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Weldability and Keyhole Behavior in Remote Welding of three Zn-Coated Steel Sheets†

LEE Su-Jin*, KATAYAMA Seiji**, KAWAHITO Yousuke***, KINOSHITA Keisuke****

Abstract

Zinc-coated steels are widely used in automobile bodies. Laser welding, which offers much advantage over the conventional welding with MAG, CO_2 arc, etc. in terms of improved weld quality, high-speed and easy automation, has been developed for cars. However, in laser lap welding of zinc-coated steel sheets without gaps, defects such as underfilled beads or porosity are easily formed due to the higher pressure of zinc vapor trapped in the molten pool because of the lower boiling point of zinc (1180 K) with respect to the melting point of steel (Fe, 1803 K). Laser lap welding results of two Zn-coated steel sheets have been reported. However, there are not enough data for welding of three Zn-coated steel sheets. Therefore, to understand laser lap weldability of three Zn-coated steel sheets, lap welding of two or three sheets with and without gaps was performed, and then molten pool motions, spattering and keyhole behavior during welding were observed by high speed video cameras and X-ray transmission real-time imaging apparatus. Lap welding of three steel sheets was difficult but acceptably good welds were produced in sheets with the upper and lower gaps of 0.1 and 0.1 mm, 0.1 and 0.2 mm or 0.2 and 0.1mm, respectively. Bubble generation leading to porosity formation was observed, and it was confirmed that welding phenomena were different depending upon the gap levels.

KEY WORDS: (Zn-coated steel), (Remote welding), (Disk laser), (Gap), (Lap welding of three steel sheets), (Keyhole behavior), (Porosity formation)

1. Introduction

Recently, safety, light-weight, lifespan and environmental protection have received considerable attention and become more important in the automobile industry. Requirements for improving durability in vehicle bodies have demanded the wide use of galvanized (zinc-coated) steel sheets as corrosion resistant materials. The zinc-coated steels have attracted attention in many industrial applications due to their high cost performance, high strength and toughness, better performance at both high and low temperatures, and high resistance to abrasion and corrosion. Therefore, zinc-coated steels are especially widely used in the automobile industry, because sacrificially protective coatings of zinc are effective in enhancing the life of steel components subjected to atmospheric or aqueous corrosion[1, 2].

Laser welding has been widely used in the automobile industry owing to its benefits of high welding speed, high precision, high efficiency and high productivity. Laser welding, which offers good advantages over the conventional techniques of TIG, MAG, MIG and CO2 arc in terms of improved weld quality, high speed and easy automation, has been developed for cars[3-5]. Currently, a large number of high power laser welding systems such as Nd:YAG and CO_2 lasers have been used in the welding processes. But at present, commercial disk and fiber lasers of smaller-sized systems offer high efficiency and high beam quality, and thus they are used as laser devices for flexible remote high-speed welding [3-7]. Development of a disk or fiber laser has been expected to lead the laser remote welding techniques which are used to enhance the flexibility of laser welding, production efficiency, welding speed and sequence control [3-8].

In this study, therefore, a high intensity disk laser was used to perform laser remote welding with a scanner head. In the lap welding of zinc-coated steel sheets without gaps, defects such as underfilling and porosity are easily formed due to the high pressure of zinc vapor trapped in the molten pool because of the low boiling point of zinc (1180 K) with respect to the melting point of steel (Fe, 1803 K). A large number of laser lap welding results of two zinc-coated steel sheets and laser welding phenomena have been reported but there are no satisfactory data for remote welding of three sheets of zinc-coated steel[9-11]. Therefore, laser lap weldability of

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three Zn-coated steel sheets was investigated with the objective of developing better remote welding procedures. To understand laser weldability, lap welding of Zn-coated steel sheets with different gaps was performed using a 16 kW disk laser with a scanner head under various welding conditions, and these welding results were evaluated. Physical phenomena such as plume ejection, keyhole behavior, molten pool motion and spattering during laser lap welding were observed by utilizing high speed video cameras and X-ray transmission real-time imaging apparatus[12-14].

Table 1 Chemical composition of Zn-coated (GA) steel used.

Material	Galvanizing	Chemical compositions (mass %)							
		C	Si	Mn	P	S	Cr	Ni	Fe
SP781	coated	0.002	0.014	0.159	0.0107	0.0048	0.01	0.01	Bal.

2. Experimental

2.1. Materials used, and optical observation methods of molten pool and keyhole during welding

The materials used in experiments are SP781 GA (Galvannealed) zinc-coated steel sheets of 50 mm width, 50 mm length and 2.6 mm, 1.4 mm, 1.2 mm and 0.65 mm thickness. The chemical composition of the material is shown in Table 1. The amount of galvanized coating layer was about 45 g/m^2.

The high intensity disk laser with a maximum power of 16 kW and a wavelength of 1030 nm was utilized, and the laser beam parameter product (BPP) was 8 mm· mrad. The laser beam was delivered by an optical fiber of 200 μm in diameter and focused on the specimen surface by a lens of 255 mm focal length. The spot size of the laser beam was about 300 μm at the focal point. A scanner head, which had a 292.5 mm ± 1.5 mm working distance, 180 mm × 104 mm working area and 10 m/s working speed, was set up as the laser head in this experiment. The laser beam was directly shot on three Zn-coated steel sheets of 1.4, 1.2 and 0.65 mm in thickness or two lap sheets of 2.6 and 0.65 mm in thickness.

Fig. 1 shows the experimental setup for laser remote lap welding of Zn-coated steels and observation during welding. Lapped steel sheets were fixed to a jig and were subjected to laser welding using a scanner head. A molten pool, a keyhole and spatter during laser welding were observed by high speed video cameras at 10,000 frames/s. The molten pool on the bottom side was also observed through a mirror.

2.2. Observation method of keyhole behavior in the molten pool by X-ray transmission imaging system

Keyhole behavior, melt flows, and bubbles and porosity formation were observed by using X-ray transmission real-time imaging system. Such observation systems were developed by Arata, et al. and Katayama, et al[12-14]. The X-ray transmission imaging system is simply described in a schematic illustration of Fig. 2. The system is composed of a micro-focused X-ray source (whose minimum diameter of X-ray beam is about 0.1 mm at the acceleration voltage of 160 kV), a visible image intensifier from X-ray and high speed video camera. Therefore, the magnified sizes of a narrow keyhole and small bubbles in the molten pool can be observed to know the real behavior. The images can be taken by a high speed video camera at 200 to 1,000 flames per second. In this study, the X-ray transmission conditions were 75 kV acceleration voltage and 0.3 mA current. The micro-focused X-ray was irradiated on narrow specimens of thin lapped steel sheets during laser welding and the transmitted X-ray images were observed.

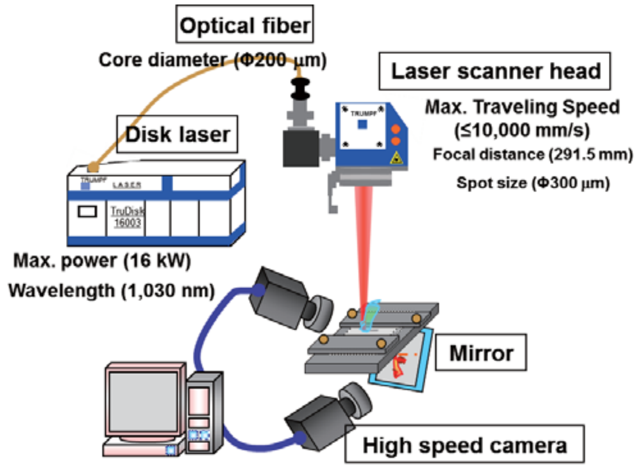


Fig. 1 Experimental setup for observation of keyhole behavior and spattering during disk laser lap welding of Zn-coated steel sheets with scanner head.

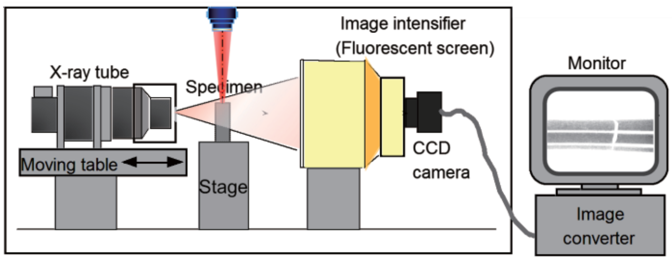


Fig. 2 Schematic arrangement of X-ray transmission real-time imaging system for observation of keyhole behavior and porosity formation.

3. Results and Discussion

3.1 Laser lap weldability of three Zn-coated steel sheets depending upon gap

Lap welding of 3 Zn-coated steel sheets of 1.4 mm, 1.2 mm and 0.65 mm in thickness was performed by changing the upper and lower gaps from 0 to 0.6 mm. Fig. 3 shows cross-sectional photos of laser full-penetration lap weld beads in three Zn-coated steel sheets with different gaps made at 4.5 kW laser power at 55 mm/s welding speed. In the case of the sheets without gaps, the unacceptable weld beads with deep concavity or severe underfilling were formed, and in the case of the upper or lower gap of 0 mm, severely deep underfilling was present in either upper or lower bead surface, respectively. Such welds are obtained in the gap conditions of “C” in Fig. 3. The formation of such underfilling should be attributed to violent spattering due to the zinc vapors. On the other hand, no welded beads were formed in the sheets with wide gaps of 0.4mm to 0.6 mm. These worst welds are formed in the conditions of "D" in Fig. 3. The formation of no welded joints is ascribed to such wide gaps as to be hardly filled up with the molten metal. The limit of gaps in laser lap welding of three Zn-coated steel sheets was about 0.6 mm for the sum of the upper and lower side gaps. Three Zn-coated steel sheets were welded under the condition of 0.5 mm (upper)-0.1 mm (lower) gap, but in the case of 0.1 mm (upper)-0.5 mm (lower) gap the weld could not be formed between 1.2 mm and 0.65 mm sheets of Zn-coated steels. Nevertheless, good welds without porosity were generally formed in sheets with the gap of less than 0.2 mm. The windows of "A" and "B" in Fig. 3 are judged to be proper and acceptable depending upon the degrees of shallow underfilling.

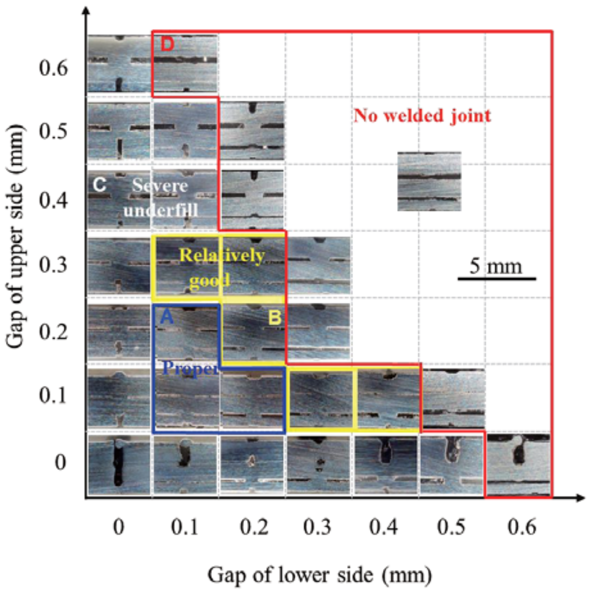
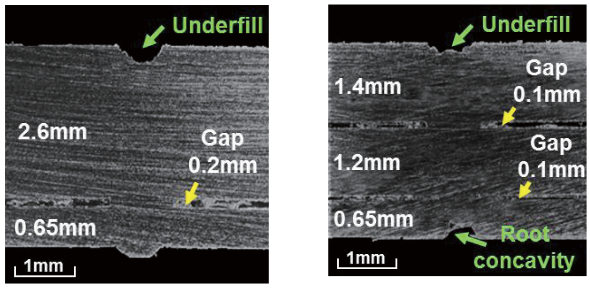


Fig. 3 Cross-sectional photos of laser lap welds made in three zinc-coated steel sheets with different gaps at 4.5 kW laser power and 55 mm/s welding speed, showing formation of weld defects such as underfilling and prosoity.

From the above results in laser lap welding of three Zn-coated steel sheets of 1.4 mm, 1.2 mm and 0.65 mm in thickness, poor laser weldability was characterized by deep underfilling, porosity formation and/or no formation of welded joints. It was almost impossible to produce sound welds in three sheets without gaps, while it was important for the production of sound welds with reduced underfilling to set the upper and lower gaps between sheets in the proper gap ranges; for example, about 0.1 and 0.1 mm, 0.1 and 0.2 mm and 0.2 and 0.1 mm, respectively.

3.2 Comparison of welding characteristics between two and three sheets during laser lap welding

Laser lap welding was performed for the production of a full-penetration weld bead in two or three sheets of Zn-coated steel under the conditions of 3 kW laser power and 50 mm/s welding speed with gap. Fig. 4 shows the cross sections of the laser weld beads obtained under these welding conditions. The underfilling of the top surfaces is observed in both beads, as shown in Fig.4 (a) and (b), while a root concavity is observed in a lap weld bead of three sheets only. The reason why the laser lap welding of three sheets is more difficult than that of two sheets is interpreted in terms of the formation of concave bead surface or underfilling on the bottom surface.



(a) (b)

Fig. 4 Cross sections of lap welds of 2 sheets (a) and 3 sheets (b) of Zn-coated steels with gaps at 3 kW laser power and 50 mm/s welding speed.

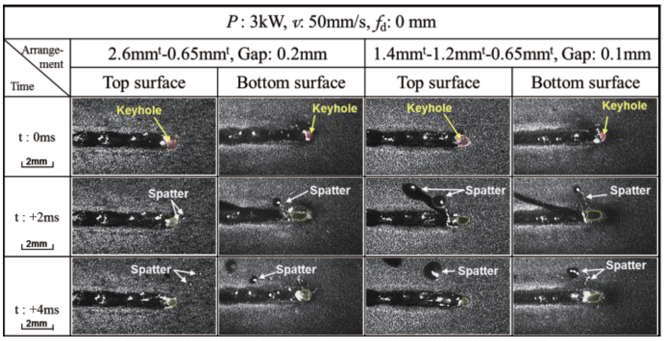


Fig. 5 High speed video observation results of keyhole and spattering behavior during laser lap welding of 2 and 3 sheets of Zn-coated steels with gaps.

Fig.5 shows high speed video observation results of the top and bottom surfaces of the molten pool during laser lap welding of two or three Zn-coated steel sheets with proper gaps, exhibiting melt motions of the pool, keyhole behavior and spattering. Spattering from the top and bottom molten pool was observed in both two and three sheets. During laser lap welding of three Zn-coated steel sheets, the molten pool moved more actively together with keyhole motion than that of two sheets, and accordingly larger-sized spatters were generated from the top and bottom molten pool in lap welding of three sheets.

In conclusion, laser lap weldability of three sheets of Zn-coated steel was characterized by easier formation of spatters although proper gaps were set between sheets, and degraded by the formation of underfilled weld beads. Especially, larger-sized spatter was ejected from the top and bottom molten pools in lap welding of three sheets.

3.3 Keyhole behavior during lap welding of three Zn-coated steel sheets

Fig. 6 shows X-ray transmission real-time images captured during laser lap welding of three Zn-coated steel sheets without gap. 3 mm wide specimens of 1.4 mm, 1.2 mm and 0.65mm in thickness were used for the clear observation of keyhole behavior, and the laser power, welding speed and defocused distance employed were 4.5 kW, 55 mm/s and 0 mm, respectively. The locations and shapes of a keyhole, bubbles and porosity were clearly observed. The keyhole fluctuated, and large bubbles were intermittently formed from Zn-coated layers, trapped by rapid solidification of the molten metal and finally remained as large pores. Fig. 6 (a) shows the picture of three lap sheets before irradiation with a laser beam, and figures (b) to (f) show a keyhole, bubbles, porosity and a melt pool according to the elapsed time. As shown in Fig. 6, the keyhole was not stable and the diameter of the keyhole was in the range of about 1 mm ~ 1.5 mm. In Fig. 6 (c), a bubble was generated from the Zn-coated layers between two sheets of steels, as shown in (1). The bubble was separated from the keyhole and remained in the melt pool (2). The bubble was expanded probably because the zinc vapor entered from the layer (3). Finally, the bubble resulted in a large pore or porosity (4).

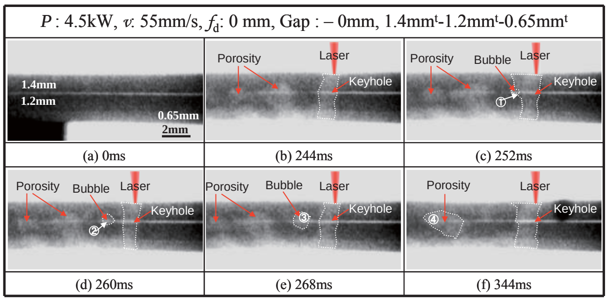


Fig. 6 X-ray transmission observation results of keyhole behavior, and bubbles and porosity formation during laser lap welding of 3 sheets without gaps.

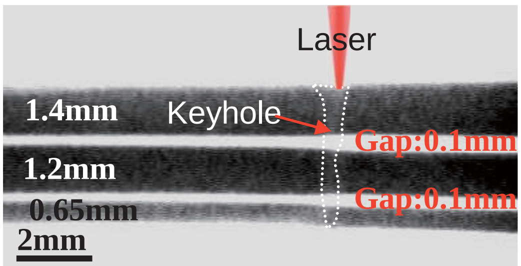


Fig. 7 X-ray transmission observation result of keyhole during laser lap welding of 3 sheets with gaps of 0.1 and 0.1 mm at 4.5 kW laser power and 55 mm/s welding speed.

Fig. 7 shows an X-ray transmission image during laser lap welding of three Zn-coated steel sheets with the upper and lower gap of 0.1 mm and 0.1 mm under the same laser welding conditions for sheets without gaps. The keyhole was about 0.4 mm narrow, and the behavior of the keyhole was more stable. No bubbles were generated during welding, and consequently there was no porosity in the weld bead after welding because the Zn vapor from zinc layers escaped through the gaps.

From the above observation results, a narrow weld bead without porosity could be present due to the narrow keyhole in laser lap welding of three sheets with proper gaps although the rough surface with underfilling or porosity was formed in the sheets without gap.

4. Conclusions

To evaluate laser lap weldability of two or three Zn-coated steel sheets of 1.4 mm, 1.2 mm and 0.65 mm in thickness, laser remote welding was performed at various gaps using a high intensity disk laser with a scanner head. Keyhole behavior, spattering and bubbles or porosity formation during laser lap welding were observed using high speed video cameras and X-ray transmission real-time imaging system. The results obtained are as follows:

1. Poor laser weldability in lap welding of three sheets was characterized by deep underfilling, porosity formation and/or no formation of welded joints. It was almost impossible to produce sound welds in three sheets without gaps. Even if the no gap was set in either upper or lower side, deep underfilling was formed due to Zn vapor from the sheets without gap.
2. The limit of gap in lap welding of three Zn-coated steel sheets was the sum of about 0.6 mm for the upper and lower sides at 4.5kW laser power and the 55 mm/s welding speed.
3. It was important for the production of sound welds with reduced underfilling to set the upper and lower gaps between sheets in the proper gap ranges; for example, about 0.1 and 0.1 mm, 0.1 and 0.2 mm and 0.2 and 0.1 mm, respectively.
4. In the case of no gaps (0 mm-0 mm), the keyhole was unstable and bubbles were generated and expanded from the location of 0 mm gap. The bubbles remained as large pores or porosity in the weld beads. On the other hand, in laser lap welding of 3 sheets with proper gaps of 0.1 mm, a more stable and narrower keyhole was formed, and bubbles were not generated, leading to no porosity in the weld beads.

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