In-process monitoring and adaptive control for micro welding of titanium†

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1. Introduction

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

In-process monitoring and adaptive control has been proposed as one of the useful procedures to stably produce sound penetration welds without welding defects. Recently, some articles have been devoted to the researches of in-process monitoring and advanced adaptive control technology in laser welding [3, 4]. The authors [3] have shown that the heat radiation signal levels increase in proportion to the molten pool diameters and accordingly the shear strengths of lap welds in thin A3003 aluminum alloy sheets, and demonstrated that adaptive control on the basis of the heat radiation signal could stably produce sound welds or on-site repaired welds.

In this research, micro butt welding of pure titanium was used with a pulsed fundamental Nd:YAG laser beam, and the reflected light and the heat radiation from the laser-irradiated area were measured as in-process monitoring signals. These in-process monitoring signals were evaluated by the correlation with the spot diameter of a molten pool, the penetration depth or the gap. Moreover, the laser peak power was controlled on the basis of both the reflected light and the heat radiation detecting the gap and the spot diameter of a molten pool in order to suppress underfilling and small spot diameters for, not only spot welding, but also seam welding with the pulsed laser.

2. Materials and Experimental Procedures

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

Micro butt welding was carried out with the pulsed fundamental Nd:YAG laser in 40-L/min Argon shielding gas. The beam was focused into a ϕ 150 μm spot diameter as shown in Fig. 1. The laser oscillator has the noteworthy feature of 50 W maximum average output power, with peak power changeable within 5 kW at intervals of 100 μs according to the external voltage signal. The reflected light and heat radiation from the laser irradiated area were monitored coaxially with the Nd:YAG laser beam. The in-process monitoring signals were measured by pin photo diode sensors. High-speed pictures of the molten area during laser irradiation were taken at the frame rate of 20,000 frames/s from the angle of 45 degrees under the illumination light of a 22-mW He-Ne laser. As for adaptive control, the laser peak power was controlled at 150 μs intervals during irradiation according to the reflected light or heat radiation to produce designed-size spot diameters with suppression of underfilling. The 150 μs-rapid adaptive control loop consists of 100 μs monitoring periods and 50 μs for the estimation of laser welding conditions on the basis of in-process monitoring signals and the change in the laser peak power.

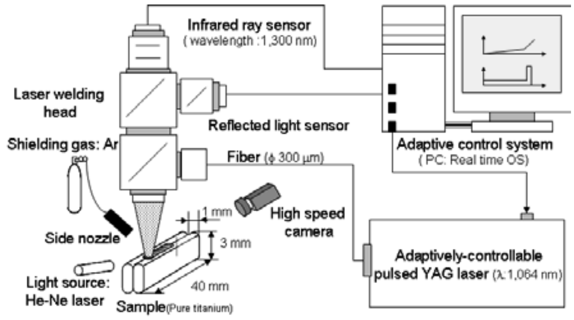

Fig. 1 Schematic experimental set-up of in-process monitoring and adaptive gap control in micro butt laser welding

3. Experimental Results and Discussion

In-Process Monitoring of Reflected Laser Beam and Heat Radiation

An example of typical monitoring results of reflected

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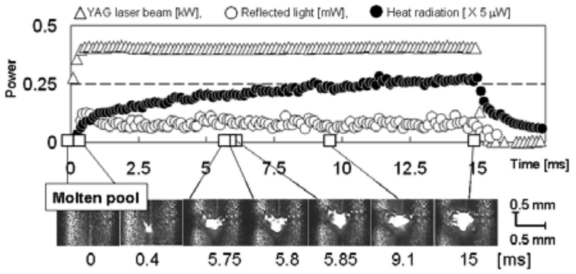

Fig.2 Monitoring results of typical butt welding, showing laser pulse shape, reflected light, heat radiation and high-speed observation images of the spot molten pool under non-gap conditions

light, heat radiation and high-speed video pictures during laser spot welding of a butt joint without a gap at 0.4 kW power is shown in **Fig. 2**. The horizontal axis is time, and the vertical axis indicates measured values of laser power and monitoring signals. The pictures show that melting started at 0.4 ms and the molten pool expanded gradually during the following laser irradiation. According to the series of pictures from 5.75 to 5.85 ms, the molten pool surface oscillated rapidly in 100 μs short periods. The molten pool grew continuously during the laser irradiation. As for the reflected light, the intensity increased until the molten area was formed at 0.4 ms, and then it became almost constant during laser irradiation. On the other hand, the intensity of heat radiation increased continuously from the start of the laser irradiation. Compared with the molten pool in the high-speed video pictures, it was found that the increase in the heat radiation was in proportion to the growth of the molten pool.

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

In order to produce the designed spots with reduction in deeply-concaved underfills or smaller spots, the laser peak power was controlled according to the flow chart as shown in **Fig. 3**. The 0.4 kW laser peak was changed to 1.6 kW on the basis of the reflected light over 80 μW indicating that a molten pool bridged a gap. The laser irradiation was terminated according to the heat radiation over 1.7 μW which predicted that the spot size reached the designed size of 0.6 mm. **Figure 4** shows typical surface appearances and cross sections produced by the adaptive control for the joints with the gaps of 60 μm and 106 μm, and as a reference the ones on the right were made with conventional rectangular pulses of 1.6 kW and 2 ms. The minimum spot width was improved from 0.4 mm to more than 0.6 mm, and the underfills were also reduced from 0.4 mm to 0.15 mm as a result of the adaptive control. Moreover, the penetration depths were kept constant at all the gap sizes.

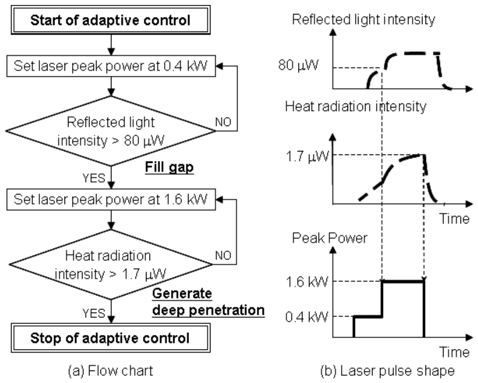

Fig. 3 Flow chart of adaptive control for narrow spot and underfilling

Furthermore, the adaptive control was applied to the laser seam welding of butt joints with a 100 μm gap. The surface appearances and cross sections under the adaptive control or with the conventional rectangle laser pulse are demonstrated in **Fig. 5**. However, the rectangle pulse had 2 ms pulse duration and 1.6 kW laser peak power. The minimum bead width increased from 0.4 mm to 0.6 mm and the maximum depth of underfills was reduced from 0.32 mm to 0.16 mm. Therefore, the bead surface appearances and underfills were improved greatly in comparison with those with the conventional rectangle laser pulse. Moreover, it was found that the adaptive control was more effective with the underfills or the smaller spots in more early laser shots, because the gap size was reduced by solidification shrinkages generated in the previous laser welds.

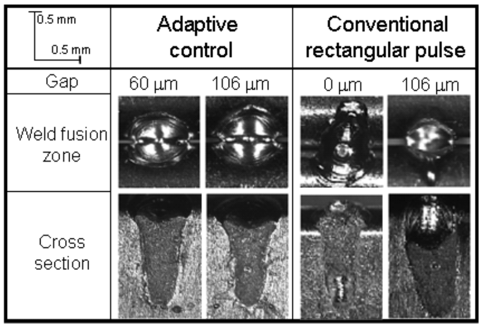

Fig. 4 Surface appearances and cross sections under adaptive control for several sizes of gap

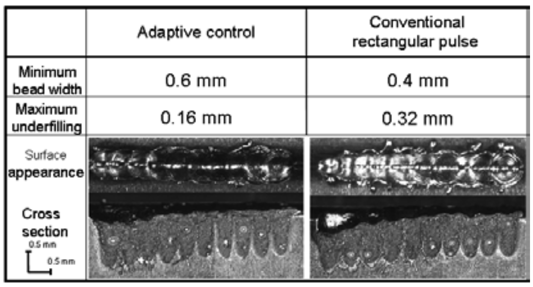

Fig. 5 Surface appearances and cross sections under the adaptive control in seam welding with Pulsed YAG laser beam

4. Conclusions

The gap is one of the most important issues to be solved in laser welding of a micro butt joint, because the gap leads to welding defects such as underfilling or a non-bonded joint. The experimental studies indicated that the adaptive control of the laser peak power on the basis of in-process monitoring could reduce the harmful effects due to gaps in micro butt laser welding with a pulsed laser beam.

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