

Experimental Investigation of Laser Welding Process in Overlap Joint Configuration

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Abstract

This paper presents an experimental investigation of laser overlap welding of low carbon galvanized steel. Based on a structured experimental design using the Taguchi method, the investigation is focused on the evaluation of various laser welding parameters effects on the welds quality. Welding experiments are conducted using a 3 kW Nd:YAG laser source. The selected laser welding parameters (laser power, welding speed, laser fiber diameter, gap between sheets and sheets thickness) are combined and used to evaluate the variation of three geometrical characteristics of the weld (penetration depth, bead width at the surface and bead width at the interface). Various improved statistical tools are used to analyze the effects of welding parameters on the variation of the weld quality and to identify the possible relationship between these parameters and the geometrical characteristics of the weld. The results reveal that the reached hardness values are similar for all the experimental tests and all welding parameters are relevant to the weld quality with a relative predominance of laser power and welding speed. The effect of the gap is relatively limited. The investigation results reveal also that there are many options to consider for building an efficient welds quality prediction model. Results achieved using an artificial neural network based simplified model provide an indication of the prediction model performances.

Keywords

Laser Welding, Nd:YAG Laser Source, Low Carbon Galvanized Steel, Taguchi Method, Overlap Welding

1. Introduction

Laser welding is more and more gaining place against resistance spot welding, which is considered as the most popular joining process in the automotive in-

dustry for several decades. This transition is due to many advantages of laser welding such as low heat input, high energy density, small heat affected zone, fast welding and deep penetration as well as esthetic weld seams. Sheets with different alloys, shapes, thicknesses or material properties can be welded using laser. However, to improve the corrosion resistance of the vehicle parts in automotive industry, various coatings alternative can be considered. Among these techniques, zinc surface coating is the most popular [1]. Due to the low boiling temperature of the zinc (1180 K) compared to the fusion temperature of steel (1808 K), the laser welding process of galvanized steel in the overlap configuration exhibits instabilities. This is caused by the premature vaporization of the zinc coating at the sheets interface generating a high pressures ranging from 50 to 100 bars at temperatures varying from 1800 to 2000 K [2]. The pressurized vapors disturb the welding process by ejecting the molten metal outside the melt pool, and zinc vapors can be trapped in the weld after solidification, as blowers and spatters [3].

Various studies are conducted for understanding the chaotic behavior of the zinc during laser welding process. Fabro *et al.* [2] reported that zinc vapors flow first into the keyhole and then expand rapidly in the volume of the molten metal, creating a jet of gas that disrupts the molten flow. A study of the dynamics of the liquid zinc flow between the overlapped sheets during laser welding process, suggests that the zinc moves away from the fusion zone when metal is liquid and moves back to the weld pool after solidification [4]. Norman *et al.* described three modes of defects evolution during welding and presented the main causes of various defects types [5] [6].

Many approaches are proposed to overcome the zinc related problems and improve the weld joint quality. Providing a gap between the sheets allows a lateral escape of zinc vapors without affecting the weld pool. Therefore, the selection of optimal gap can lead to defect free welds [7]. In contrast, an inappropriate gap reduces the weld quality. In fact, a very small gap is not sufficient to release the vapor, while a large one does not allow the fusion of the two parts to be welded together [8]. A study of the laser overlap welding process behavior of galvanized steels reported that a gap ranging from 0.04 to 0.15 produces high strength and homogenous welds [9]. To produce acceptable welds, Akhter *et al.* [10] proposed a simplified model illustrated by equation below to estimate the size of the required gap from the volume of the zinc vapor to be exhausted. However, the difficulty to maintain a constant gap along the weld line remains unresolved.

$$g = kv t_{zn} t_p^{1/2}$$

where, g is the gap, k is material constant, t_{zn} is the zinc coating thickness and t_p is sheet thickness and v is the welding speed.

Several other methods, using additional elements that can interact with zinc before its evaporation, such as copper or aluminum have been tested [11]. Although these elements contributed to the stability of the laser welding process,

some of the added elements affected negatively the mechanical properties of the weld. Mechanical removal of the zinc coating layer before welding leads to a good weld quality while losing the resistance to corrosion [11]. Furthermore, those methods require additional production costs or added manufacturing steps for an industrial scale generalization.

Several experimental studies are conducted to evaluate the weld quality in a nondestructive manner [12] [13] [14] [15] [16]. Sinha *et al.* investigated the relationship between the variation in weld bead width, measured at the top surface of the lap welded joint, and the mechanical properties of the weld bead, as well as the effects of the gap and other welding parameters on this variation [12]. This study reported that a wide width variation reflects a poor quality of the weld. Zhao *et al.* conducted an experimental study in order to evaluate the effects of laser welding parameters on the weld bead geometry in the overlap configuration of thin-gauge galvanized steels by using response surface methodology [13]. It was demonstrated that an optimal combination of these parameters increases the aspect ratio of the weld joint by 30%. Wei *et al.* reported that the increase in laser power makes it possible to switch from the conduction welding mode to the keyhole mode [14]. Consequently, the keyhole mode can be considered as a degassing channel, but the deal lies in the stability of the keyhole during the welding process. Elongating the keyhole in order to facilitate the zinc vapor escape can be achieved by defocusing the laser beam, by tilting it, or by using multiple laser spots [15]. Fabro reported that an elongated keyhole improves weld quality with CO₂ laser beam but not with Nd:YAG laser source [2]. A fast frequency modulation of laser power allows partial reduction of zinc-related defects during lap welding of galvanized steels [15]. Using an optimum speed-power combination, Pieters and Richardson reveal that defect free welds can be achieved in overlap configuration without gap or special manipulation technique. This is possible only with full penetration mode [16].

Based on these remarks, it is obvious that a good quality welds during overlap laser welding of galvanized steels depends on the adjustment of the laser parameters and the size of the gap between the sheets. A structured experimental design combined to improved statistical analysis tools can provide a deep understanding of the effects of laser parameters, welding conditions and their interactions on the variation of the geometrical and mechanical characteristics of the welded joints and can conduct to efficient and robust model for predicting the welds quality. This paper presents an experimental investigation of overlap laser welding of zinc coated low carbon steel. Based on a structured experimental design, the investigation is focused on the evaluation of the effects of various laser welding parameters and conditions on the variation of the geometrical and mechanical characteristics of the weld quality.

2. Experimentation

2.1. Parameter Identification

The experimental investigations are conducted using ASTM A635CS galvanized

steel with A40 coating type. Three sheet thicknesses varying from 0.8 to 3.6 mm are selected for the experimentations to conform to the thickness range commonly used in the automotive industry. The sheet specimens having 1, 2 and 3 mm thickness are cut using hydraulic shear at the size of 30×50 mm. The sheets are then superimposed two by two to perform the laser overlap welding. **Table 1** illustrates the chemical compositions of the used sheets provided by the steel manufacturer. Note that the very small variations in chemical composition are neglected.

Laser power (P), welding speed (S), laser spot diameter (D) and Gap (G) are the considered parameters in this experimental investigation. The upper and lower limits of these parameters are set using some results from the conducted preliminary tests and others relevant information extracted from the related literature.

2.2. Experimental Setup

The experimental investigation is carried out using a welding laser cell composed of a FANUC M-710iC six-axis robot, directing a laser beam coming from a HIGHYAG BIMO laser head powered by an IPG YLS-3000-ST2 fiber laser source. The laser power is transferred through an optical fiber with a diameter of $200 \mu\text{m}$. The maximum power that can be emitted by the Nd:YAG laser source is 3 KW with a wavelength of 1070 nm. The laser head is equipped with a variable-zoom collimator and a fixed focusing lens. The collimator adjustment provide, circular focal spots with a diameter ranging from 340 to $520 \mu\text{m}$, for a focal length of 300 mm. **Figure 1** shows the used laser welding setup for the experimentations.

Table 1. Chemical composition of the used material.

| Sheet thicknesses | C | Mn | P | S | Si | Cu | Ni | Cr | Al | N |
|-------------------|------|------|-------|-------|-------|-------|-------|-------|-------|--------|
| 3 mm sheet | 0.04 | 0.19 | 0.005 | 0.002 | 0.01 | 0.01 | 0.02 | 0.009 | 0.038 | 0.0039 |
| 2 mm sheet | 0.09 | 0.35 | 0.005 | 0.01 | 0.02 | 0.05 | 0.04 | 0.06 | 0.03 | 0.0029 |
| 1 mm sheet | 0.05 | 0.24 | 0.009 | 0.013 | 0.007 | 0.029 | 0.012 | 0.037 | 0.04 | 0.0024 |



Figure 1. Laser overlap welding setup.

After welding, the samples are processed following a standard metallography procedure: 1) cutting assemblies perpendicular to the weld to obtain the desired cross section, 2) specimens preparation for microscopic observation including grinding polishing, etching and finally 3) microscopic observation using a Clemex MMT Type A microscope. The microscope is equipped with contour identification programme permitting the evaluation of the weld geometrical attribute in the cross section.

As defined in **Figure 2**, the measured weld dimensions are the depth of penetration (*DOP*), bead width at the surface (*WS*) and bead width at the interface (*WI*). Each measurement was taken three times and then averaged to constitute the database used for the statistical analysis. Vickers micro-hardness testing is also conducted using a load of 500 g and a dwell time of 15 s. The base material measurements are taken far from the fusion zone.

2.3. Preliminary Tests

Due to the anticipated difficulties related to the zinc vapors present at the interface of the parts during overlap welding of galvanized steels, preliminary tests are carried out in order to define the range of variation of the gap to achieve welds with a good visual appearance and to set the upper and lower limits of laser welding parameters to reach depths exceeding the interface without breaking down the bottom sheet. By varying one parameter at a time, the combination of maximum power-minimum speed-minimum diameter produces the maximum deep-seam weld (3 mm), while the reverse combination produces a weld at the minimum depth (1 mm), so the min/max limits for each of the settings are obtained; *i.e.* 2000/3000 W for the power, 40/70 mm/s for the speed and 300/490 μm for the diameter. It is also found that welds with acceptable visual aspect are obtained with gap ranging from 0.05 mm to 0.15 mm.

2.4. Design of Experiments

Factorial designs are the simplest experimental designs to use. They provide the maximum data on the process to be studied. However, the number of necessary tests grows exponentially as soon as an additional factor or level are introduced to the design, making the experience more expensive and more time consuming. However, fractional plans achieve fewer tests and allow a very good ratio between

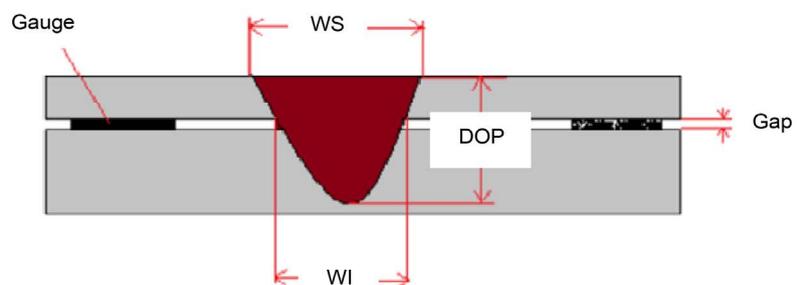


Figure 2. Geometric characteristics of weld cross section in overlap configuration.

experimental cost and generated data. For this reason, an experimental design is established according to the Taguchi method. An L_9 matrix consisting of 3 factors at three levels aims to examine the impact of the selected laser welding parameters on the geometrical characteristics of the weld cross section. The choice of three levels for each factor is proposed in order to study the linearity of factors effects on the weld geometry characteristics. Laser parameter levels are identified in **Table 2** and the experimental design is presented in **Table 3**.

To understand the effect of the interface and that of the gap size on the variation of the shape and the dimensions of the weld, two experimental variants are suggested to conduct the proposed designs. The first variant consist to use the 3 mm thickness sheet alone by passing the laser beam along the sheet surface in order to evaluate the size of the melted zone without any joining. This variant constitutes the first L_9 design. The second variant consists to replace the 3 mm thick sheet by two superimposed sheets of 1 mm and 2 mm thicknesses respectively and reproduce the same experimental design, but this time for performing overlapping welds. This experimental variant is reproduced three times using three gap values (0.05 mm, 0.1 mm and 0.15 mm). For that, gauges of different thicknesses are interposed between the sheets to form a gap allowing lateral evacuation of the zinc vapors present at the interface. The zinc vapors are known to have disruptive effects on the overlap welding process of galvanized steels. Therefore, three based gap L_9 matrices are used.

2.5. Repeatability Tests

In order to establish a measurement quality reference, 8 repeatability tests are

Table 2. Factor and levels for the experiments.

| Factor | Level 1 | Level 2 | Level 3 |
|----------------------------------|---------|---------|---------|
| Power (W) | 2000 | 2500 | 3000 |
| Welding speed (mm/s) | 40 | 55 | 70 |
| Focal diameter (μm) | 300 | 395 | 490 |

Table 3. L_9 design of experiments.

| Tests | Power (W) | Speed (mm/s) | Spot diameter (μm) |
|-------|-----------|--------------|---------------------------------|
| 1 | 2000 | 40 | 300 |
| 2 | 2000 | 55 | 395 |
| 3 | 2000 | 70 | 490 |
| 4 | 2500 | 40 | 395 |
| 5 | 2500 | 55 | 490 |
| 6 | 2500 | 70 | 300 |
| 7 | 3000 | 40 | 490 |
| 8 | 3000 | 55 | 300 |
| 9 | 3000 | 70 | 395 |

done using the median values used in the experimental design (2500 W for power, 55 mm/s for speed, 395 μm diameter and 0.1 mm for gap). To estimate the total measurement error due to the uncontrolled factors, such as maintaining a constant gap along the welding line, applying the same conditions during welding, an average of the quality attributes, standard deviations and relative errors are estimated. The results summarized in **Table 4** present a very good repeatability. The variations are less than 10%. These results ensure the measurement method validity and prepare for the experimentation phase with confidence.

3. Results and Discussion

3.1. Evaluation of the Laser Parameter Effects

Globally, the produced welds present acceptable visual characteristics, nevertheless some discontinuities of the welds and some projections of the metal observed in the case of certain samples representing experiments with 0.05 mm gap. **Figure 3** presents typical welds achieved using $P = 3000$ W, $S = 70$ mm/s, $D = 395$ mm and $G = 0.05$ mm.

The experimental data are analyzed using three statistical tools: the graph of the average effect for each factor, the percent contribution of factors extracted

Table 4. Repeatability test results.

| Quality attributes | $DOP(\mu\text{m})$ | $WS(\mu\text{m})$ | $WT(\mu\text{m})$ |
|--------------------|--------------------|-------------------|-------------------|
| Max | 1341 | 1336 | 1288 |
| Min | 1317 | 1209 | 1254 |
| Mean | 1329 | 1248 | 1269.5 |
| Std-deviation | 7.76 | 43.74 | 11.94 |
| Relative error | 1.8% | 10% | 2.7% |

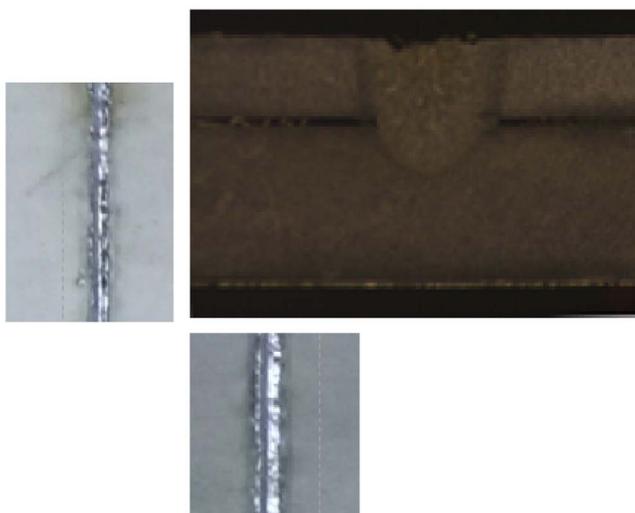


Figure 3. Typical cross section shape of overlap welded galvanized sheets.

from the analysis of variance (ANOVA) and the correlation between various weld characteristics and laser parameters. The percent contribution of a factor reflects the portion of the total variation observed in the experiment that is attributed to that factor. Ideally, the total percent contribution of all considered factors must add up to 100. Any difference from 100 represents the contribution of other uncontrolled factors and experimental errors. As the experiments are designed using an OA, the estimates of the average effect of a given factor on various responses will not be biased.

The experimental results extracted from the 3 designs related to the overlap laser welding with a gap, respectively of 0.05, 0.1 and 0.15 mm are averaged in an L_9 Taguchi design, and then analyzed using the three statistical tools: graph of effects percent contribution and correlation between geometric characteristics of the welds and laser welding parameters. ANOVA results in **Table 5** and graphs of average effects in **Figure 4** show that the laser power has positive effect on the variation of the weld characteristics. This effect is almost linear on *DOP* and *WS* and non-linear on *WI*. The contribution of the power in *WS* variation is 50% against 40% in *WI* variation and 14% for *DOP*. A nonlinear and significant negative effect of the welding speed on the variation of the three studied weld properties is observed. The speed contribution in *DOP* variation is 71%, against 37% for *WS* and 40% for *WI*. The effect of the laser spot diameter is not very important with negative effect on *DOP* variation and a contribution of 13%. The laser spot diameter contribution in *WS* variation is 12%. Its effect on *WI* variation is positive for small diameters and negative for large diameters with 13% of contribution.

The previous observations are confirmed by the correlations analysis between geometrical attributes of the weld and laser welding parameters presented in **Table 6**. A very significant correlation between the welding speed and the different characteristics of the weld is observed. The focal diameter presents a weak

Table 5. ANOVA of averaged weld dimensions results.

| Source | <i>DOP</i> | | <i>WS</i> | | <i>WI</i> | |
|----------|------------|----------------|-----------|----------------|-----------|----------------|
| | F-value | Contribution % | F-value | Contribution % | F-value | Contribution % |
| Power | 5.76 | 13.88 | 131.01 | 50.23 | 7.25 | 39.34 |
| Speed | 29.80 | 71.72 | 97.2 | 37.26 | 7.45 | 40.45 |
| Diameter | 4.98 | 12 | 31.63 | 12.12 | 2.73 | 14.79 |
| Error | | 2.41 | | 0.38 | | 5.43 |

Table 6. Coefficient of correlation between laser parameters and weld dimensions.

| Correlation (%) | Power | Speed | Diameter | <i>DOP</i> | <i>WS</i> | <i>WI</i> |
|-----------------|-------|-------|----------|------------|-----------|-----------|
| <i>DOP</i> | 37 | 82 | 20 | 100 | - | - |
| <i>WS</i> | 70 | 60 | 26 | 65 | 100 | - |
| <i>WI</i> | 57 | 62 | 29 | 78 | 72 | 100 |

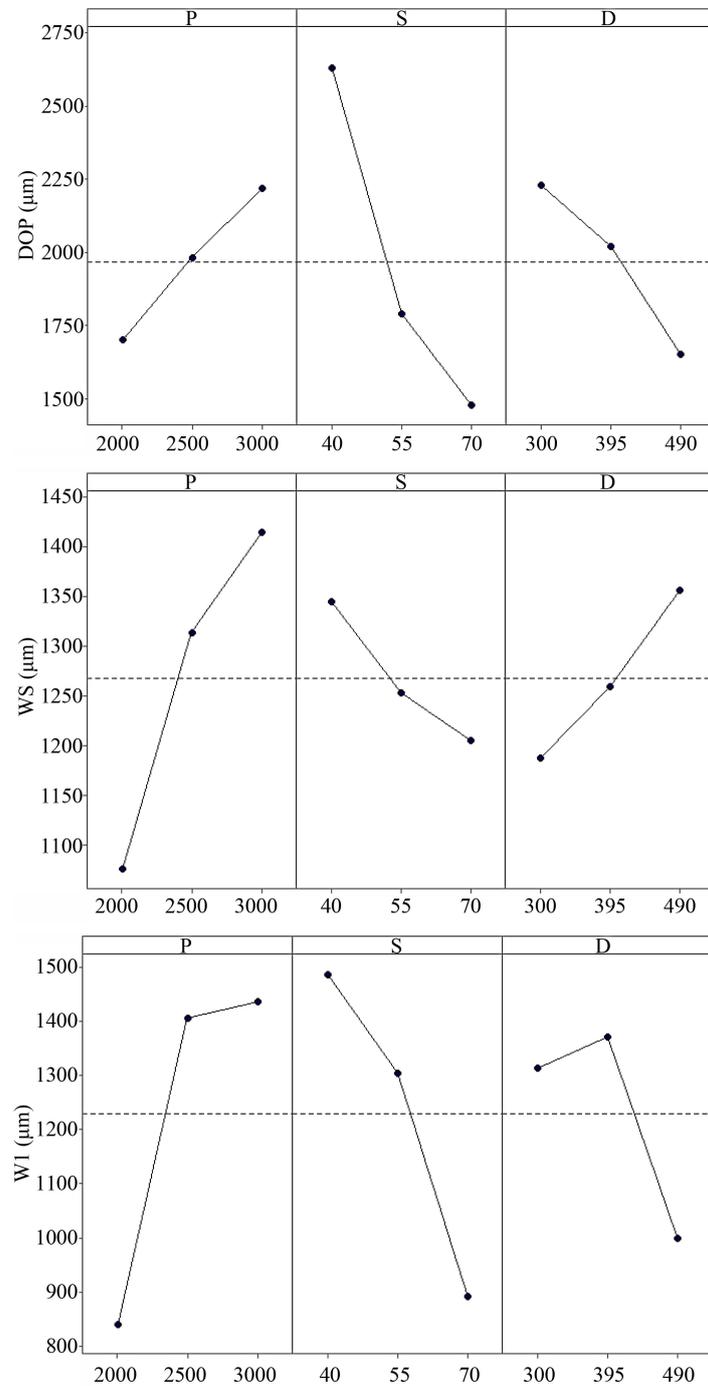


Figure 4. Graph of average effects of laser welding parameters on weld dimensions.

correlation with weld dimensions with correlation coefficients less than 30%. Laser power is strongly correlated with the *WS*. As expected, strong correlations are observed between different weld characteristics.

3.2. Evaluation of the Gap Effects

An L_{27} orthogonal array using four three-level factors is formed from three L_9

blocks to allow the integration of the gap factor into an extended design. ANOVA results in **Table 7** and graphs of average effects in **Figure 5** show a relatively limited effect of the gap on the variation of different weld geometrical characteristics. The maximum contribution of the gap is observed on *DOP* variation by 7.3%.

Figures 6-8 present the effects of the interface and the gap size on the contributions of the laser welding parameters (power, speed and diameter) in the variation of the weld geometrical characteristics. These values are extracted by comparing the results obtained from the four designs for understanding the effects of the interface and the gap size on the weld quality. In these figures, it can be observed that the presence of the interface does not affect the percentage of contribution of laser power in the variation of weld dimensions, but a small gap considerably reduces the contribution of laser power in *WI* variation, and a wide gap decreases the contribution of laser power in *DOP* variation. The presence of the interface increases drastically the contribution of the welding speed on *WS* and *WI* variations, whereas the contribution in *DOP* variation is slightly affected. The contribution of speed in the variation of the weld dimensions is almost insensitive to the size of the gap. The contribution of the focal diameter in *DOP* variation is also insensitive to the interface and the gap size, while its contribution in *WS* variation is negatively affected by the presence of the interface and by the gap size. The percentage of contribution of laser spot diameter in *WI* variation increases considerably in the presence of the interface and decreases by increasing the gap size.

3.3. Micro Hardness

Figure 9 shows the hardness profile in the penetration direction of the weld. The hardness test shows coherent results with an increase in the weld hardness from 150 Hv (hardness of base metal) to 250 Hv (hardness recorded on the cross section of the weld bead).

3.4. Simplified ANN Prediction Model for Weld Dimensions

The laser welding parameters that have important effects on weld quality variation are identified. Weld characteristics exhibit a complex and nonlinear relationship with specific parameters. To be able to implement an effective prediction

Table 7. Results of ANOVA performed on the L_{27} blocked design.

| Source | <i>DOP</i> | | <i>WS</i> | | <i>WI</i> | |
|----------|------------|----------------|-----------|----------------|-----------|----------------|
| | F-value | Contribution % | F-value | Contribution % | F-value | Contribution % |
| Power | 5.76 | 13.02 | 226.70 | 46.98 | 40.43 | 37.35 |
| Speed | 29.80 | 67.28 | 168.18 | 34.85 | 41.47 | 38.40 |
| Diameter | 4.98 | 11.25 | 31.63 | 11.34 | 15.17 | 14.04 |
| Gap | 7.38 | 3.81 | 23.54 | 4.96 | 2.02 | 1.87 |
| Error | | 4.64 | | 1.87 | | 8.33 |

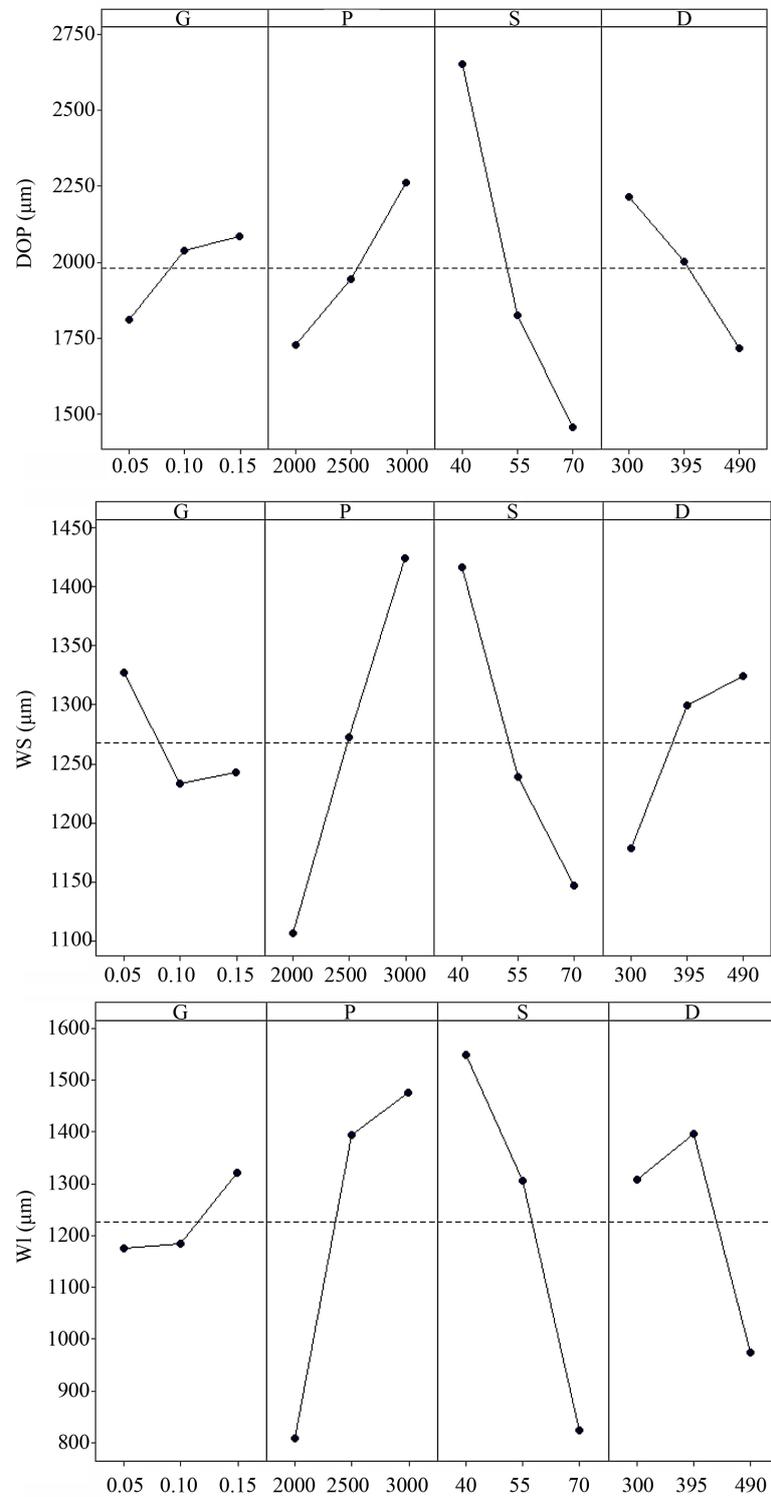


Figure 5. Graph of average effects of laser welding parameters including gap.

approach, it is necessary to develop an efficient and robust model. Although several techniques can be used to produce such a model, artificial neural networks (ANN) have been proven to be an effective tool for this type of applications [17] [18]. Thus, ANN is chosen in this study for an illustrative example of

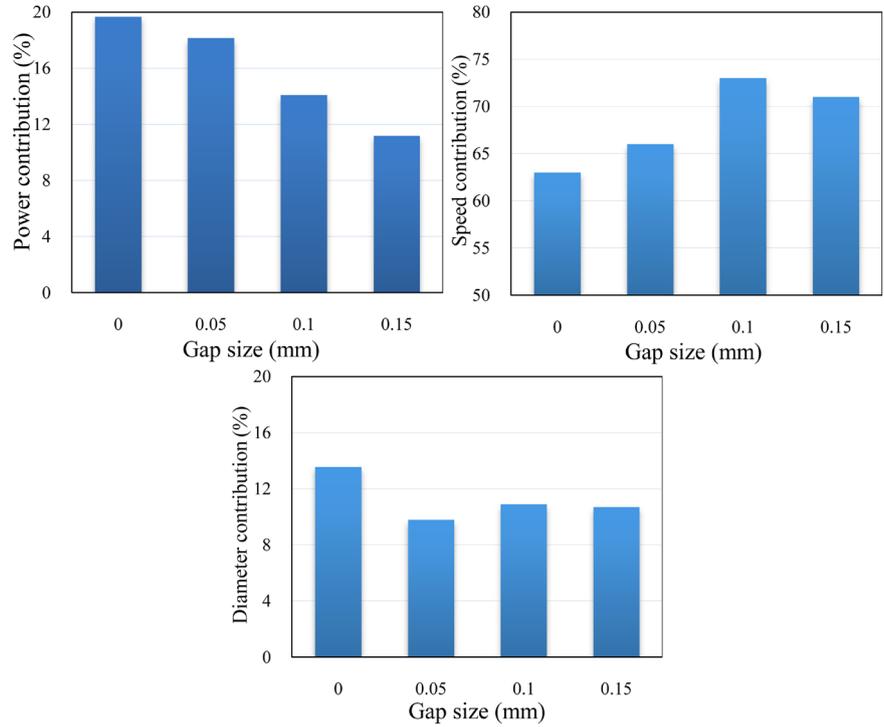


Figure 6. Percentage contribution of laser welding parameters in *DOP* variation.

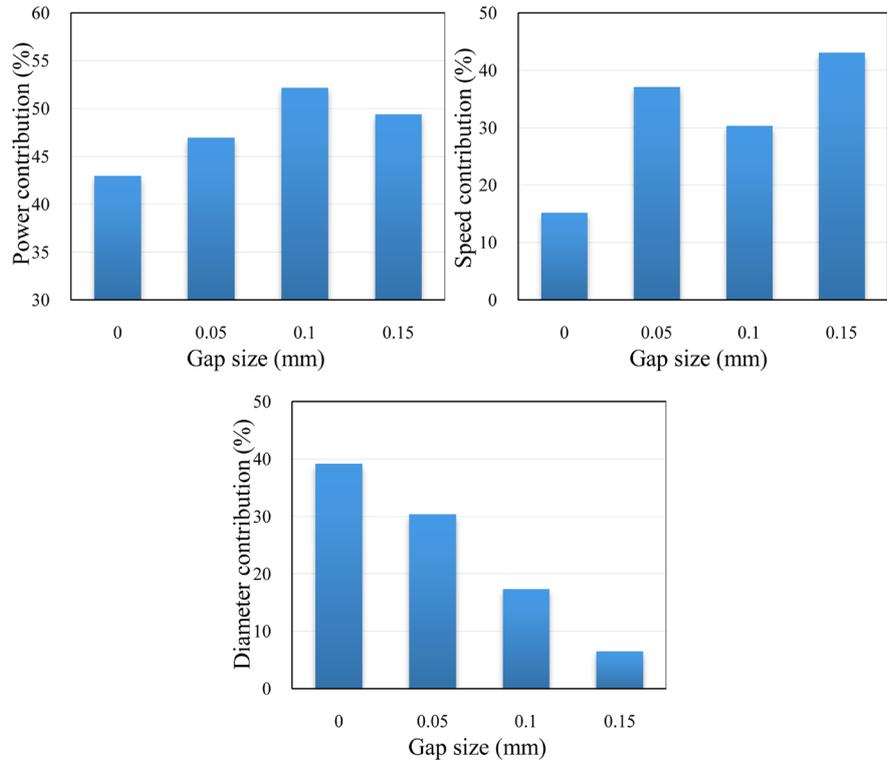


Figure 7. Percentage contribution of laser welding parameters in *WS* variation.

weld dimensions prediction model. The experimental data from the three L_9 design is used to train the ANN based prediction model. The experimentation

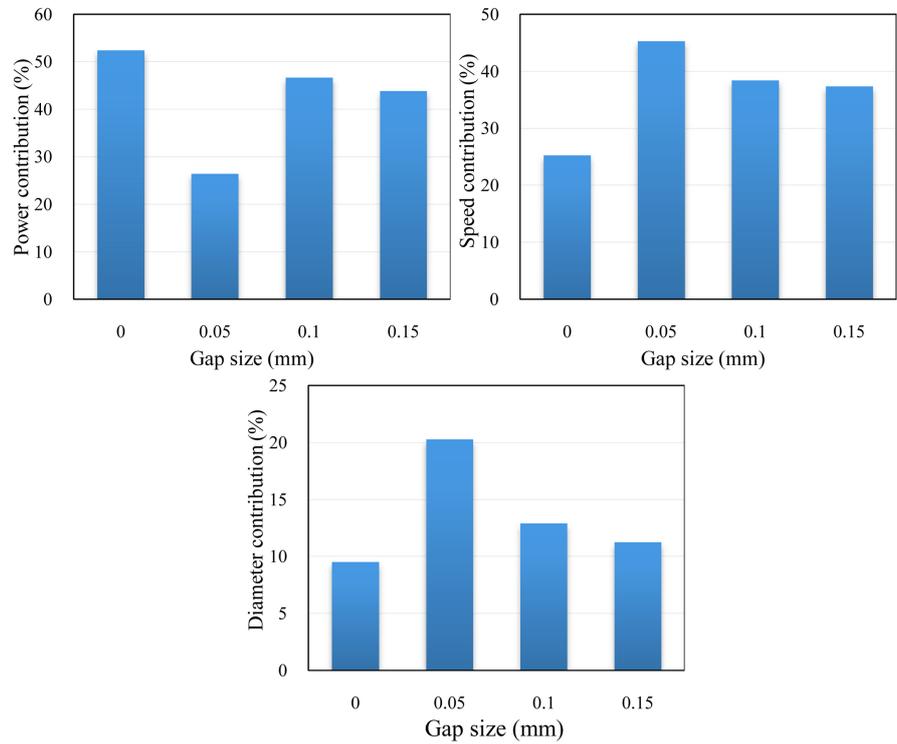


Figure 8. Percentage contribution of laser welding parameters in *WI* variation.

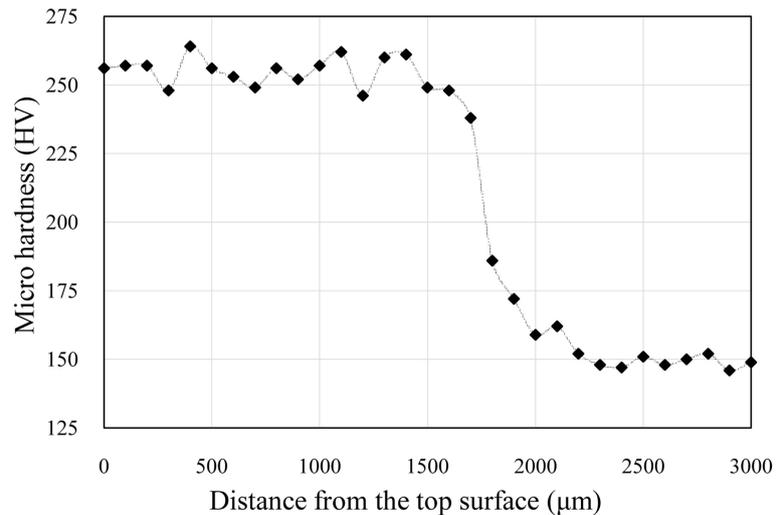


Figure 9. Hardness profile of welded sheets.

results suggest that power, speed, fiber diameter and gap are the largest contributors to the geometrical weld characteristics variation (*DOP*, *WS* and *WI*). Consequently, *P*, *S*, *D* and *G* are used as input to the predictive model. The modelling results demonstrate that the models can accurately predict the weld characteristics with an error less than 12%. The measured and predicted *DOP*, *WS* and *WI* are shown in **Figure 10**. These results suggest that the modeling approach can be effective for weld quality prediction. A more accurate definition of the weld quality attributes, an experiment covering more laser welding parameters

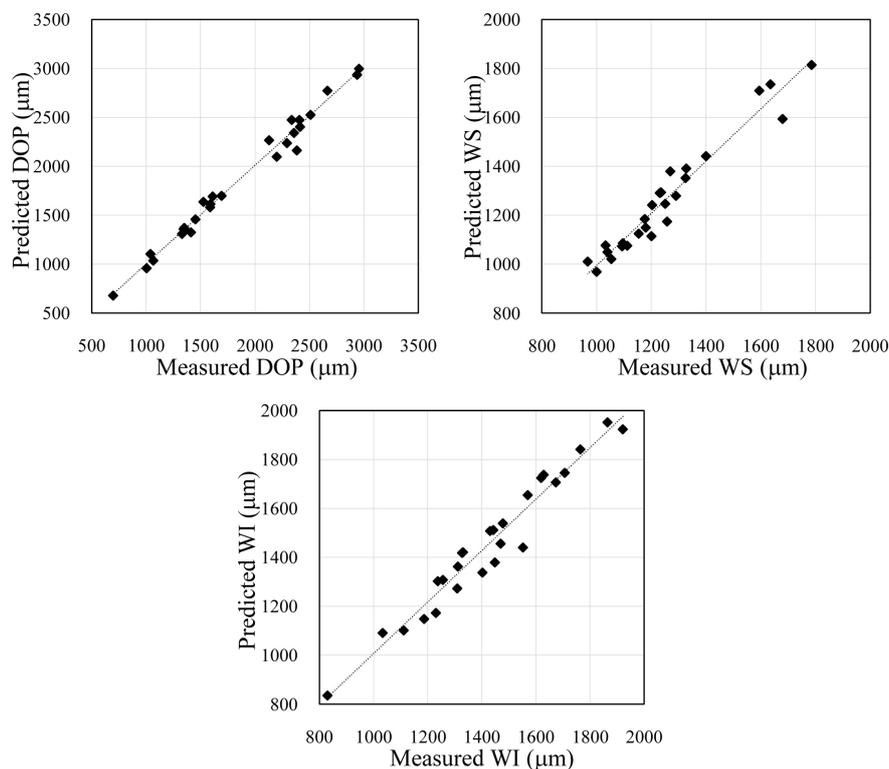


Figure 10. Measured and predicted weld dimensions.

and more factor levels for more training and validation data as well as an improvement of the modeling procedure can lead to more accurate and efficient models. This may probably lead to model improvement decreasing the modeling error to less than 5%.

4. Conclusion

This paper presents an experimental investigation of laser overlap welding of low carbon galvanized steel. The experimental work is focused on depth of penetration, bead width at the surface, and bead width at the interface and hardness using various laser welding parameters such as laser power, welding speed, laser fiber diameter, and gap between sheets and sheet thickness. There are 27 experimental tests taken as all factors known to have an influence on welds quality to conduct a systematic study using an efficient and structured experimental design. An error of less than 10% achieved in repeatability tests ensures that the measurement results are consistent and robust. Based on these measurements and using various statistical analysis tools, the average effects of the laser welding parameters and the effects of their interactions on different weld geometrical characteristics variation are estimated and analyzed. Their contributions in weld quality variation are also evaluated. The micro hardness measurements show coherent results with an increase in the weld hardness from 150 Hv to 250 Hv. A multivariate analysis reveals that each weld geometrical attribute is correlated to a specific group of welding parameters. Explicit and

quantified criteria are used to identify the most relevant variables for a consistent and practical predictive modeling. The welding parameters that have significant effects on the weld quality are laser power, welding speed and laser fiber diameter. The gap between sheets has a very limited effect. Confirmed by a multiple correlation analysis between weld geometrical attributes and welding parameters, the results suggest that many options can be considered for building an efficient weld quality prediction model. An artificial neural network based simplified predictive model is given as an example to demonstrate the possible and promising performance of weld quality prediction that can be achieved.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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