Toward Process Optimization in Pulsed Nd : YAG Laser Seam Welding of Zinc Coated Steel*

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The study investigates the feasibility of pulsed laser seam welding of zinc coated steel sheets in lap configuration using Lumonics JK 701 Nd : YAG laser. This is a useful and beneficial joining technique for the automotive industry in the assembly lines. Laser seam welds were produced in 0.7 mm thick electro-galvanized steel sheets in the lap-joint configuration with rectangular power pulses. A wide range of process parameters is identified. These includes average peak power density (APPD), mean laser power, traverse speeds, and pulse duration, etc. To optimize the welding process, the effects of these parameters on weld quality are thus systematically investigated. The experimental study suggests that APPD is the most critical factor in governing pulsed laser seam welding application. It is followed by average power and travel speed. As such, the processing map for APPD effects is developed as a guide for effective control and execution of welding application. Accordingly, the pulsed Nd : YAG laser seam welding process can be further optimised by proper choices of APPDs, mean powers, and traverse speeds for producing the best quality welds. That is, welds with no porosity inside the fusion zone.

Key Words: Pulsed Nd : YAG Laser Welding, Lap-Joint Configuration, Electro-Galvanized Steel

1. Introduction

New regulations on cosmetic durability have been agreed and cars must now not show perforation corrosion for 10 years. This can be achieved by using Zn coated steel, plastic coated steel, or very thick paint. Most car manufacturers are opting for Zn coated steel in the lower parts of a car⁽¹⁾. This poses welding problems regardless of the chosen process.

The traditional welding technique for Zn coated steel sheet in lap-joint configuration in the automotive industry is resistance spot welding. As an increasingly important alternative, laser welding offers advantages such as higher operating speed, the usage of smaller overlap material leading to significant weight reduction and a seam weld in place of spots to increase the weld strength. In addition, the simplicity of welding from a single side and the advantage of no direct contact with the workpiece while welding render this

technique all the more desirable. These advantages when used together could reduce the car body weight, manufacturing time and production cost if appropriately integrated in the autobody design and in the production line. As a result, the car performance would be significantly improved, which is the target of automobile manufacturers operating in a competitive international market.

The CO₂ laser is currently the main industrial laser. The main drawback of using this laser to weld Zn coated steel sheet is the need to maintain a small gap between the sheets to be welded to allow Zn gas to blow-out without upsetting the weld bead. Understandably, even with very accurate alignment of the sheets, the gap size would differ. In addition, flexible beam transmission systems for CO₂ lasers require articulated arm optics which are sometimes awkward to insert into a production line. These disadvantages led to the alternative of using a pulsed Nd : YAG laser to undertake the welding of this material.

Compared to CO₂ laser, pulsed Nd : YAG laser possesses a ten times shorter wavelength 1.06 μm , a much higher peak power, and more flexible beam delivery through fibre optics. These advantages ren-

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der it a promising replacement for both the continuous wave CO₂ laser welding and the conventional spot welding. However, the introduction of more variables into the pulsed mode operation, such as the pulse energy, the pulse duration, the pulse repetition rate, and the pulse shaping, etc. inevitably increases the complexity of the pulsed laser welding applications.

Few studies have been reported on the quality of seam welds in Zn coated steel made with pulsed Nd:YAG laser⁽²⁾. Most of these research focused on a non-systematic controlling-parameter investigation of welding process. In the past, good-quality seam welds which require no gaps for gas blow-out were reported as a success by Norris et al.^{(3),(4)} However, the mechanism of Nd:YAG laser seam welding of Zn coated steel sheet has so far been unclarified. This work attempts to not only establish a systematic methodology for pulsed Nd:YAG laser seam welding of zinc coated sheet steel in lap-joint configuration with no gap in between, but also to optimize welding process parameters so as to produce quality lap welds with good surface topography and no porosity.

2. Proposed Welding Mechanism

The basic theory of pulsed laser seam welding of zinc coated steel is based on the following principles:

2.1 Venting theory

A pulsed Nd:YAG laser beam is able to penetrate the workpiece deeper due to its beam characteristics described above. Depending on the processing parameters, the laser can evaporate the substrate to give a good 'keyholing effect'. This means creating a vent which might aid in exhausting the high pressure Zn gas and reducing the risk of explosive ejection of material.

2.2 Overlapping theory

Pulsed Nd:YAG laser seam welding process is essentially a series of periodic spot welds partially overlapping each other to form a seam weld. This is schematically illustrated in Fig.1. The successive overlapping of the power pulses partially refills the preceding fusion zone and thus could effectively reduce pores left in the fusion zone by previous pulses. Therefore, an appropriate partial overlapping percentage of weld spots may be capable of producing a desirable seam weld. In addition, zinc gas can be significantly regulated by periodic power-offs in the pulse trains of the laser beam. As a result, the production of visually sound welds of zinc coated sheet steel theoretically seems highly possible.

3. Design and Control of Pulsed Nd:YAG Laser Parameters

As shown in Fig. 1, the mathematical descriptions

Fig. 1 Schematic diagram of a typical of rectangular laser power pulse trains, and a corresponding series of partially overlapping spot welds with porosity inside

about the output power of the pulsed Nd:YAG laser can be formulated as below:

$$P_M = E_P \times PRR \quad (1)$$

$$= \frac{E_P}{T_P} \times \frac{T_P}{T_F} = P_P \times C_D \quad (2)$$

$$= \frac{E_P}{T_P \times \frac{\pi D^2}{4}} \times \left(\frac{\pi D^2}{4} \right) \times \frac{T_P}{T_F} \quad (3)$$

$$= P_D \times \left(\frac{\pi D^2}{4} \right) \times C_D \quad (4)$$

$$= P_D \times \left(\frac{\pi D^2}{4} \right) \times T_P \times PRR$$

where P_D is the average peak power density (APPD), and D the laser spot diameter.

Equation (1) suggests that for a given laser power P_M , there are various combinations of E_P and PRR and their relationship is inversely proportional. This principle applies to the other relevant mathematical expressions and it indicates the flexibility and the complexity in the selection of pulsed parameters. The question thus arises is how to make a satisfactory selection of the processing parameters which enable efficient and effective pulsed laser welding application.

For pulsed laser seam welding process, more complicated combined processing parameters than CW CO₂ laser welding have to be considered. They are:

1. the average peak power density governing the power intensity during laser-on period:

$$\frac{P_M}{\frac{\pi D^2}{4}} = P_D \left(= \frac{E_P}{T_P \times \frac{\pi D^2}{4}} \right) \times C_D \quad (5)$$

2. the interaction time (T_{IN}):

$$T_{IN} = \frac{D}{V} \times C_D \left(= \frac{T_P}{T_F} \right) \quad (6)$$

3. the average thermal input per unit square of the seam weld (E_{av}):

$$E_{av} = \frac{P_P \times T_P \times PRR}{D \times V} = \frac{P_P \times C_D}{D \times V} = \frac{E_P}{D \times V \times T_F}$$

$$= \frac{P_M}{D \times V} = \frac{P_P \times T_{IN}}{D^2} = (\pi/4) \times P_D \times T_{IN} \quad (7)$$

4. the welds overlapping rate⁽⁵⁾:

$$P_{ER} = \left[1 - \frac{V \times T_F}{W + V \times T_P} \right]$$

$$= \left[1 - \frac{1}{\frac{W \times D \times E_{av}}{E_P} + \frac{T_P}{T_F}} \right]$$

$$= \left[1 - \frac{1}{\frac{W \times D \times E_{av}}{E_P} + C_D} \right]$$

$$= \left[1 - \frac{1}{\frac{W \times T_{IN}}{D \times T_P} + C_D} \right] \quad (8)$$

The Lumonics JK701 Nd:YAG laser machine used in this study has a relatively low mean output power (400 W), as such attention is particularly put in the selection of suitable APPDs for meeting the demand of a high power intensity for seam welding applications. It is suggested to set the laser spot on the focal point for the smallest spot size (about 0.8 mm) for a wider choice of APPDs. The types of shielding gas, its compositions and flow rates are not considered in the design of welding process parameters due to its unappreciable effects on zinc gas exhaustion⁽²⁾.

It is observed in Eqs. (1)–(4) that just controlling the selected levels of three main processing parameters P_M , E_P , and T_P leads to a series of induced dependent parameters (P_D , C_D and PRR) while D is kept constant. P_D is determined simply by selecting proper combination of E_P and T_P on the laser controller for a constant spot size (D).

To produce good welds, there should exist a range of suitable APPD (P_D), coupled with a range of suitable pulse durations (T_P), mean powers (P_M) and travel speeds (V). Once these parameters are adjusted, the pulse energy E_P , the pulse repetition rate PRR , the interaction time (T_{IN}), the average thermal input per unit square of the seam weld (E_{av}), and the welds overlapping percentage (P_{ER}) would be all controlled at the same time.

4. Material and Methods

A Lumonics JK701 Nd:YAG pulsed laser welding machine with a maximum mean laser power of 400 W was used in the experiments. The materials used was electro-galvanized coated steel which is 0.7 mm thick with 7.5 μ m pure Zn coating on both sides. The chemical compositions in weight percentage of the

Table 1 Chemical compositions of steel substrate

Steel substrate	Chemical compositions (%)
Zinc coated steel	C: 0.01, S: 0.008, P: 0.013, Mn: 0.160, Al: 0.036, N ₂ : 0.0027, S: 0.006, Ti: 0.054, Nb < 0.01

Table 2 Parameters set-up for experiments

Pulse shape	Rectangular without a leading-edge power spike at the front of the pulse (see Figure 2).
Laser power : P_M	396, 363, 330, 297 W.
Speed	0.4 $\Rightarrow$ 8 mm/s.
Pulse duration : T_P	4, 8, 12 ms.
Pulse energy : E_P	5.9, 7.5, 11, 15 J for 4ms. 11.8, 15, 22, 30 J for 8ms. 17.7, 22.5, 33, 45 J for 12ms. (This is arranged to keep the duty cycle and average peak power density constant.)
Focal location	Approximately focused on the top surface of the material.
Lens	120 mm focusing lens from Lumonics Ltd. (Borosilicate crown glass)
Spot size : d_s	0.8mm
Shielding gas	Argon gas blowing at constant rate of 20 litres/min at 45 degree onto the leading edge of the focused position.

Table 3 Experimental set-up of the pulsed laser parameters

Average peak power density P_D (W/m ²)	Pulse duration (T_P)									Duty
	4 ms			8 ms			12 ms			
	E_P (J)	PPR (1/s)	P_M (W)	E_P (J)	PPR (1/s)	P_M (W)	E_P (J)	PPR (1/s)	P_M (W)	
2.98×10^9	5.9	67.1	396	11.8	33.6	396	17.7	22.4	396	0.268
	5.9	61.5	363	11.8	30.8	363	17.7	20.5	363	0.246
	5.9	55.9	330	11.8	28.0	330	17.7	18.6	330	0.224
	5.9	50.3	297	11.8	25.2	297	17.7	16.8	297	0.201
	7.5	52.8	396	15.0	26.4	396	22.5	17.6	396	0.211
3.73×10^9	7.5	48.4	363	15.0	24.2	363	22.5	16.1	363	0.194
	7.5	44.0	330	15.0	22.0	330	22.5	14.7	330	0.176
	7.5	39.6	297	15.0	19.8	297	22.5	13.2	297	0.158
	11.0	36.0	396	22.0	18.0	396	33.0	12.0	396	0.144
	11.0	33.0	363	22.0	16.5	363	33.0	11.0	363	0.132
5.47×10^9	11.0	30.0	330	22.0	15.0	330	33.0	10.0	330	0.120
	11.0	27.0	297	22.0	13.5	297	33.0	9.0	297	0.108
	15.0	26.4	396	30.0	13.2	396	45.0	8.8	396	0.106
	15.0	24.2	363	30.0	12.1	363	45.0	8.1	363	0.097
	15.0	22.0	330	30.0	11.0	330	45.0	7.3	330	0.088
7.46×10^9	15.0	19.8	297	30.0	9.9	297	45.0	6.6	297	0.079

Note: E_P : pulse energy, PPR : pulse repetition rate, and P_M : mean power

steel substrate are:

The laser processing parameters set-up are listed 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. For ease of understanding the experimental strategy, the key processing parameters are rearranged in Table 3. It is clearly seen that there are four levels of APPDs and mean powers, eleven levels of pulse energy, three levels of pulse durations, sixteen levels of duty cycles, and forty-three levels of pulse repetition rate.

The laser welding experiments were conducted using 60 $\times$ 100 mm zinc coated steel sheet specimens. The clamping arrangement is crucial. It has to be ensured that there is no gap between the clamped sheets and that the weld distortion does not create a gap while welding. The schematic diagram of the lap-joint arrangement is shown in Fig. 3.

Fig. 2 An example of the real rectangular power pulses

Fig. 3 The weld joint geometry proposed for laser seam welding of coated steel sheet for the material

5. Results and Discussions

5.1 Weldability of zinc coated steel

Acceptable quality laser beam welds were produced in the electro-galvanised sheet steels when there was no gap between the two sheets of the lap-joint. The entire detailed results are presented in Figs. 5 and 6. This usually could not be accomplished using CW CO₂ lasers unless a gap is left between the sheets. The successful welding is due mainly to the efficient venting of the Zn vapor through the keyhole. It is because that in this work the sheets are tightly clamped and thus the only route for exhausting the Zn vapor is through the weld pool along with the vapor of iron formed in the keyhole.

5.2 Effects of the key processing parameters on weldability

APPD value is observed to be the most sensitive parameter governing the quality of the welds due to its essential control of the weld formation on a single spot. Small variations in APPD value leads to significant changes in welding results. For effective and efficient governing of pulsed laser seam welding application, the processing map on APPD effects is constructed. The duty cycle effects are included into the map as well because of its close interaction with APPD. The processing map for the combined effects of APPD and duty cycle is shown in Fig. 4.

As shown in Fig. 4, two groups of APPD values, one for the lower-medium level (7.5 J for 4 ms, 15 J

Fig. 4 The processing map showing the effects of the pulse energy, the pulse duration setting, the duty cycle, and the APPD on the welds of Nd:YAG pulsed laser processing

for 8 ms, 22.5 J for 12 ms) and the other for the upper-medium level (11 J for 4 ms, 22 J for 8 ms, 33 J for 12 ms) are found to be the bounds of the operating region of APPD for the production of satisfactory welds. Coupled with a constant spot size 0.8 mm, the operating range of APPD is calculated to be within 3.73×10^9 to 5.47×10^9 W/m². The effects of the above key parameters on weldability are illustrated in the processing map, Fig. 4. Three major regions dependent upon the APPD setting were identified in the welding of zinc coated steel:

1. Cutting effects region, whereby the APPD is higher than that required for the production of sound welds. This results in violent and rapid ejection of molten metal.
2. Appropriate zone, whereby sound welds can be produced by matching the APPD in this region with other suitable mean powers and travel speeds.
3. Incomplete penetration region, whereby the APPD is lower than that required for the production of sound welds.

In Fig. 4, for a given mean laser power of 396 W and focal spot size of 0.8 mm, the appropriate zone for production of acceptable weld quality by pulsed laser welding is between the duty cycles 14.4% and 21.1%. As the duty cycle is decreased beyond 10.6%, most of the material from the surface of the weld is rejected instantly which results in a cutting effect. However, if it is increased further beyond 26.8%, insufficient average peak power density can easily lead to incomplete penetration of the weld. Such a trend is observed in other values of mean laser power; i.e. 297, 330, and 363 W.

As for other less crucial parameters, acceptable

Fig. 5 A typical pulsed laser weldability envelope for producing varied quality welds at $\text{APPD}=3.73 \times 10^9 \text{ W/m}^2$ ($T_p=4 \text{ ms}$, $E_p=7.5 \text{ J}$, and $D=0.8 \text{ mm}$).

traverse speeds are found to be within 1 mm/s to 3 mm/s, mean power approximately from 297 to 396 W for 1.4 mm lap-joint coated steel sheets. The entire weldability envelopes containing the effects of the various processing conditions are presented in Figs. 5 and 6.

5.3 Operating window pattern

The weldability envelope of the operating window shown in Fig. 5 is part of the results for the case of $\text{APPD}=3.73 \times 10^9 \text{ W/m}^2$, $T_p=4 \text{ ms}$ and $E_p=7.5 \text{ J}$. The common unacceptable defects beyond the low bound of travel speeds are serious root concavity and deep slumping on the top. The cause is strong metal vapor venting effect including zinc gas explosion blowing away the molten material through both end of the molten pool. An additional defect for travel speeds above the higher bound is incomplete penetration of welds accompanied by possible blow-holes and pittings on the top surface. This is a result of low thermal input leading to insufficient 'keyholing' effect.

As seen in Fig. 5, 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

mm/s to 2.2 mm/s. Beyond the critical value of 2.2 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'. Incomplete penetration appears as well. As the welding speed is decreased below 1 mm/s, serious root concavity and deep slumping appear on the top of the weld bead. Hence, for a given mean laser power, a range of welding speeds that will produce acceptable welds prevails. The same explanation applies to the other arranged mean powers of 297, 330, and 363 W.

5.4 Effects of key processing parameters on operating window

5.4.1 Effects of mean power and travel speed

It is observed in Figs. 5, 6 that mean power and travel speed are other dominant factors governing the pulsed laser seam welding process, aside from the peak power density. The ratio of the mean power to travel speed controls the average thermal input per unit square of the weld. Combinations of the APPD, the mean power and the travel speeds govern the interaction time and the overlapping of spot welds.

Low mean power certainly leads to low operating speeds. The low ratio is also inclined to generate unstable and insufficient 'keyholing' effect for the exhaustion of zinc gas which may cause the damage of the weld topography. Therefore, low mean power produces a narrow range of suitable welding speeds. From the experimental results, it is seen that for mean powers less than 297 W, the production of acceptable seam welds is difficult.

5.4.2 Effects of APPD

It is observed that high APPD speeds up the pulsed laser welding process because of stronger heat flow and thus results in an operating region of higher travel speeds. However, the high APPD also produces more powerful thermal and hydrodynamic effects within the molten pool bringing about a strong Zn gas expulsion. Moreover, it elevates the risk in toppling the force equilibrium within the keyhole. In other words, the shear stresses induced by ablated materials increase, so would the recoil pressure and also, to a lesser extent, the hydrostatic head. The surface tension of the pool would also be lowered if the surface temperature is high. As a result, the weld bead profile and root concavity is more likely to be damaged by the substantial loss of molten metal by stronger zinc gas exhaustion through both ends of the keyhole. These factors eventually contribute to the narrowing of the entire operating window.

It is noticed that there is a significant shrinkage in the operating window for the highest pulse energy at upper-medium APPD (33 J). This is the result of the combination of a high APPD and the longest laser-on

Fig. 6 Pulsed laser weldability envelopes for producing varied quality welds at

- (a) $APPD = 3.73 \times 10^9 \text{ W/m}^2$ ($T_P = 8 \text{ ms}$, $E_P = 15 \text{ J}$),
- (b) $APPD = 3.73 \times 10^9 \text{ W/m}^2$ ($T_P = 12 \text{ ms}$, $E_P = 22.5 \text{ J}$),
- (c) $APPD = 5.47 \times 10^9 \text{ W/m}^2$ ($T_P = 4 \text{ ms}$, $E_P = 11 \text{ J}$),
- (d) $APPD = 5.47 \times 10^9 \text{ W/m}^2$ ($T_P = 8 \text{ ms}$, $E_P = 15 \text{ J}$),
- (e) $APPD = 5.47 \times 10^9 \text{ W/m}^2$ ($T_P = 12 \text{ ms}$, $E_P = 33 \text{ J}$).

period which imposes the highest vapor pressure within the keyhole. Thus, the operating region of welding speed is understandably reduced. It can thus be concluded that each power pulse at lower-medium APPD setting has a larger operating window than at upper-medium level.

5.4.3 Effects of pulse duration It is observed that as the pulse duration is increased from 4 ms up to 8 ms with a constant APPD level, the entire operating window generally tends to yield a higher range of welding speeds, except for low mean power. This result is due to increased heating time from the longer pulse duration which then allows full penetration at higher speed. The same observation applies for increasing pulse duration of 8 ms to 12 ms and when shifting from lower-medium to the upper-medium APPD. As pulse duration is inversely proportional to pulse repetition rate (PRR) for a given mean power and APPD, the maximum welding speeds rise with the reduction in PRR due to an increase in pulse duration.

It is worth remembering that the size of the acceptable zone can be taken as a measure of the weldability of a material. A large zone indicates a greater tolerance to changes in production conditions and vice versa. The size of the operating window decreases with increasing pulse duration whereby the smallest is produced by 12 ms and the biggest by 4 ms. The observation here suggests that the effects of pulse duration on operating windows are closely associated with the balance between the keyhole effect and the vapor production within the molten pool. It is thought that the pulse duration 12 ms is capable of venting Zn gas and metal vapor most efficiently at higher welding speeds due to better keyhole effect caused by prolonged heating. However, at lower travel speeds more vapor is produced which has adverse effects such as weld top slumping and weld root concavity. The narrowing of the welding operating window is therefore expected. This observation is clearer at higher APPD because of its relatively more heat energy input during heating time.

5.4.4 Optimization zone The problems with CO₂ laser welding of zinc coated steel sheets has been fully resolved by the proposed welding mechanism and strategy for control of key process parameters using Nd:YAG laser. The Nd:YAG laser has been effectively applied at optimal welding conditions. It is noted in Figs. 5, 6 that there exists a small zone within each operating windows in which acceptable welds are produced without any defects such as the surface faults of deep slumping and blow-holes, and porosity inside the fusion zone. The 'no porosity' zone in the operating window can be therefore regarded as the optimal choice of the parametric settings for defined

welding process.

In the study, the experimental results show that the combinations of APPD, pulse duration, and mean power have profound effects on optimization zone. It is observed that for a given mean power, longer pulse duration gives a smaller area of optimal welding parameters. It is due to that the lower pulse repetition rate, the less likely the pores within the fusion zone are eliminated by the refilling of successive laser power pulses. The same finding applies to those with an increase in APPD. Pulse duration 4 ms at a lower-medium APPD ($T_P=4$ ms, $E_P=7.5$ J, and $D=0.8$ mm) hence produces the largest size of the optimization zone and the smallest is by 12 ms at upper-medium APPD ($T_P=12$ ms, $E_P=33$ J, and $D=0.8$ mm).

5.4.5 Toward optimization in process parameters To produce quality welds without defects, there is a need not only to optimize the main laser processing parameters, but also to have a large optimization zone during the welding process. The experimental study suggests that it can be made simply by proper selection of APPD, pulse duration (T_P). Pulse duration 4 ms at a lower-medium APPD ($T_P=4$ ms, $E_P=7.5$ J, and $D=0.8$ mm) is the best choice toward optimization in process parameters for the pulsed Nd:YAG laser welding. Figure 5 shows that 'no porosity lap welds' can be made for the operating speeds of 1 mm/s to 1.5 mm/s at the mean power of 396 W level. It is also available from 1 mm/s to 1.3 mm/s for 363 W, and 1 mm/s for 330 W.

6. Conclusions

The proposed simple and yet useful mechanism which accounts for pulsed Nd:YAG laser seam welding process has been shown. Proper control of the weld production on electro-galvanized coated sheet steels were possible. It is recognized that the operating window of the welding conditions that give smooth weld beads are controlled mainly by the average peak power density, followed by the mean power, the travel speed, and the pulse duration.

The processing map for determining proper zones of average peak power density (APPD) is developed to optimize the welding process. It offers an useful guide for effective control of pulsed Nd:YAG laser seam welding application. Good quality lap welds with no gap between the sheets are made consistently and easily by rectangular power pulses over an operating range of the key welding conditions. The optimal process parameters' values for producing 'no porosity' welds are achieved by further careful selection of APPDs, pulse durations, mean powers, and traverse speeds in the operating window.

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