Welding Phenomena and Reflected Beam Monitoring during YAG Laser Lap Welding of Zn-Coated Steels†

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Abstract

A study was performed with the objectives of understanding lap welding phenomena of Zn-coated steels with a Nd:YAG laser as well as obtaining a fundamental knowledge of monitoring signals for the formation of sound or bad weld beads. The behavior of the molten pool and a reflected beam was simultaneously observed through a high-speed video and the monitoring of reflected beam intensity. The effect of sheet gap on porosity formation and bead appearance was confirmed, and characteristic monitoring signals were obtained according to these gaps at high welding speeds. In the case of no gap, spatter was frequently generated, and the reflected beam fluctuated intensely at low frequencies. On the other hand, in welding sheets with a wide gap, lap welds were not produced and the high frequency signals of a reflected beam were detected. Moreover, sound welds were produced in the sheets with a proper gap, and a moderate reflected beam was monitored. From these results, it was concluded that the reflected beam was dependent upon the sheet gap, and its signals and analytical results were beneficial for the judgment of sound welds, underfilled welds due to spattering and incomplete lap welds due to a wide gap.

KEY WORDS: (YAG laser), (laser welding), (lap welding), (monitoring), (reflected beam), (Zn-coated steel)

1. Introduction

Zn-coated steels are used in various industry fields because of low prices and high corrosion resistance. When they are subjected to laser welding, it is well known that Zn may cause spatter or porosity in laser lap welding[1)-4)]. It is thus of great importance to understand laser welding phenomena in Zn-coated steels, to interpret the formation mechanisms of porosity or underfilled weld beads, to reveal the welding conditions and processes for the formation of sound weld beads, and to establish the monitoring system for instant judgment of sound or bad weld beads.

In this study, therefore, lap joint welding was performed on sheets with a YAG laser under various conditions to determine proper welding conditions for the formation of sound beads as well as to clarify the characteristics of welding defects, and the effects of Zn-coating layer thickness and sheet-gap on the formation of welding defects. Subsequently, the behavior of a molten pool and a reflected beam was simultaneously observed through a high speed video together with the monitoring of reflected beam intensity to confirm the effect of sheet gap on weld bead appearances and to obtain data of characteristic monitoring signals.

2. Materials and Experimental Procedures

The materials used are Zn-coated sheet steels with Zn-10%Fe content of 0.045 or partly 0.06 kg/m^2, and normal sheet steel without Zn-coating of about 0.8 mm in thickness. The gap was produced with stainless steel sheets of 0.02 to 0.5 mm in thickness.

The laser apparatuses employed were NEC Nd:YAG laser machines of 1.8 kW and 4 kW maximum power (P_l=1.6 kW and 3.5 kW on the plate surface) in continuous wave (cw) mode. Lap welding was performed at P_l = 0.3 ~ 1.5 kW or 3 kW and v = 1 ~100 mm/s in Ar shielding gas (nozzle diameter: 6 mm, and flow rate: 8x10^{-4} m^3/s). Monitoring experiments were carried out during welding at P_l = 3 kW and v = 50 mm/s (3 m/min) or 66.7 mm/s (4 m/min).

X-ray inspection as well as observation of surface appearance and cross-sectional microstructure of weld beads was performed to clarify the degree of welding defects. Plume behavior and spattering were observed during welding under the formation conditions of

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characteristic weld beads by ultra-high speed video and a reflected beam was monitored and observed during welding at the power of 3 kW, as shown in **Fig. 1**. The reflected beam was detected through a sensor with an interference filter and an analyzer at the sampling frequency of 50 kHz. Welding phenomena were also observed by a micro-focused X-ray transmission imaging system[5]. The fractured surfaces were observed by SEM, and Fe and Zn contents on spattered particle surfaces, artificially fractured surfaces and internal porosity were analyzed with EDX.

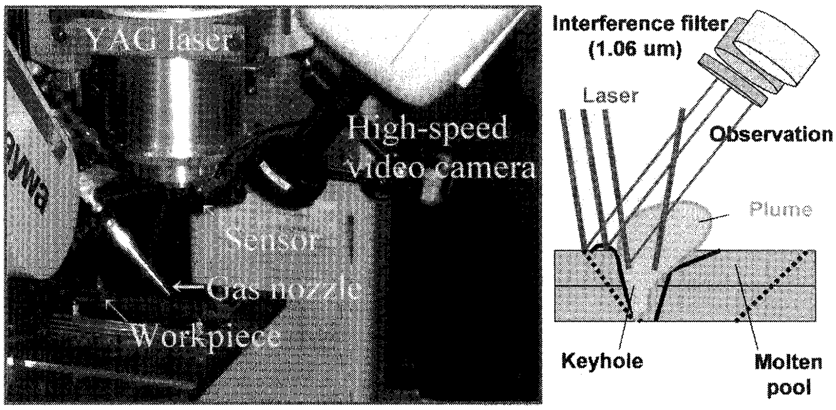


Fig. 1 Experimental setup for observation of welding phenomena and monitoring of reflected laser beam (left) and schematic simultaneous observation of molten pool behavior and reflected beam intensity (right).

3. Experimental Results and Discussion

3.1 Lap weldability with continuous wave laser

Lap welding of Zn-coated steel sheets of 0.8 mm thickness was carried out with a cw YAG laser under various conditions. It was confirmed that different characteristic weld beads were formed. Even in the same single weld bead, or under the same welding conditions, a sound weld and/or a weld containing underfills and/or porosity were formed. In cw laser welding, the conditions, under which sound lap welds were always produced, could not be found.

The effects of a sheet gap and Zn-coated layer thickness on weldability were investigated. The results are shown in **Fig. 2**. Even in the case of two Zn-coated sheets of 0.045 or 0.06 kg/m^2, sound welds were made with the gap of about 0.03 mm or more. On the other hand, for only one Zn-coated sheet of 0.045 kg/m^2, sound welds were produced in sheets without a gap. This suggests that the gap and the Zn-coated layer thickness between sheets exert a great influence on weldability. These results are in good agreement with the previously reported papers[1-3]. The reason for the formation of a sound and/or bad weld in one bead under the same conditions is attributed to the effect of a gap induced during welding.

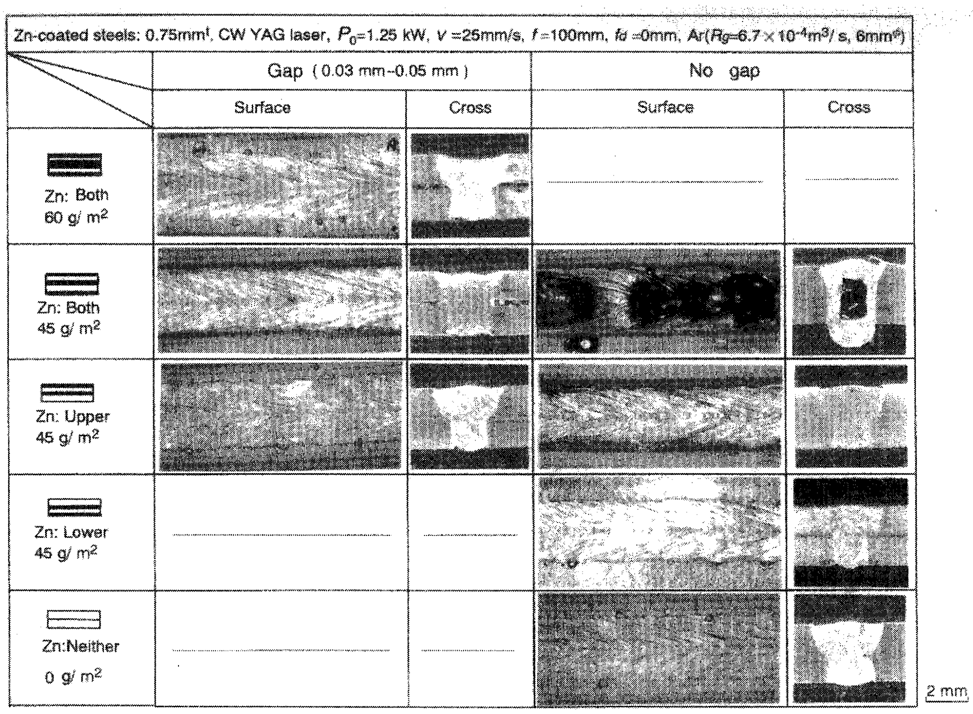


Fig. 2 Surfaces and cross-sections of Zn-coated steels with different Zn layers and mild steels welded with cw YAG laser, showing effects of gap and Zn coating layer thickness between sheets on welding results.

3.2 High speed video observation results

Welding phenomena such as plume and spattering behavior were observed during laser welding under the formation conditions of characteristic weld beads in lapped steel sheets by ultra-high speed video. **Figure 3** shows the surface appearances, cross sections and metallic plume and/or spattering observed during YAG laser lap welding of Zn-coated steel sheets at slow and high speeds. It was observed that spattering was not violent in welding steel sheets without Zn-coating layer under any conditions as well as during cw laser welding of Zn-coated steel at the slow speed. In the case of the slow welding speed, a bright plume was seen but little spatter was observed. It is therefore interpreted that pits or underfilled weld beads formed at slow welding speeds are produced by the formation of bubbles from the lapped parts. On the other hand, at the high welding speed, severe spatter occurred due to the evaporation of Zn and the difficulty of liquid accommodation because of a small molten pool. Consequently, it is judged that heavy underfilling was generated owing to intense spattering. When a gap exists, spattering is suppressed.

According to the microfocused X-ray transmission imaging system, it was confirmed that spatter and pores were produced by Zn from the coating layer, not only in the front part, but also in the peripheral lapped region of the molten pool. It was observed that porosity was not formed in the lapped sheets with a gap of about 0.04 mm.

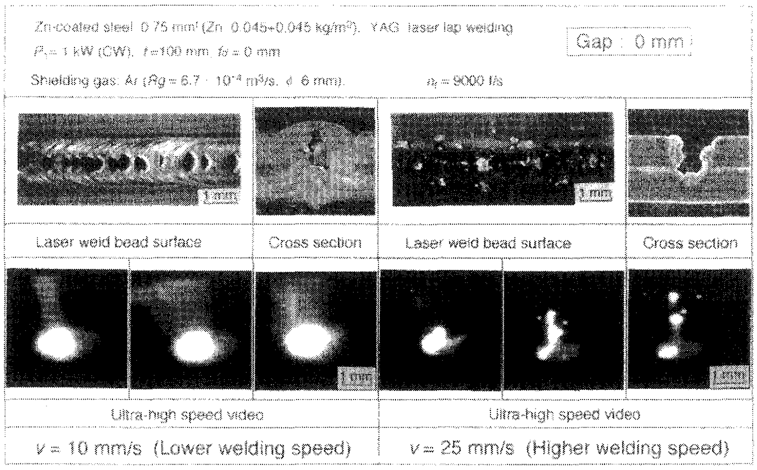


Fig. 3 High speed video pictures showing plume and spattering behavior during cw YAG laser lap welding of Zn-coated steels with Zn layers of 0.045 kg/m^2 at slow and high speeds.

3.3 Metallurgical investigation

Ultrafine particles were formed in the plume by evaporation, and spatter was produced from the molten pool and attached to the weld bead or base metal sheet surfaces. These were analyzed by an EDX analyzer. As a result, about 30 mass% Zn was detected in the ultrafine particles, but Zn was not observed in the spatter. This suggests that most of the Zn was evaporated from coating layers and formed into ultrafine particles. On the other hand, it is presumed that spatter was generated by splashing iron melts from the molten pool. According to the analytical results, internal porosity and pit were covered all over with a Zn(-enriched) layer. This means that evaporated Zn penetrated into the molten pool, and caused bubbles and porosity to be formed. On the other hand, Zn was found not to be included in the laser weld metals.

3.4 Interpretation of laser lap welding results

On the basis of the above results, the lap welding phenomena of Zn-coated steel sheets with a cw or pw laser are schematically represented for respective characteristic weld beads in **Fig. 4**. In the case of slow speed welding of sheets without a gap, as shown in (a), the volume of molten pool appears to be large enough to reduce the degree of spattering as a consequence of

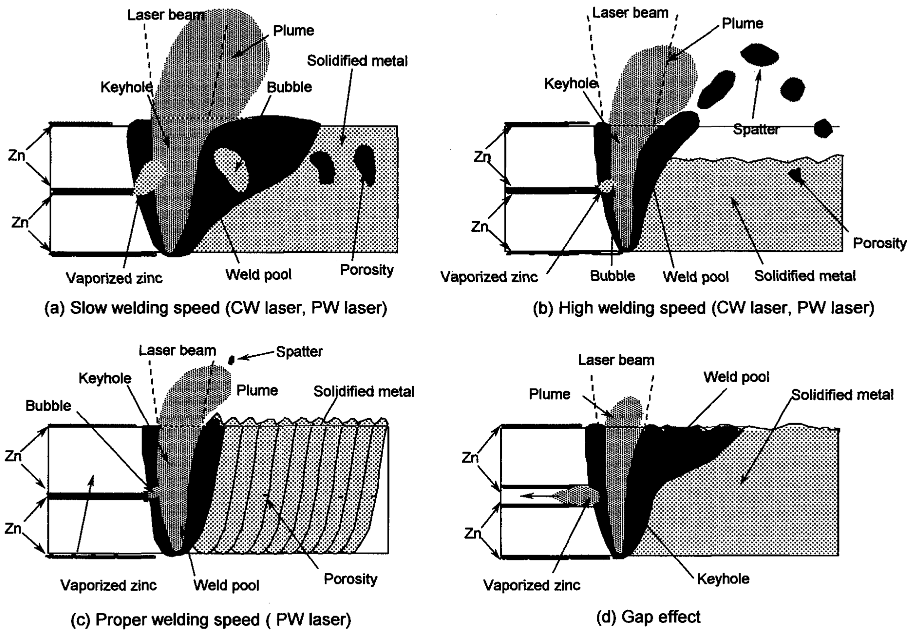


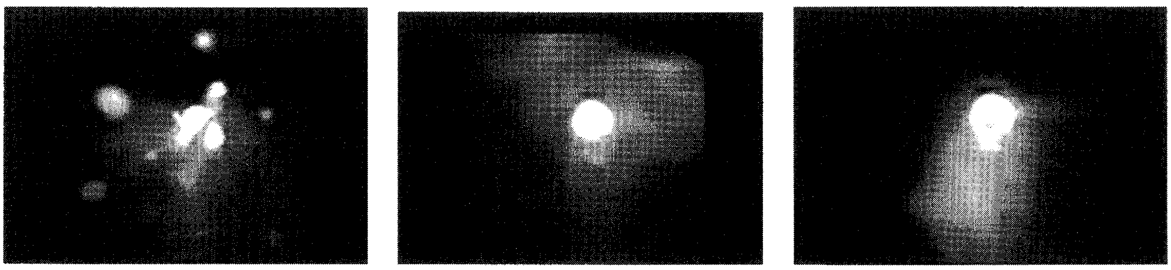
Fig. 4 Schematic representation of cw or pw YAG laser lap welding behavior of Zn-coated steels.

accommodating the evaporation pressure of Zn in addition to recoil pressure. Because of the large heat input and wide heat-affected zone, a large number of bubbles are formed in the molten puddle from the lap part, and sideward and backward bubbles grow toward the central upper surface of the weld bead. When their tips reach the surface, the bubbles shrink but remain as porosity without complete healing. In the case of high speed welding without a gap, as seen in (b), the molten pool becomes small, and is easily splashed by the pressure of evaporated Zn. Consequently, underfilled weld beads are readily formed. On the other hand, under the conditions of proper pw laser welding, a small amount of spatter occurs and thus a good weld bead can be formed without a gap, as shown in (c). This is interpreted by considering that the power is lowered and terminated before the generation of spatter, and that the extent of bubbles invading from the sideward lap part is reduced because of the small heat input. Moreover, when the gap exists, as seen in (d), the degree of spattering is decreased, bubbles hardly invade, and consequently a sound weld bead is formed under the wide welding conditions.

3.5 Monitoring and high-speed observation during laser lap welding at 3 kW

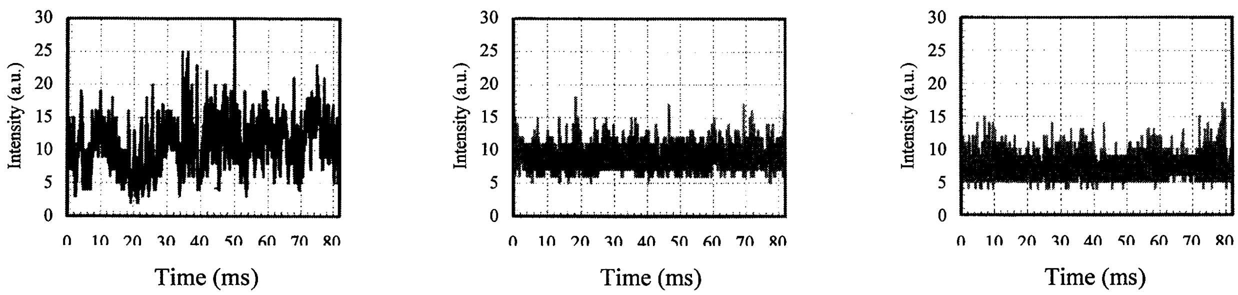
The feasibility of monitoring of welding results was investigated by detecting signals of a reflected beam during laser lap welding at 3 kW. The results of underfilled, sound and incomplete lap weld beads were examined according to the level of the gap. Weld beads with large pores or pits, frequently present at low welding speeds, were not detected, probably because the welding speeds of 3 and 4 m/min were high enough to suppress the bubble invasion from the side or the back of the molten pool in the lap part. Typical examples of high-speed video observation at the welding speed of 50 mm/s are shown at the initial gaps of 0, 0.1 and 0.5 mm in **Fig. 5**. A plume with or without spattering was observed. Only in the case of 0.5 mm gap, a black spot was frequently observed in the bright keyhole. This is thought to represent the keyhole bottom of the upper sheet. In this case solidification occurred separately for the upper and lower sheets, and no lap welds were formed. For thin sheets of 0.8 mm thickness, the gap of 0.5 mm is judged to be too large to weld with a laser.

The intensity of a reflected laser beam was also monitored with a photodiode sensor. The measured and analyzed intensities are respectively indicated at the gaps of 0, 0.1 and 0.5 mm in **Figs. 6** and **7**. At the gap of 0 mm, a wide variation in intensity was detected. In particular, the ratio of low frequency to high frequency was high. At 0.5 mm gap, the level of the reflected beam is low, and the amplitude of high frequency (such as 10 to 20 kHz) was slightly high in comparison with the other data. The data are expressed as a function of the amplitudes of low and high frequencies in **Fig. 8**. The data include the results obtained at the power of 3 kW and the welding speed of 67 mm/s. This figure indicates that welding results are correlated with the frequency signals. It is clear that the levels of low frequency are high in the case of underfilled weld beads at the gap of 0



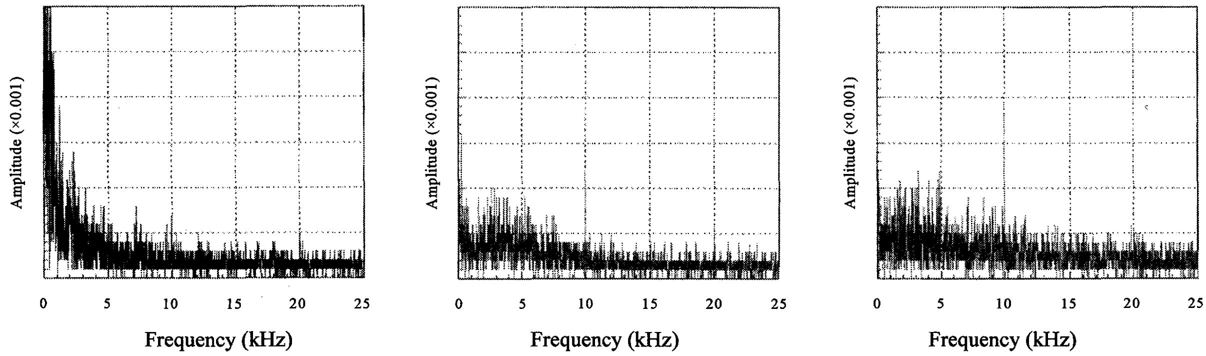
(a) 0 mm gap (b) 0.1 mm gap (c) 0.5 mm gap

Fig. 5 Photos near molten pool during laser welding of Zn-coated steel sheets with gaps.



(a) 0 mm gap (b) 0.1 mm gap (c) 0.5 mm gap

Fig. 6 Monitoring signals (enlarged) of reflected YAG laser beam from surface



(a) 0 mm gap (b) 0.1 mm gap (c) 0.5 mm gap

Fig. 7 FFT results from reflected laser beam intensities.

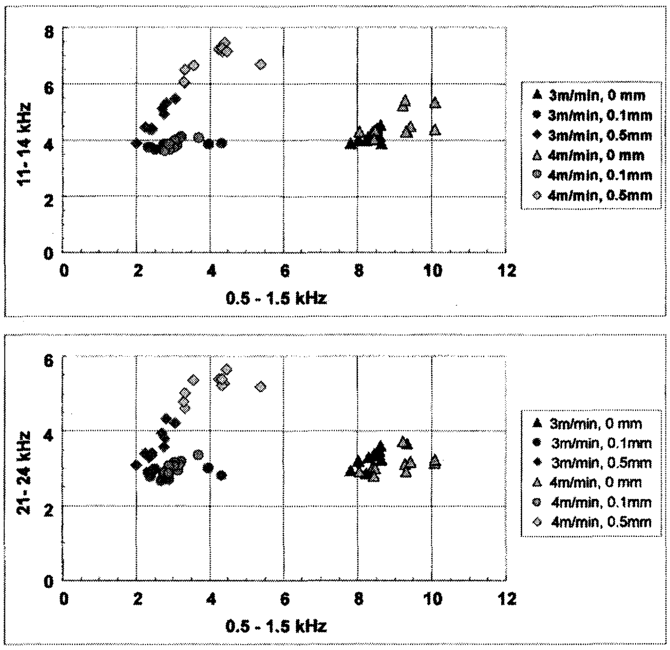
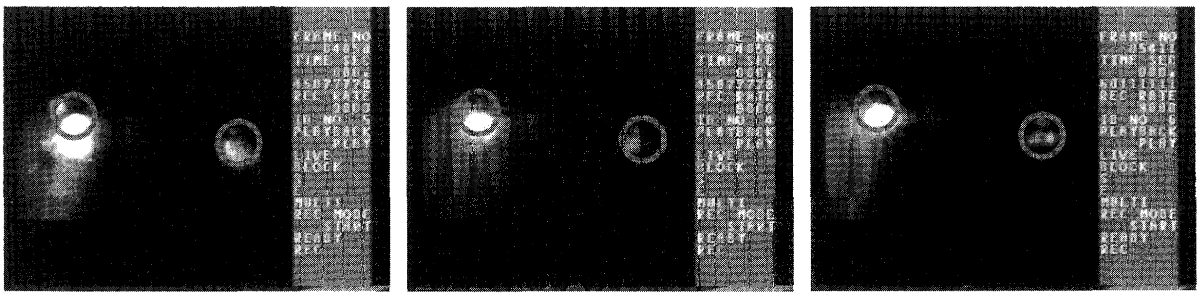


Fig. 8 Formation ranges of respective weld beads indicated as function of low and high frequency of FFT results of reflected beams.

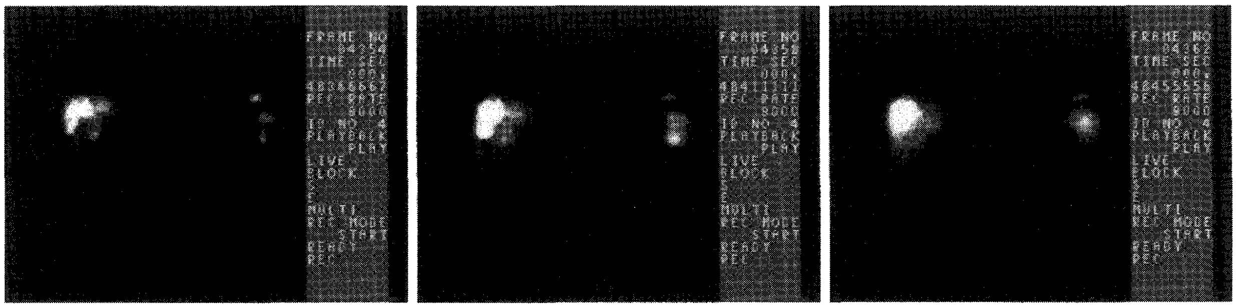
mm, while the levels of low and high frequencies are low and high respectively for the formation of incomplete lap welds at the gap of 0.5 mm. From these results, it is confirmed that the intensity level and its FFT data of a reflected beam are beneficial as signals for the judgment of good or bad weld beads (i.e. weld quality).

To further interpret the monitoring results, molten pool behavior and reflected beam intensity were observed together with monitoring signals. Examples of the results are shown in **Figs. 9** and **10**. The left and right photos show molten pool behavior and reflected beam intensity, respectively. The keyhole was formed just after the laser beam irradiation. The reflected beam was detected chiefly from the front of a keyhole, and partly from the front vicinity of the molten pool. In the case of the 0 mm gap, the secondary reflected beam was also detected from the rear molten puddle surface when the melt there was ejected and splashed out. It was understood that the reflected beam was weak when it was blocked or hindered from spattering liquid droplets, and became strong after the melt was splashed. Thus the intensity of the reflected beam fluctuated to a large extent for the 0 mm gap. On the other hand, the molten pool surface fluctuated at high frequency probably because of the small amount of liquid, leading to the reflected beam of high frequencies. The laser lap welding phenomena were better understood as a result of using high-speed video and monitoring system.



(a) 0 mm gap (b) 0.1 mm gap (c) 0.5 mm gap

Fig. 9 Observed photos of molten pool (left) and reflected beam (right) during YAG laser lap welding of Zn-coated steel sheets with gaps of 0 mm, 0.1 mm and 0.5 mm.



0.44 ms (1.8) 0.89 ms (2.9) 1.33 ms (3.9)

Fig. 10 Examples of observed photos of molten pool and reflected laser beam during laser welding of Zn-coated steel sheets with 0 mm gap. Elapsed time (monitored intensity)

4. Conclusions

Welding of Zn-coated steel sheets was performed under various conditions, and the results obtained are as follows:

(1) Laser lap welding results were interpreted by considering their main dependence upon the gap between the steel sheets.
(2) In the case of no gap, spatter was frequently generated, and a reflected beam fluctuated intensely at low frequencies.
(3) Sound welds were produced in the sheets with a proper gap, and a moderate reflected beam was monitored.
(4) In welding sheets with a wide gap, lap welds were not produced and the high frequency signals of a reflected beam were detected. This may be attributed to the smaller amount of melt in the upper sheet molten pool.
(5) From these results, it was concluded that monitoring of a reflected beam and its FFT data were beneficial for the formation judgment of sound, under-filled or incomplete lap welds

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