptive control for the stable production of sound welds in thin sheets. The bead-on-plate welding of 0.1-mm-thick stainless steels was performed with a 75-W fiber laser beam of 1,090 nm in wavelength. The stability of bead widths of laser welds made with or without monitoring and adaptive control was investigated in welding the sheet with or without a heat sink plate. It was revealed that the heat radiation signal was sensitive to the increase in the bead width when the heat transfer process was changed to the heat-insulated process. Moreover, the peak power was controlled in the minimum 2-ms-short period in order to produce stable bead width regardless of the existence of the heat sink plate, and the limit cycle of the adaptive control was investigated by comparison with the bead width of the weld made without adaptive control. It was consequently confirmed that a fiber laser was an excellent oscillator for the adaptive control in laser micro welding.

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Keywords: In-process monitoring, Adaptive control, Laser micro welding, Fiber laser

1. Introduction

Fiber laser has excellent beam quality enough to be applied for micro welding in several industries such as electronics or automobile, because the laser beam is easily focused into a small spot diameter of less than 100 μm. Fiber laser is also regarded as a promising heat source for adaptive control since the laser peak power can be changed within sub-micro-second period owing to laser diode (LD) pumping. Recently, several articles have been devoted to the researches on in-process monitoring and advanced adaptive control technology in laser micro welding [1)-9)]. The authors [1)] clarified the correlation of the heat radiation signal levels to the molten pool diameters in micro lap-spot welds of pure titanium with pulsed YAG laser, and demonstrated the reduction in spatters and porosity by controlling the laser peak power according to the heat radiation-monitoring signal. However, no studies have been devoted to such monitoring and adaptive control with continuous wave (CW) fiber laser.

In this research, in-process monitoring and adaptive control were undertaken for spot welding or bead-on-plate welding of thin stainless steels with a CW fiber laser beam. With respect to in-process monitoring, reflected light and heat radiation from the molten area were measured in the direction coaxial with the incident laser beam, and the molten pool behavior was synchronously observed in order to understand welding phenomena. As for adaptive control, a feasibility of adaptive control of laser peak power was investigated for stability of weld bead in spit of surrounding conditions of heat transfer which was one of fatal factors in micro welding.

2. Material used and experimental procedures

The material used is commercially available Type 304 stainless steel sheet of 0.1 mm in thickness and 5 mm in width.

Micro spot welding and micro bead-on-plate welding were carried out with a 100-W fiber laser of 1,090 nm in wavelength (SPI-100) under 25-*l*/min argon shielding gas, as shown in **Fig. 1**. The beam with 5.3-mm diameter and 0.3-mrad divergence is focused into 50-μm spot diameter

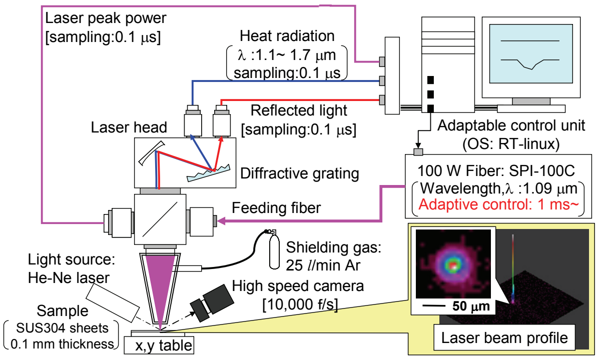


Fig. 1 Schematic experimental set-up of in-process monitoring and adaptive control system with 100 W CW fiber laser.

by 150-mm focusing optics. The laser peak power is changeable at 1-ms interval according to the external voltage. Reflected light and heat radiation from the laser-irradiated area are separated by a diffractive grating and are measured by pin photo diode sensors. The high-speed observation of molten pool behavior is taken at the frame rate of 10,000 f/s from the angle of 15 degrees to the sample surface under the illumination light of a 22-mW He-Ne laser. As for adaptive control, the laser peak power is controlled from 2-ms to 80-ms intervals during irradiation according to the heat radiation in order to stably produce the designed-size bead width in spite of surrounding heat transfer conditions. The limit cycle of the adaptive control was investigated. One cycle of the adaptive control consists of in-process monitoring with 1-MHz sampling, estimation for laser welding conditions and 1-ms-rapid change in the laser peak power.

3. Experimental results and discussion

3.1 In-process monitoring for micro-spot welding of stainless steel with fiber laser

Spot welding was exploited with a rectangular laser pulse shape with laser peak powers of 25 W or 75 W. The laser pulse duration was 25 ms.

At first the typical surface appearances and monitoring results of reflected light, heat radiation and high-speed observation video images at 25-W laser power are shown in **Fig. 2**. A partial penetration weld was obtained with a 70-μm-spot weld fusion zone as shown in Fig. 2(a) and (b). The lower photos in Fig. 2(c) demonstrate that melting started at 0.4 ms and a molten pool expanded to 2.4 ms and then the pool size was almost constant during the following laser irradiation. The laser power signal was measured to become highly unstable from the laser irradiation start to 13.2 ms. The unstable laser power seemed to be caused by strong back reflection out of the small molten surface. At 13.3 ms the laser power signal returned to in stable normal level and then was stable until the irradiation was completed. The intensity of the reflected light also dropped down at 13.2 ms. It means that a concave surface was formed in the small molten pool at 13.2 ms, so that the reflection was widely reduced. On the other hand, the heat radiation intensity was kept a low level during laser micro spot welding.

At last the spot weld appearances and monitoring results at 75-W laser power are shown in **Fig. 3**. A barely full penetration weld was obtained as shown in Fig. 3(a) and (b). The spot diameters on the laser-irradiated or bottom surface achieved 360 μm or 50 μm, respectively. The photos in Fig. 3(c) indicate that a molten pool grew up during laser irradiation. The molten pool was also observed to decrease from 520 μm to 360 μm in the diameter due to filling up the concave with melt or solidification shrinkage after the laser irradiation. The reflected light was on a low level during the irradiation, which appeared to be derived from the concave surface. On the other hand, the heat radiation increased gradually from the start of the laser irradiation and was proportional to the size of the molten area. Here, the relationship between the molten pool diameter and heat radiation intensity during the laser irradiation is plotted in **Fig. 4**. It was found that the heat radiation was clearly in proportion to the molten pool diameter. Therefore, the molten pool diameter could be monitored in real time by measuring the intensity of the heat radiation.

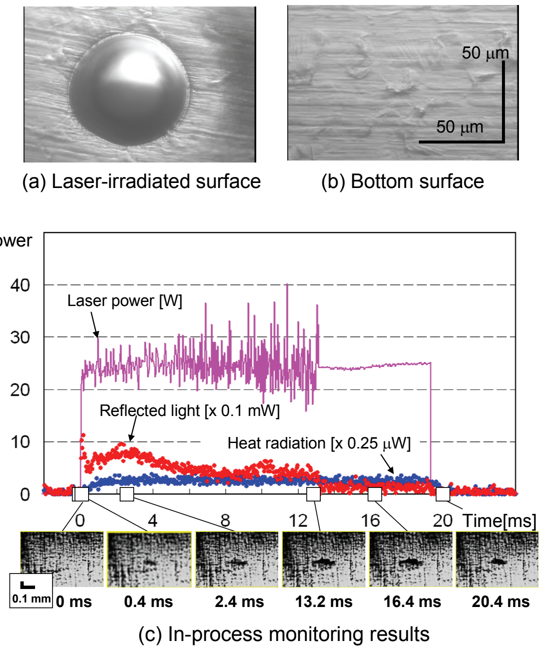


Fig. 2 Surface appearances and monitoring results of spot weld of SUS304 thin sheets, showing laser pulse shape, reflected light and heat radiation signals, and high-speed observation images of molten pool at 25-W laser power.

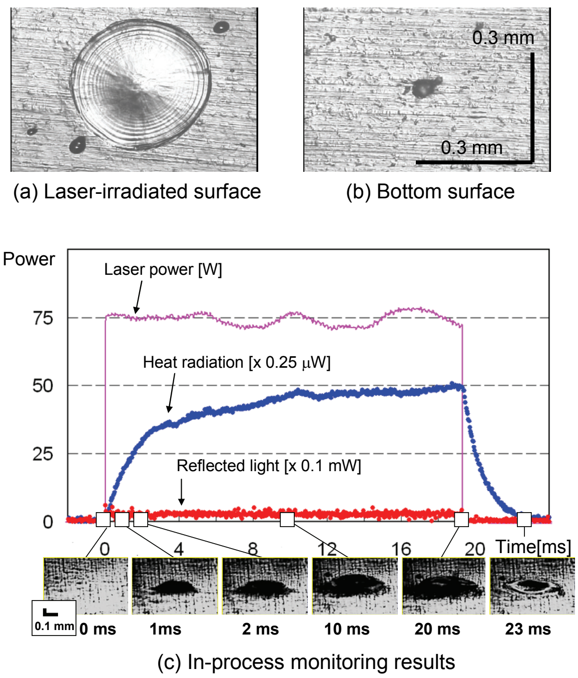


Fig. 3 Typical surface appearances and monitoring results in micro spot welding at 75-W laser power.

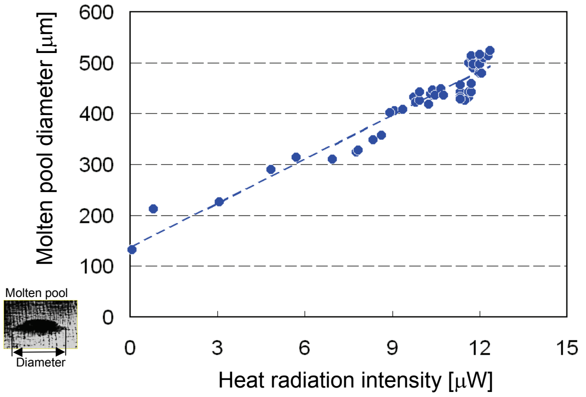


Fig. 4 Relationship between diameter of surface molten pool and intensity of heat radiation during spot welding at 75-W power.

From the above results, it was observed at 25-W-low laser power that the power signal was highly unstable due to strong back reflection from the surface until the concave molten pool was formed. On the other hand, it was found at 75-W-high laser power that the heat radiation was clearly in proportion to the molten pool diameter. Consequently, it was important to select an adequate in-process monitoring signal for each welding process produced at respective laser powers.

3.2 In-process monitoring for micro bead-on-plate welding of stainless steel with fiber laser

Bead-on-plate welding of 0.1-mm-thick stainless steel sheets was exploited with a 75-W fiber laser beam and 10-mm/s welding speed under surrounding conditions of a 1-mm-thick aluminum heat sink plate with a 2-mm-diameter through-hole as illustrated in **Fig. 5**. The obtained weld bead appearance is shown in **Fig. 6**. The bead width was 320 μm on the average on the heat sink, while it increased to 790 μm at the maximum on the through-hole position. It seemed to derive from the wide difference in heat transfer between the aluminum heat sink and the through-hole as indicated in **Fig. 7**. In the case of the existence of the heat sink, heat could transfer not only in the horizontal direction but also in the vertical direction through the aluminum heat sink owing to a lap joint part as shown in the cross section picture in Fig. 7. On the other hand, in the through-hole case, heat transferred only in horizontal direction so that molten pool expanded to double size. In other words, the micro bead-on-plate welding was changed from heat transfer process to heat-insulated process and then returned to heat transfer process in vertical direction.

A typical example of the monitoring results of laser power, heat radiation and high-speed observation images is shown in **Fig. 8**. A molten pool was observed to grow up to double size and then decreased into the normal size while the laser beam spot passed through the through-hole position. Then the reflected light was kept almost constant in spite of the through-hole position. However, the heat

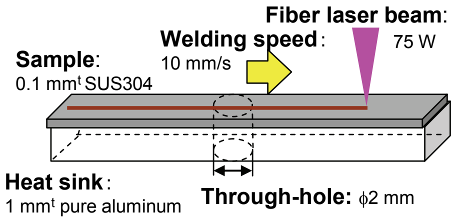
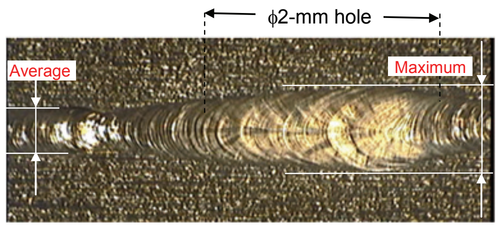


Fig. 5 Schematic illustration of micro bead-on-plate welding of 0.1-mm-thick stainless sheets with heat sink containing ϕ 2-mm through-hole by 75-W laser power.



Position	Bead width
On through-hole	Maximum: 790 μm
On heat sink	Average: 320 μm

Fig. 6 Weld bead surface appearance near through-hole position.

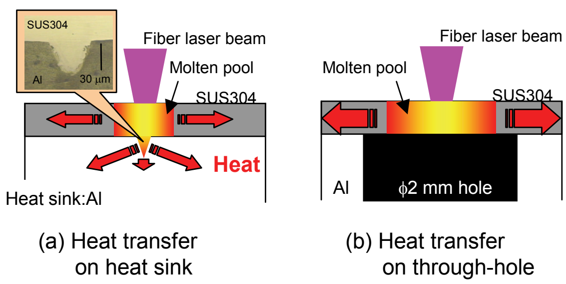


Fig. 7 Schematic illustration of heat transfer on heat sink and at through-hole position.

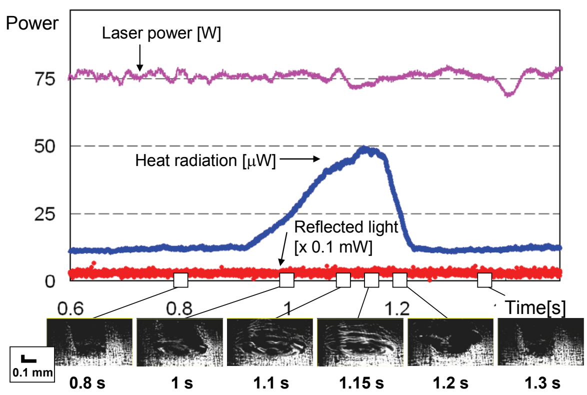


Fig. 8 Typical in-process monitoring results in micro bead-on-plate welding influenced by surrounding conditions of aluminum heat sink with ϕ2 mm through-hole.

radiation intensity increased more than twice as high as that measured on the aluminum heat sink, and then dropped down to the normal level measured on the heat sink.

Subsequently the relationship between the heat radiation and the surface molten pool diameter is plotted in **Fig. 9**. It was found that the heat radiation intensity was in proportion to the molten pool diameter perpendicular to the welding direction. Therefore, the heat radiation was so sensitive to expansion and contraction of the molten pool that it was useful as an in-process monitoring signal for detecting the surface molten pool diameter as well as that in the micro spot welding.

From the above results, it was found that the weld bead was so influenced by surrounding conditions with or without aluminum heat sink that the bead width increased from 320 μm to 790 μm at the maximum. Moreover, the heat radiation intensity was in such a proportion to the molten pool diameter that it was useful as for detecting the surface molten pool in real time as well as that in the micro spot welding.

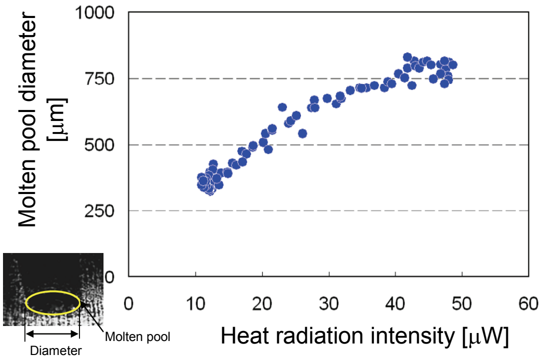


Fig. 9 Relationship between heat radiation and surface molten pool diameter perpendicular to welding direction.

3.3 Adaptive control for stable production of weld bead influenced by surrounding conditions

In order to stably produce the designed bead width, the laser peak power was controlled according to the flow chart shown in **Fig. 10**. The laser peak power was dropped down by 8-W laser peak power when the heat radiation intensity exceeded 16.8 μW, or the laser peak power was raised up by 8-W laser power when the heat radiation was below 16.2 μW. Under the other conditions, the laser peak power was maintained at the current state. Here, the heat radiation intensities from 16.2 μW to 16.8 μW indicated a 430-μm molten pool diameter as shown in Fig. 9. The cycles of the adaptive control are 2 ms, 4 ms, 8 ms, 20 ms and 40 ms.

A typical experimental result under the adaptive control at 2 ms cycle is shown in **Fig. 11**. The lower photos demonstrate that the molten pool size was almost constant in spite of the through-hole. Then the laser peak power showed such rapid and complicated changes that the heat radiation intensities were kept from 13.4 μW to 19 μW on the through-hole position.

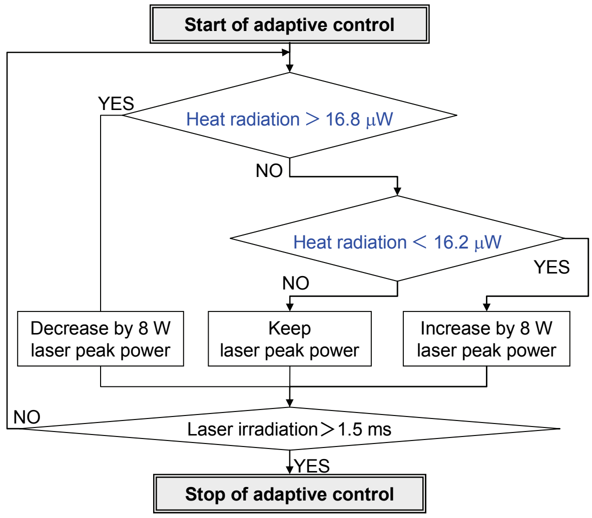


Fig. 10 Flow chart of adaptive control for stable production of weld bead width in micro bead-on-plate welding influenced by surrounding conditions.

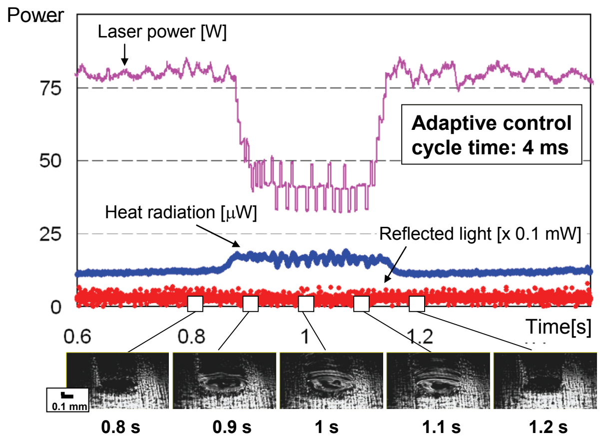
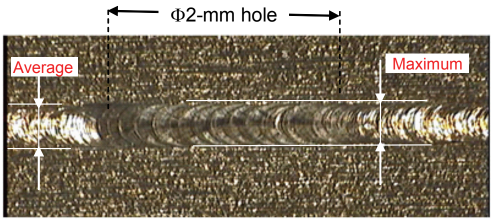


Fig.11 Monitoring results in micro bead-on-plate welding under adaptive control for suppression of bead expansion induced by surrounding conditions.

The obtained weld bead appearance is shown in **Fig. 12**. The bead width was 320 μm on the average on the heat sink, while the bead width was about 430 μm at the maximum on the through-hole position. Therefore, it was found that that adaptive control was effective for the suppression of the bead width expansion induced by the ϕ2-mm through-hole.

At last, the relationship between the cycle of the adaptive control and the maximum bead width is plotted in **Fig. 13**. It was found that the cycle below 10 ms produced the bead width of about 430 μm on the through-hole position. Taken into account that the laser beam spot took 0.2 s to pass through the through-hole position, effective adaptive control required more than twenty controls of the laser peak power. On the other hand, a few controls of the



Position	Bead width
On through-hole	Maximum: 430 μm
On heat sink	Average: 320 μm

Fig. 12 Weld bead surface appearance near through-hole position under adaptive control with 2-ms cycle.

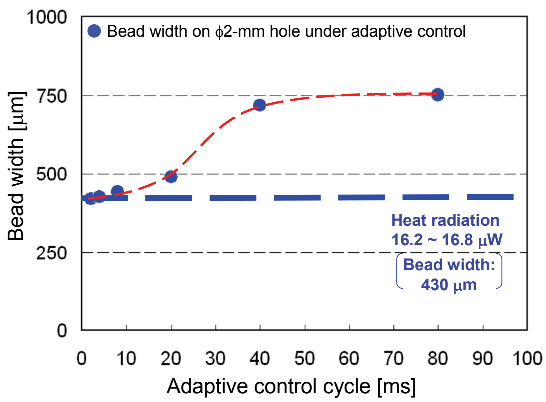


Fig. 13 Relationship between cycle of adaptive control and weld bead.

laser power indicated such a poor feasibility that the bead width was almost same as that without the adaptive control.

From the above results, it was found that adaptively-controlled peak power in micro welding with CW fiber laser was beneficial to stable production of a weld bead regardless of the existence of the heat sink plate. Furthermore, the cycle of the adaptive control below 10 ms was effective for the suppression of the bead width expansion induced by the ϕ2-mm through-hole. Consequently, the fiber laser was an excellent oscillator for the adaptive control in laser micro welding.

4. Conclusions

In-process monitoring and adaptive control has been developed for micro welding of Type304 stainless steel thin sheets with CW fiber laser. The effectiveness of in-process monitoring for molten pool in micro spot welding or bead-on-plate welding, and the feasibility of adaptive control for the stable production of bead width in spite of existence of heat sink were evaluated. The results obtained are as follows:

1) Concerning in-process monitoring for micro-spot welding of stainless steel with fiber laser

1. Laser power signal was measured to be highly unstable due to strong back reflection from the molten pool surface until a concavity was formed in a small molten pool at 25-W laser power.
2. It was found that heat radiation intensity was clearly proportional to surface molten pool diameter at 75-W laser power. Therefore, the heat radiation was useful as an in-process monitoring signal for detecting the molten pool diameter.
3. It was important to select an adequate in-process monitoring signal for each welding process produced by laser peak power.

2) Concerning in-process monitoring for micro bead-on-plate welding of stainless steel

1. It was found that the weld bead was so influenced by surrounding conditions with or without aluminum heat sink that the bead width increased from 320 μm to 790 μm at the maximum.
2. The heat radiation intensity was in proportion to the molten pool diameter perpendicular to the welding direction. Therefore, the heat radiation signal was useful for detecting the surface molten pool diameter in real time as well as that in spot welding.

3) Concerning adaptive control for stable production of weld bead influenced by surrounding conditions

1. Adaptively-controlled peak power in micro welding with CW fiber laser was beneficial to the stable production of the weld bead width regardless of the existence of a aluminum heat sink plate.
2. The cycle of the adaptive control below 10 ms was effective for the suppression of the bead width expansion induced by a ϕ2-mm through-hole at 10-mm/s welding speed.
3. Fiber laser was found to be an excellent oscillator for adaptive control in laser micro welding.

5. Acknowledgements

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