Pulsed Nd:YAG Laser Seam Welding of Zinc-Coated Steel

Successful welds without gas-formed porosity are made in tightly clamped lap joints of zinc-coated sheet steel

BY Y-F. TZENG

ABSTRACT. This paper examines the weldability of zinc-coated steel sheets in a lap joint configuration without a joint clearance by pulsed Nd:YAG laser beam welding. A mechanism for sufficient exhaustion of zinc gas for the formation of acceptable quality welds is proposed.

The pulsed laser beam welding process is controlled by a variety of parameters. These include average peak power density (APPD), mean laser power, traverse speeds and pulse duration. The present study focuses on the effects of these main processing parameters on weld quality. Laser beam welds were produced in 0.7-mm-thick electrogalvanized and 0.7-mm-thick galvanneal steel sheets with rectangular power pulses.

It was experimentally found that average peak power density (APPD) is the most critical factor in governing pulsed laser beam welding. Excessive APPD tends to result in cutting effects. Conversely, insufficient APPD has a high tendency to cause incomplete penetration. The other factors include average power and travel speed. High quality lap joint welds can thus be produced mainly by proper selection of APPDs, mean powers and traverse speeds.

Introduction

The automotive industry uses a variety of galvanized products to enhance the durability of vehicle structures. Weld joints in the automotive industry are now generally made by spot welding, of which, for safety reasons, a large number of them are. If a high-power laser is used for welding, the joints would be made more quickly and with better quality, which makes it attractive as an alternative joining technology for vehicle body fabrication and assembly. In addition, the advantage of single-side access and no direct contact with the workpiece while welding render this technique all the more desirable.

The studies on the weldability of zinc-coated steel sheet have been undertaken to overcome zinc gas explosion problem mainly encountered while using CO_2 lasers. Many different techniques were reported to successfully produce acceptable lap joint seam welds in zinc-coated steel sheet, mostly using multi-kilowatt CO_2 lasers (Refs.1–19). The pulsed method using 2.5 kW CO_2 laser with no root opening first claimed to be successful in producing visually sound full-penetrated welds by Heydon, *et al.*, in 1989 (Ref. 1). In 1990, Hurley, *et al.*, reported a success again (Ref. 2). Unfortunately, in both studies visually acceptable welds were made with a very small window of processing parameters, and the effects of the laser processing parameters on the welding process were not sufficiently investigated.

The use of a continuous wave (CW) laser on a joint with no clearance between sheets, which was carried out in 1991 by Bilge, *et al.*, from General Motors, was patented in the United States as a novel way of welding zinc-coated steel with a CO_2 laser (Ref. 3). The special feature is that the sheets are positioned and moved vertically during welding while the laser beam is applied to sheets horizontally. This idea has been seen rarely in other academic publications probably due to the difficult positioning and movement of steel sheets.

The technique of prior zinc removal in the weld area on a joint with no clearance between sheets was applied by Pennington, *et al.* (Refs. 4–5). The treated zone was replaced by nickel coating, which does not vaporize appreciably at the steel fusion temperature to reduce porosity and provide corrosion protection. The disadvantage with this technique is the prohibitive additional processing cost.

The method using a joint clearance was investigated by Akhter, *et al.*, who put spacers between sheets to provide a path for venting gas formed from heating the coating material (Refs.1, 6–11, 16). This method is useful for CO_2 laser welding of members coated with materials having a lower melting point than the base metal. However, there is the difficulty of maintaining a constant joint clearance during the welding process due to thermal distortion and the variation of coating thicknesses.

The altered joint geometry technique, which offers controlled channels between the sheets to exhaust zinc gas, was used by Piane, *et al.*, to laser weld zinc-coated sheet steels (Refs. 12–16). Altered joint geometry is usually created as convex and concave surfaces in the top sheet. It has the additional advantage that weld quality is not sensitive to dimensional variation of the clearance formed between the sheets (Ref. 16).

Pulsed Nd:YAG laser beam welding has better energy coupling and a more flexible beam delivery using fiber optics,

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KEY WORDS

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Zinc-Coated
Seam Weld

which renders it a promising replacement for both CW CO_2 laser beam welding and conventional spot welding. However, complexity when using the pulsed mode of this laser for welding is increased due to the introduction of more variables in the process, namely pulse energy, pulse duration, pulse repetition rate, mean power, peak power and pulse shaping.

Few experimental results have been reported on the quality of seam welds in zinc-coated steel made with a pulsed Nd:YAG laser (Ref.17). Good quality welds, which require no joint clearance for gas blowout, were reported as a success by Norris, *et al.* (Refs. 6, 16, 18–19). However, the reason for their success and the mechanism of Nd:YAG laser beam seam welding of zinc-coated steel sheet is far from being fully understood. It follows that the systematic study of the weldability of zinc-coated sheet steel tightly clamped in a lap joint using pulsed Nd:YAG laser is required in order to boost confidence in industrial applications. This is what this paper aims to provide.

Pulsed Nd:YAG Laser Parameters

Figure 1 illustrates a schematic of the laser power output for a series of constant energy pulses in a self-designed shape. To help clarify the approach used in this study, nomenclature associated with Nd:YAG laser material processing is defined below.

$$P_P = [E_P/T_P] \quad (1)$$

$$P_D = \frac{E_p}{T_p \times A} \quad (2)$$

$$P_M = E_P \times PRR = [E_P/T_F] \quad (3)$$

$$C_D = [T_P/T_F] \quad (4)$$

where P_P is average peak power (kW), E_P pulse energy (J), T_P pulse duration (ms), P_D average peak power density (kW/m2), A laser spot area (m2), P_M mean laser power (kW), PRR pulse repetition rate (1/s), T_F pulse-to-pulse time (ms) and C_D duty cycle.

Pulsed Welding of Zinc-Coated Steel

Proposals for successful welding of zinc-coated steel in a lap joint without a joint clearance using pulsed Nd:YAG laser are as follows:

A pulsed Nd:YAG laser beam is able to penetrate the workpiece deeper than a CW CO_2 laser beam due to its higher average peak power density and its shorter wavelength of 1.06 μm, which results in a higher heat absorption by the substrate. Depending on the setup of the thermal input rate, pulsed laser welding can vaporize the substrate to give a good keyhole effect. This creates a vent that might aid in exhausting high-pressure zinc gas and thus reduce the risk of explosive ejection of material.

As illustrated in Figs. 2A and B, zinc, which boils at 900°C, will generate vapor both in the fusion zone and in the surrounding heated area. The quantity of zinc vapor is dependent on the coating thickness at the interface between the sheets to be lap welded and also on the pulsed laser heating cycle, which determines the extent of the surrounding zone above 900°C. This quantity of zinc vapor has to be exhausted. The fusion zone is at approximately 1600°–3000°C, and hence, the saturated vapor pressure of the zinc (as described by the Clausius-Clapeyron equation) will be 66 ~ 1060 atmosphere pressure.

In the work of Akhter (Ref. 20), the zinc vapor was exhausted between steel sheets by arranging a joint clearance. He calculated the joint clearance to be approximately 0.1 mm for successful gas evacuation. In the present work, the sheets were tightly clamped, a condition imposed by the requirements of industry. Thus, the only route for exhausting the

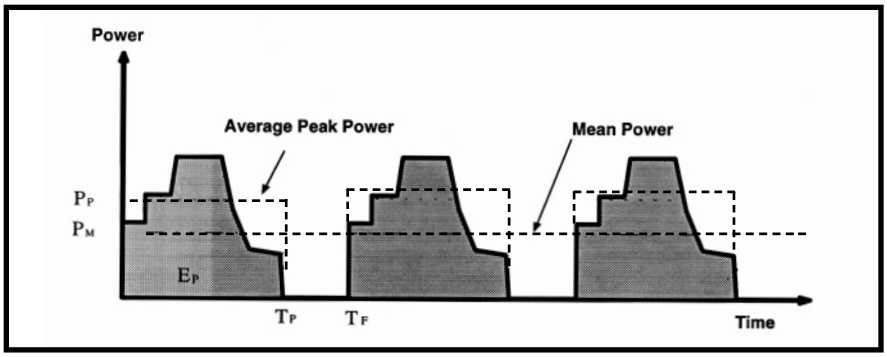


Fig. 1 — Schematic of the output power pulses with illustrations of the defined average peak power, the mean power, the pulse duration and the pulse-to-pulse time.

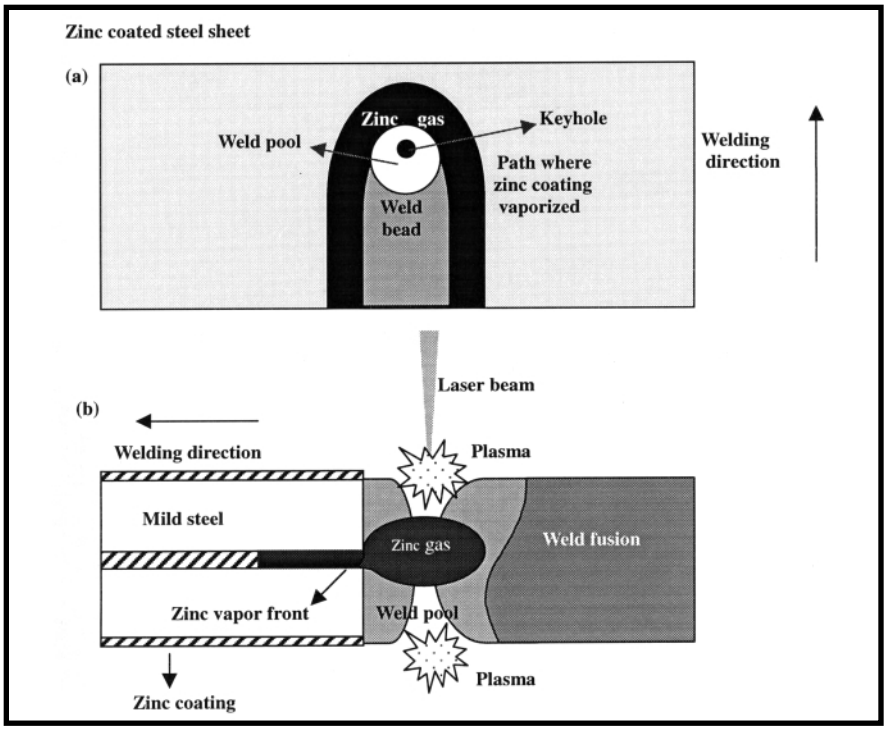


Fig. 2 — Schematic of zinc gas movement: A — Between the steel sheets; B — through the keyhole.

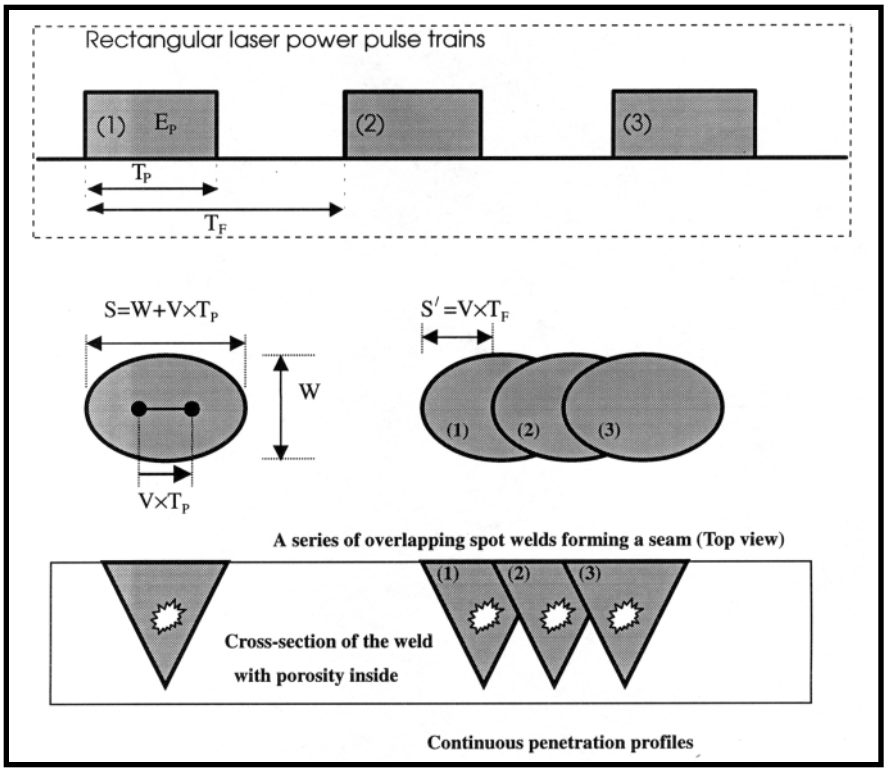


Fig. 3 — Schematic diagram of a typical rectangular laser power pulse train and a corresponding series of partially overlapping spot welds with porosity inside.

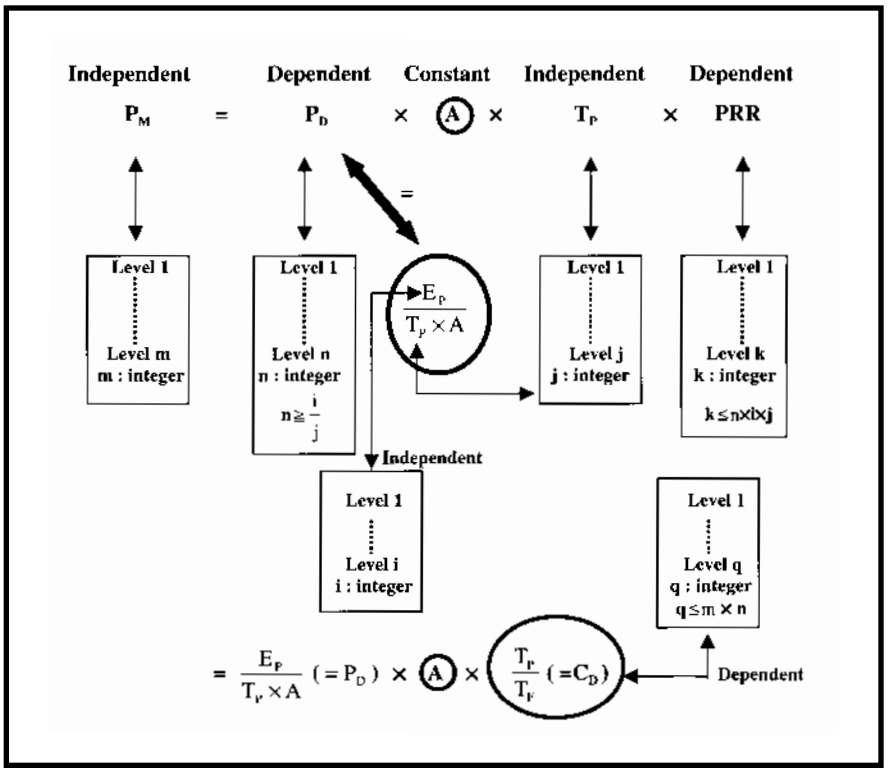


Fig. 4 — Suggested idea for strategic control of pulsed Nd:YAG laser parameters.

zinc vapor is through the weld pool along with the iron vapor formed in the keyhole. The high pressure of the zinc at the leading edge of the weld will distort the location of the keyhole forward. But if the material solidifying at the rear is sound, the weld produced will be sound.

Pulsed Nd:YAG laser beam welding of zinc-coated sheet steel is essentially a series of periodic spot welds partially overlapping each other to form a weld seam. The partial overlapping of the successful power pulses refills the preceding fusion zone and thus could effectively reduce pores left in the fusion zone by previous pulses. This is illustrated in Fig. 3, which schematically shows the development of partially overlapping spot welds by pulsed laser beam welding. Therefore, appropriate partial overlapping of weld spots, plus the previously good keyhole effect, may be capable of producing a desirable weld. In addition, zinc gas can be significantly reduced by periodic power-offs in the pulse trains of the laser beam. As a result, the production of visually sound welds on zinc-coated sheet steel may be possible.

It is seen in Fig. 3 that the more closely the overlapping of the spot welds, the smoother the central longitudinal section of the weld profile, *i.e.*, a more continuous fusion zone is obtained at the base of the weld. The following equations describe the overlapping of the spot welds in pulsed laser beam welding:

$$P_{ER} = \frac{[S - S']}{S} \times 100\% = \left[1 - \frac{S'}{S}\right] \times 100\% \quad (5)$$

$$= \left[1 - \frac{V \times T_F}{W + V \times T_P}\right] \times 100\% \quad (6)$$

where P_{ER} = the percentage of overlap in the X-axis direction; $S' = V \times T_F$, the length in a single spot not overlapped by successive welding spots; $S = W + V \times T_P$, the major diameter of spot weld formed from a laser spot plus movement during a pulse; V = the travel speed; and W = the minor diameter of the spot weld.

For pulsed laser beam welding applications, the general constraint $0 \leq P_{ER} < 1$ applies to Equation 6 because there is a relative motion between the pulsed laser beam and the workpiece. Equation 6 can thus be rearranged as follows:

$$0 < V \leq \frac{W}{T_F - T_P}. \quad (7)$$

It can be deduced from Equation 7 that the travel speeds suited to longitudinal welding applications with a constant laser spot setup depend on the mean output power. The use of higher mean power leading to smaller difference between the

pulse-to-pulse time and the pulse duration indicates higher travel speeds. In reality, for pulsed laser beam welding processes, P_{ER} can be estimated to be at least greater than 50% in order to produce a weld with consistent full penetration. Therefore, the operating range of the travel speeds can be predicted to fall within the following constraint:

$$0 < V < \frac{W}{2T_F - T_p}. \quad (8)$$

Referring to Figs. 2 and 3, the relationship between the parameters can be expressed in various mathematical equations as follows:

$$P_M = E_P \times PRR = \frac{E_P}{T_P} \times \frac{T_P}{T_F} \quad (9)$$

$$= P_P \times C_D \quad (10)$$

$$P_M = \frac{E_P}{T_P \times A} \times A \times \frac{T_P}{T_F} \quad (11)$$

$$= P_D \times A \times C_D \quad (12)$$

$$P_M = P_D \times A \times T_P \times PRR. \quad (13)$$

It is observed from Equations 9 and 13 that for a given laser power P_M there are various combinations of E_P and PRR, and their relationship is inversely proportional. This observation applies to the other relevant mathematical expressions and it indicates the flexibility and complexity in the selection of pulsed parameters. The question that arises is how to select a satisfactory combination of the parameters to enable an efficient and effective pulsed laser welding application.

For spot welding by single laser power pulse, the most crucial processing parameters are average peak power density (P_D) governing the thermal input rate upon the laser treated area, and pulse duration (T_P) controlling the interaction time between the laser radiation and the workpiece. While switching to the pulsed laser beam welding applications by pulse trains, other crucial processing parameters have to be taken into careful consideration. They are mean laser powers (P_M) and travel speeds (V). The ratio (P_M/V) basically determines the extent of the average thermal input per unit weld.

Table 1 — Chemical Compositions of Steel Substrate M1 and M2

Steel Substrate	Chemical Compositions (%)
M1, M2	C: 0.01, S: 0.008, P: 0.013, Mm: 0.160, Al: 0.036, N_2: 0.0027, S: 0.006, Ti: 0.054, Nb<0.01

Table 2 — Parameter Setup for Experiments

Pulse shape	Rectangular (Fig. 5)
Laser Power: P_M	396, 363, 330, 297 W for M1 & M2
Speed	0.4 ⧫ 15 mm/s
Pulse duration: T_P	4, 8, 12 ms
Pulse energy: E_P	5.9, 7.5, 11, 15 J for 4 ms 11.8, 15, 22, 30 J for 8 ms 17.7, 22.5, 33, 45 J for 12 ms
Focal location	Focused on the top surface of the material
Lens	120-mm focusing lens from Lumonics Ltd
Spot size: d_s	0.8 mm
Shielding gas	Argon gas blowing at constant rate of 20 L/min at 45 deg onto the leading edge of the focused position

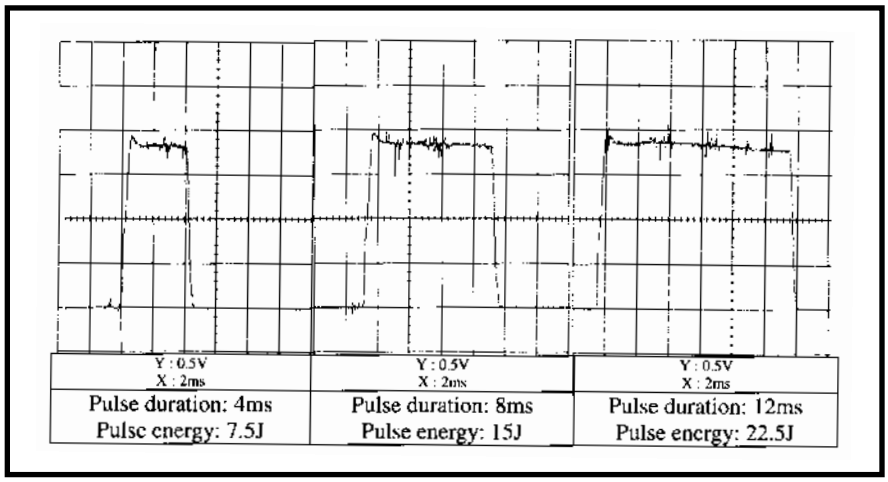


Fig. 5 — Example of the real rectangular power pulses.

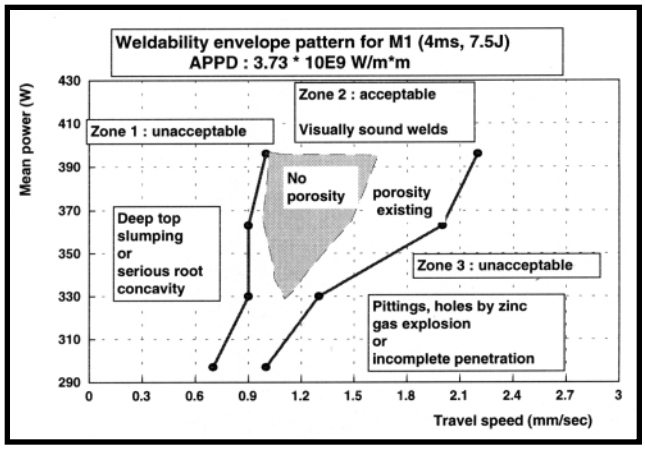


Fig.6 — A typical pulsed laser weldability envelope for producing varied quality welds for the material M1.

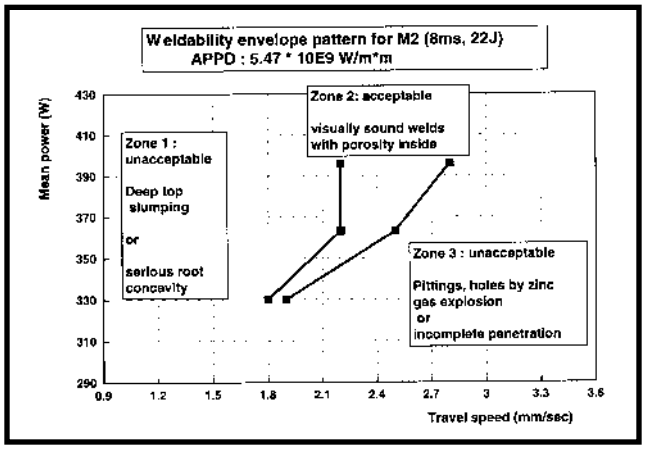


Fig. 7 — A typical pulsed laser weldability envelope for producing varied quality welds for the material M2.

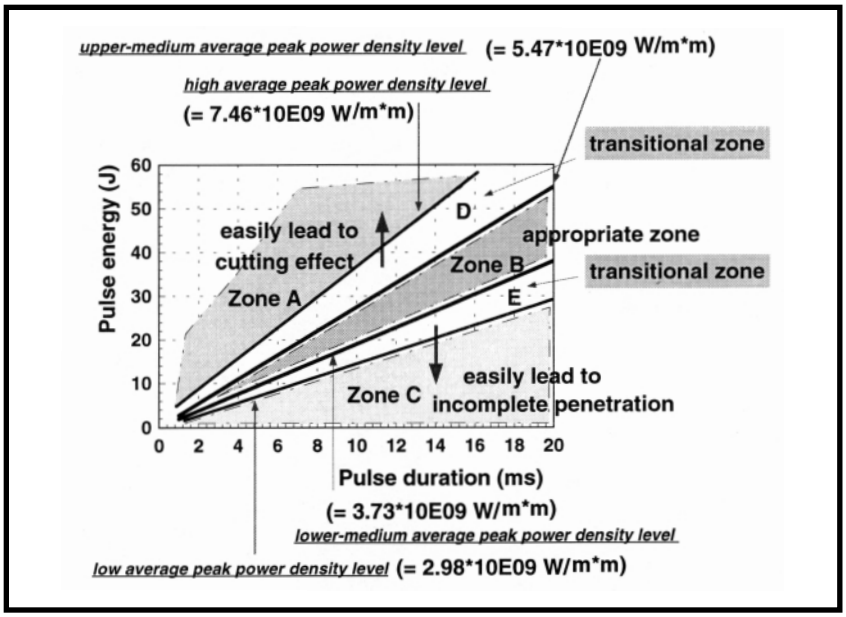


Fig. 8 — The processing map showing the effects of the APPD on the weld quality using pulsed Nd:YAG laser.

The mathematical relationship is expressed as

$$E_{ave} = \frac{P_P \times T_P \times PRR}{d_S \times V} = \frac{E_P}{d_S \times V \times T_F} = \frac{P_M}{d_S \times V} \quad (14)$$

where E_{ave} is average thermal input per unit weld for the laser spot size d_S. The value also determines the overlapping of spot welds. This is understood by combining Equation 6 and Equation 14

$$P_{ER} = \left[1 - \frac{1}{\frac{W \times ds \times E_{ave}}{E_P} + \frac{T_P}{E_P}}\right] = \left[1 - \frac{1}{\frac{W \times ds \times E_{ave}}{E_P} + C_D}\right]. \quad (15)$$

The Lumonics JK701 Nd:YAG laser machine used in this study has a low mean output power (400 W), as such the operating welding speeds are expected to be much slower compared to a high-power CW CO_2 laser. Therefore, to meet the demand of a high-power intensity for the seam welding applications of lasers, the importance lies in the selection of suitable APPDs. To achieve a suitable APPD, the laser spot size has to be carefully selected due to the restriction of the low mean power available. It is also suggested that the laser spot be set on the focal point for the smallest spot size (about 0.8 mm) leading to a wider choice of APPDs. As for the types of shielding gas, their compositions and flow rates are not considered in the design of welding process parameters due to their negligible effects on zinc gas exhaustion (Ref.17).

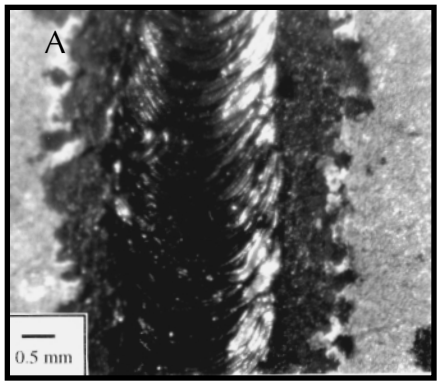
Based on the previous discussions, the strategy for governing the main pulsed laser processing parameters used in the experimental trials is shown in Fig. 4. It is noted that the spot area A is kept constant because of the reason stated before. The attributes of variables being "independent" or "dependent" in the mathematical equations are arbitrarily defined from the standpoint of ease in operating a pulsed Nd:YAG laser machine and in experimental trials.

It is noted in Fig. 4 that just controlling the selected levels of three independent parameters P_M, E_P and T_P leads to a series of induced dependent parameters (P_D, C_D and PRR). P_D is determined simply by selecting the proper combination of E_P and T_P on the laser controller for a constant spot size A. The strategy used in controlling the pulsed laser processing parameters herein enables a systematic comparison of experimental trial results.

Materials and Experimental Methods

The materials used are M1 and M2, whose specifications are as follows:

1) M1: Electro-galvanized sheet steel (EZ), 0.7 mm thick with 7.5 μm pure zinc coating on both sides.



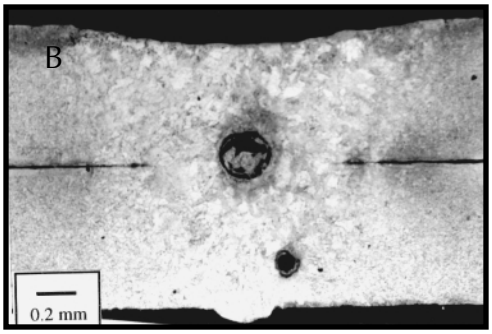
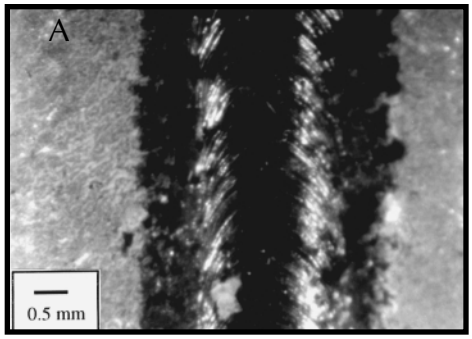


Fig. 9 — A — Top view; B — transverse section of a visually acceptable seam weld produced in galvanized steel M1 at 2 mm/s using low-medium APPD (3.73 x 10^9 W/m^2, E_P = 22.5 J, T_P = 12 ms), and mean power 396 W.



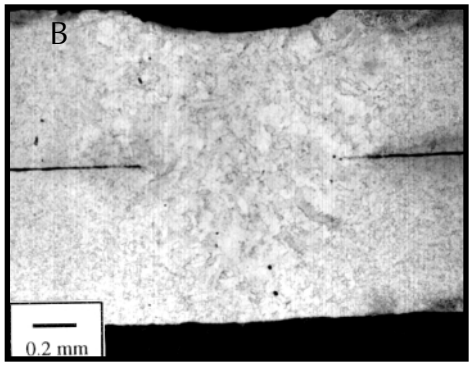


Fig. 10 — A — Top view; B — transverse section of a visually acceptable seam weld produced in galvanized steel M1 at 1.5 mm/s using low-medium APPD (3.73 x 10^9 W/m^2, E_P = 7.5 J, T_P = 4 ms), and mean power 363 W.

Table 3 — Summary of the Results from Extensive Experimental Trials

Laser Welding Machine		Lumonics JK 701 Nd:YAG	Maximum Power 400 W		Pulsed Mode
Average peak power density level (W/m^2)		low (2.98×10^9)	lower-medium (3.73×10^9)	Upper-medium (5.47×0^9)	high (7.46×10^9)
Pulsed energy	4 ms	5.9 J	7.5 J	11 J	15 J
	8 ms	11.8 J	15.0 J	22 J	30 J
	12 ms	17.7 J	22.5 J	33 J	45 J
General results		Obviously incomplete penetration even for extremely slow travel speeds (<0.6 mm/s)	Operating window available for travel speeds between 1 and 3 mm/s		Cutting effect even for high travel speeds (>8 mm/s)

2) M2: Galvanneal sheet steel (IZ), 0.7 mm thick with 6.0 μm zinc coating on both sides. The Galvanneal zinc coating is typically 10.8% iron, 0.4% aluminium, with balance around 89% zinc.

The chemical compositions in weight percentage of the steel substrate M1, and M2 are displayed in Table 1. The laser processing parameter set up is shown in Table 2. The key experimental strategy of setting up the pulsed laser processing parameters is to maintain a constant duty cycle and average peak power density, while varying the pulse duration and the pulse energy for consistent comparisons of the experimental results. Before welding, the surfaces of the specimens were cleaned up using acetone solution to remove dirt and oil. The laser beam welding experiments were conducted using 60 x 100-mm zinc-coated steel sheet specimens. The clamping arrangement is crucial as described previously. It has to be ensured there is no joint clearance between the clamped sheets and the weld distortion does not create an opening while welding.

Experimental Results and Discussions

Weldability of Zinc-Coated Steel

The entire experimental results are summarized in Table 3 and show that it is possible to weld lap joints in tightly clamped specimens of zinc-coated steel sheet with a pulsed Nd:YAG laser. Figures 6 and 7 display the typical operating windows resulting in acceptable welds with visually sound appearance, no internal cracks, and no zinc gas blow-holes or pitting on the top surface for the materials M1 and M2, respectively. The reason for the success of welding is due mainly to the venting of the zinc vapor through the keyhole. The venting mechanism for zinc gas has been discussed in the previous section. This is a function of weld pool size vs. overlap or travel speed. The successful venting process is slow, approximately between 1 to 3mm/s, as seen in Table 3, due to the use of low average laser power available in the study.

Effects of Average Peak Power Density on Weldability

Table 3 shows the APPD value greatly affects the results of welds on zinc-coated steel sheet. For ease in controlling the pulsed laser welding process, it may be required to construct the processing map for APPD effects. It can serve as a useful guide for industrial practitioners to effectively execute welding applications.

The processing map in Fig. 8 shows the higher the APPD, the more likely it is that the coated steel sheet vaporizes, leading to cutting. Conversely, the lower the APPD, the more likely the presence of incomplete penetration. It is noted in Fig. 8 the appropriate zone widens with increasing pulse duration. This phenomenon does not imply that the operating window of the travel speed behaves likewise since it involves a more complicated balance of the keyholing effects and the zinc gas blow-out phenomenon at different processing conditions. However, there is not much difference in the operating speeds due to all being slow.

The processing map applies to the two types of zinc-coated steel sheets investigated in the study, as there is not much variation in the coating. As noted in Fig. 8, there are four arbitrarily defined levels of APPD values. They are high, upper-medium, lower-medium and low level. It comprises five different zones each with their own distinctive processing effects. They are discussed below.

Zone A — Cutting effects region, APPD ≥ 7.46 x 10^9 W/m^2, whereby the APPD is higher than that required for the production of sound welds. This results in violent and rapid ejection of molten metal.

Zone B — Appropriate zone, 5.47 x 10^9 W/m^2 ≥ APPD ≥ 3.73 x 10^9 W/m^2, whereby sound welds can be produced by matching the APPD in this region with other suitable mean powers and travel speeds.

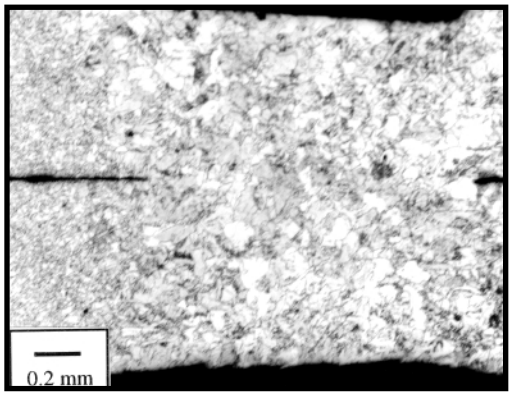


Fig. 11 — Transverse section of a visually acceptable seam weld produced in galvanized steel M1 at 1.8 mm/s using upper-medium APPD (5.47 x 10^9 W/m^2, E_P = 22J, T_P = 8ms), and mean power 363 W.

Zone C — Incomplete penetration region, APPD ≤ 2.98 x 10^9 W/m^2, whereby the APPD is lower than that required for the production of sound welds.

Zone D — Transitional zone, 7.46 x 10^9 W/m^2 ≥ APPD ≥ 5.47 x 10^9 W/m^2, whereby the APPD is close to zone A. A cutting effect tends to result.

Zone E — Transitional zone, 3.73 x 10^9 W/m2 ≥ APPD ≥ 2.98 x 10^9 W/m^2, whereby the APPD is approaching zone C. Incomplete penetration of welds tends to result.

Effects of Mean Power and Travel Speed on Weldability

It was confirmed through experimentation that mean power and travel speed are two other major factors governing the pulsed laser seam welding process besides APPD. It is observed in Fig. 6, at 396 W mean power level, the weld bead quality will reach what is regarded as the

acceptable quality for welding speeds ranging from 1.6 to 2.5 mm/s. Beyond the critical value of 2.5 mm/s, the surface of the weld pool would usually be broken and pittings or holes would be left behind giving rise to the condition termed "zinc gas expulsion." It is due to too low thermal input rate at which keyholing effect is not sufficiently developed, in conjunction with incomplete penetration. As the welding speed is decreased below 1.6 mm/s, serious root concavity and deep slumping appeared on the bottom and the top of the weld bead, respectively. It is however due to a overly high thermal input rate. Hence, for a given mean laser power, a narrow range of welding speeds that will produce acceptable welds prevail. The same explanation applies to the other arranged mean powers of 363, 330 and 297 W.

Effects of Pulsed Duration on Weldability

It is reported that the variations in the pulse duration with constant pulse energy for the spot welding applications result in appreciable effects on the weld dimension and quality (Refs. 21–24). This is due to the alterations in the peak power density. But, for the pulsed laser seam welding application, the effects caused by the changes in the pulse duration are observed to be insignificant on the weldability envelope. It is due mainly to its short range (0.5–20 ms) available from the laser controller and the low mean power (400 W) available. For the seam welds processed by the same mean power and the APPD, the variations in pulse duration eventually changes the pulse repetitive rate (PRR) of power pulses and the resultant heating process dynamics. As such, the increase in pulse duration leads to somewhat faster operating speeds due to stronger heating effects.

Conclusions

The problem with welds in lap joints without a joint clearance in zinc-coated steel sheet being damaged by zinc gas explosion during laser beam welding has been resolved. The use of 400-W Nd:YAG laser operating in pulsed mode has proven to be successful. The target for a better understanding of the related processing parameters affecting total performance of pulsed laser welding process has been achieved. However, compared to work previously done with a CO_2 laser by other researchers, the operating speeds using Nd:YAG laser are found to be lower. This might be improved by using high-power lasers.

The experimental study shows that the operating window for the welding conditions that give smooth weld beads are controlled mainly by the average peak power density, followed by the mean power and the travel speed. Rectangular power pulses always produce good quality welds in lap joints over an operating range of the dominant processing parameters. The operating ranges for the parameters are found to be average peak power density (APPD) between 3.73×10^9 and 5.47×10^9 W/m^2, mean powers between 297 and 396 W, and travel speeds between 1 and 3 mm/s, respectively. The variations in the pulse duration over the operating window did not appreciably affect the seam weld quality except of leading to a small difference in the welding speeds.

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