An Investigation of the Laser Welding Process for Dual-Phase Steel via Regression Analysis

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Abstract In this work, a systematic investigation was undertaken to explore the effects of welding process parameters on the mechanical performances of the welding joints in the laser welding process for DP600. Welding experiments were arranged by a uniform experimental design method with four control factors (laser power, welding speed, focal point position, and side-blowing shield gas flow). The tensile strength of the welding joints was used to quantify the welding quality. A mathematical model based on stepwise regression analysis was employed to correlate the welding process parameters and the tensile strength. The effects of the welding process parameters on the welding quality were discussed. The genetic algorithm was then employed to select the optimum welding parameters. The verification test results proved that the method proposed in this paper could effectively evaluate and optimize the welding quality within the range of process parameters, which could enhance the welding performance in the laser welding process as feasibly and effectively as possible.

1. Introduction
Fuel consumption and gas emission are the main subjects of global interests in these years, one of the promising strategies is using high strength steel to reduce the weight of vehicles. Dual-phase steel, as a new generation of steel, has the advantages of high strength, good ductility and satisfying welding performances compared with traditional kinds of steel. Thus, it has been increasingly employed in the manufacturing industry. Laser welding is widely used in aviation, automobile, shipbuilding industry and considered to be a promising welding technique, as it has the advantages of deep penetration, high productivity and little distortion. As is known to all, laser welding is a complicated thermal-electrical process that implicates mechanical, electrical, thermal and metallurgical factors and the weld quality is highly affected by various process conditions, noise, and errors [1]. During the practical production, it is not an easy task for skilled operators to select suitable process parameter combinations to obtain sound welding quality. Exploring an effective approach to enhance and optimize the quality of laser welding joints for dual-phase steels has become a key issue [2].
There are some literature reports concerning modeling the welding process and establishing the mathematical models correlating welding quality and technological parameters via the Taguchi method, response surface methodology, gray relational analysis and soft computing. Moradi et al. [3] employed the central composite design to investigate the effects of laser power, scanning speed and focal plane position on the tensile strength for the AISI 410 sheet and the optimum levels of parameters were finally determined. Yuce et al. [4] studied influences of laser power, welding speed and focal position on the mechanical and microstructural properties of the welding joints using a Taguchi approach, the optimum parameters for the maximum tensile strength with the minimum heat input were also predicted. Yaakob et al. [5] implemented the response surface methodology to establish a mathematical model correlating the welding parameters and tensile strength. The optimized welding parameters were obtained and improvement in welding quality was achieved due to complete welding penetration using the optimized welding parameters. Prabakaran et al. [6] employed the grey relational analysis to characterize the multiple quality characteristics of welded joints and figured out that the optimal welded joint had good mechanical properties after post-weld heat treatment. Ai et al. [7] developed the relationships between the weld bead integrity and process parameters by the genetic algorithm (GA) optimized backpropagation neural network. The results indicated that the laser power was the most significant factor in the weld bead integrity and weld area. Kannan et al. [8] modeled the relationship between welding speeds, shielding gas and fusion zone, bead width, depth of penetration, pore area via an artificial neural network. The results indicated that the artificial neural network model could reveal the relationship between the process parameters and the weld geometry. The proposed approach provided a deeper understanding of the welding process.

The side-blowing shield gas is a significant laser welding process parameter. Whereas, there is little academic reference available concerning the effect of the side-blowing shield gas on the welding quality, not to mention the interaction effects of the side-blowing shield gas and other welding parameters. To overcome these shortcomings, first, the welding power, welding speed, focal position, and side-blowing shield gas were selected as the welding parameters, the tensile strength of the welding joints was treated as the welding quality index. The welding experiments were carried out based on uniform experimental design. The empirical mathematical model quantifying the relationship between the process parameters and the tensile strength was obtained by using stepwise regression analysis. Variance analysis was also conducted to reveal whether the regression model was robust and satisfactory. The effects of the welding parameters on the welding quality were investigated based on the developed model. Finally, the GA was proposed to calculate the optimal process parameters and the verification test was also performed to check the validity of the model.

2. Experimental detail
This paper was planned to optimize the welding parameters of DP600 dual-phase sheets with thicknesses of 1.7 mm. The unique properties of DP600 include high strength, good weldability, and corrosion resistance [9]; its major chemical compositions (percent by weight) are Si 1%, Mn 1.52%, P 0.015%, C 0.079%, S 0.0049%, Al 0.023%, N 0.0037%. The DP600 sheets were cut into 120 mm × 40 mm and installed as butt weld joints.

A fiber laser welding machine composed of the YLR-4000 fiber laser system was employed to conduct the welding experiments. The laser power, welding speed, focal position and quantity of shielding gas flow were considered to be the key factors affecting the welding quality. The welding experiments were arranged based on a uniform experimental design [10]. The universal tensile testing machine was used to perform tensile-shear tests and the loading speed was set at 10 mm/min. The tensile strength was employed to reveal the welding quality and it was obtained from the load-displacement curve. Table 1 presents the results of the welding experiments.
Table 1. Experimental results based on uniform experimental design.

| No. | Laser power $P$ (kW) | Welding speed $V$ (mm/s) | Shielding gas flow $Q$ (m$^3$/h) | Focal position $F$ (mm) | Tensile strength $R$ (kN) |
|-----|----------------------|--------------------------|----------------------------------|------------------------|--------------------------|
| 1   | 0.9                  | 12                       | 2.3                              | 1                      | 26.02                    |
| 2   | 1                    | 18                       | 2                                | 0.5                    | 37.90                    |
| 3   | 1.1                  | 24                       | 1.7                              | 0                      | 39.00                    |
| 4   | 1.2                  | 8                        | 2.5                              | $-0.5$                 | 34.96                    |
| 5   | 1.3                  | 14                       | 2.2                              | $-1$                   | 37.39                    |
| 6   | 1.4                  | 20                       | 1.9                              | 1                      | 38.98                    |
| 7   | 1.5                  | 26                       | 1.6                              | 0.5                    | 39.63                    |
| 8   | 1.5                  | 10                       | 2.4                              | 0                      | 36.33                    |
| 9   | 1.7                  | 16                       | 2.1                              | $-0.5$                 | 38.04                    |
| 10  | 1.8                  | 22                       | 1.8                              | $-1$                   | 41.06                    |

3. Results and discussion

3.1. Failure modes of the welding joints
Figure 1 indicates three kinds of failure modes of the welding samples in the tensile tests. They are respectively sample 1 in Figure 1 (a), sample 7 in Figure 1 (b) and sample 10 in Figure 1 (c). The sample in Figure 1 (a) indicates it fails in the welding zone, while the welding joints fail in the heat-affected zone in Figure 1 (b). As for the sample in Figure 1 (a), the surface of the observed joint is not smooth and appearance defects could be found in the welding seam, which indicates the welding joints present poor permeability. The welding heat supplied to the welding zone is relatively low under the welding process parameters and the metal in the welding zone fails to melt completely, the tensile strength is far less than that of the base metal. In this case, the crack appears in the welding seam and its tensile strength is only about 382.71 MPa, which is far less than of the DP600. The welding sample in Figure 1 (b) presents good mechanical performances and the maximum tensile force is about 550 MPa, which is still less than the value of the base metal DP600. It also indicated that crack gradually develops from the heat-affected zone until the whole welding joints fail. The welding joints of Figure 1 (c) presents the best quality. The tensile strength of the welding zone is much larger than that of the base material, which indicates the failure occurs in the base material rather than the welding seam; the tensile strength is about 600 MPa [11].

Figure 1. Three types of failure fractures in the tensile tests.

Figure 2 presents the load-displacement curves for the three kinds of welding joints in the tensile test. It seems that the mechanical performances of the welded joints are quite different from each other. The maximum displacement of sample 10 is the largest and its failure energy is also much larger than others, which indicates its failure mode is a plastic failure. Sample 1 reveals the worst mechanical performances with small tensile strength and failure energy, in this case, it is a brittle fracture, since the welding heat input is not sufficient enough, the welding seam size is not large enough so that it can not tolerate large tensile strength. It can be concluded that the mechanical properties of sample 10 are the best.
3.2. Polynomial regression analysis

Nonlinear polynomial regression is a statistical and mathematical method quantifying the relationship between two variables. The mapping relationship between the variable $y$ and independent variables $x_1, x_2, \ldots, x_n$ can be expressed as follows [12]:

$$y = f(x_1, x_2, \ldots, x_n)$$

(1)

It is necessary to estimate the true relationship between dependent variables $f(x_1, x_2, \ldots, x_n)$ and independent variables $x_1, x_2, \ldots, x_n$. In general, a group of the general polynomial model is usually employed as follows:

$$f(x_1, x_2, \ldots, x_n) = a_0 + \sum_{i}^{n} a_i x_i + \sum_{i}^{n} a_{ij} x_i^2 + \sum_{i}^{n} a_{ijk} x_i x_j + \cdots + \varepsilon$$

(2)

where $\varepsilon$ is the model error, the least square regression method is usually employed to obtain the regression coefficients based on experimental results.

In this study, the mathematical model characterizing the relationship between welding parameters (laser power, welding speed, focal position, and shielding gas flow) and the tensile strength of the welding joints for DP600 was attempted to figure out utilizing regression method. Table 2 lists the analysis of variance results of the linear mathematical model via software Matlab2017b. The linear regression model was rejected as its P-value is larger than 0.05 [13].

| Term         | Regression coefficient | Upper confidence limit | Lower confidence interval |
|--------------|------------------------|------------------------|---------------------------|
| Constant     | 0                      | 0                      | 0                         |
| $P$          | 4.5373                 | -5.4195                | 14.4940                   |
| $V$          | 0.8174                 | 0.3745                 | 1.2603                    |
| $Q$          | 8.2722                 | 3.8827                 | 12.6617                   |
| $F$          | -1.8130                | -5.6742                | 2.0482                    |
| RMSE         | 0.6862                 | F-value                | 4.3745                    |
| P-value      | 0.0590                 | R-Squared              | 8.2827                    |

Figure 3 is a residual graph of the linear regression model. The vertical line indicates the residual and its confidence interval of the regression model. If the confidence interval of the residual does not contain 0 points, the corresponding experimental result is abnormal [14]. According to Figure 3, it can be concluded that the first set of the data is abnormal, in this case, it should be rejected.
The stepwise regression method is a statistical method that can select several important variables to construct the regression equation. In this study, the stepwise quadratic regression analysis is carried out using the software MATLAB 2017b, and the P values of terms $Q$, $F$, $QP$, $QF$, $P^2$, $V^2$, $Q^2$, $F^2$ are larger than 0.1, and they should be eliminated [15]. The final results of the analysis of variance for the second-order regression model are presented in Table 3.

**Table 3. Variance analysis results of the quadratic regression model.**

| Term   | Coefficient | t-stat  | P-value | Confidence interval |
|--------|-------------|---------|---------|---------------------|
| Constant | 39.5825     | 47.2694 | 0.0004  | 35.9796 43.1855     |
| $P$    | -6.2659     | -10.6040| 0.0088  | -8.8083 -3.7235     |
| $V$    | -0.6806     | -12.1810| 0.0067  | -0.9210 -0.4402     |
| $PV$   | 0.4317      | 13.5830 | 0.0054  | 0.2949 0.5684       |
| $PF$   | 4.5510      | 12.3130 | 0.0065  | 2.9607 6.1414       |
| $VQ$   | 0.2767      | 16.5000 | 0.0037  | 0.2045 0.3488       |
| $VF$   | -0.3574     | -12.8533| 0.0060  | -0.4770 -0.2378     |

Notes: $R^2=0.9996$; Adj $R^2=0.9985$; RMSE=0.07112; F value =861.88; P value =0.001159.

The determination $R^2$ and the adjusted $R^2$ characterize the fitting degree of the regression model [16]. A relative larger $R^2$ indicates that the model is sound and satisfying. The maximum error of estimated tensile strength is about 0.164 kN testifying that the model developed by the stepwise analysis is valid and flexible. Based on the above analysis, the regression coefficients of the fitted regression model for the laser welding process of DP600 were achieved and described as follows:

$$R=39.5825-6.2659P-0.6806V+0.4317PV+4.5510PF+0.2767VQ-0.3574VF$$

(3)

Subjected to

$$0.9 \text{ kW} \leq P \leq 1.8 \text{ kW}, 8 \text{ mm/s} \leq V \leq 26 \text{ mm/s}, -1 \text{ mm} \leq F \leq 1 \text{ mm}, 1.6 \text{ m}^3/\text{h} \leq Q \leq 2.5 \text{ m}^3/\text{h}$$

(4)

3.3. Welding process parameters analysis and optimization

Figure 4 is a contour plot of the tensile strength with different welding speeds and side-blown gas flows. While the welding power is kept at 1.35 kW and the focal position is 0 mm. The tensile strength of the welding joints increases with the increase of the side-blown gas flow and welding speed. The higher the welding speed is, the less the heat input supplied to the welding zone will be absorbed, in this case, the welding penetration and the weld size will reduce, and the mechanical properties are poor [17]. However, too slow welding speed not only leads to welding defects such as weld beads but also reduces...
production efficiency. The side blowing gas flow prevents the molten metal from chemically reacting
with the air during the welding process, it also affects the welding quality by changing the area and
height of the plasma. The side blow gas flow blows the plasma away, the larger the gas flow value is,
the smaller the plasma amount will be, and the less loss of the welding heat input will be dissipated [18].
So larger side blow gas flow can effectively improve the welding penetration and the welding seam size,
thus the welding quality will be improved.

![Figure 4. The interaction effect of the welding speed and side-blowing shield gas flow on tensile strength.](image)

The GA was employed to optimize welding process parameters in this study. Unfortunately, there is
not a theoretical basis available for determining GA parameters, and it is generally determined by trial
and error [19]. The population size was chosen to be 40, the maxima hereditary algebra was 50, each
code length was 20, the generation gap was 0.95, the crossover probability was 0.7, and the mutation
probability was 0.01. The tensile strength of the welding joints changes continuously in the GA
calculation progresses and eventually reaches a fixed value. The result obtained by the GA is the
maximum tensile strength of the welding joints within the welding process parameters investigated in
this study, which is 49.86 kN. The corresponding combination of welding process parameters is laser
welding power of 1.716 kW, welding speed of 24.979 mm/s, side blowing gas flow of 2.409 m³/h, and
focal position of –0.998 mm.

The confirmation experiment aims to certificate the feasibil ity and reproducibility of the results
determined by the regression model and the optimization method [20]. In this paper, the test was conducted
using the optimum levels of the welding parameters obtained by the GA to justify whether the welding
quality is improved, as tabulated in Table 4. From Table 4, we can see that the mechanical behavior of
welded joints is higher than the maximum shear strength in Table 1. It proved the parameter combination
obtained by the proposed approach performed well for the welding quality optimization problem.

| Optimization method | P (kW) | V (mm/s) | Q (m³/h) | F (mm) | R (kN) | R in Table 1 (kN) | R_{pred} (kN) |
|---------------------|-------|----------|----------|--------|-------|------------------|--------------|
| GA                  | 1.7   | 25       | 2.4      | –1     | 49.56 | 41.06            | 49.86        |

4. Conclusions
1. The developed quadratic polynomial regression model for quantifying the relationship
between the input variables (welding power, welding speed, side blowing gas flow, and focal position)
and the tensile strength is robust and flexible.
2. Larger welding speed and side blowing gas flow together with appropriate welding power
and focal position are desirable. The optimum parameters for the maximum achievable tensile strength
in this investigation were found to be as follows: laser welding power of 1.7 kW, welding speed of 25
mm/s, side blowing gas flow of 2.4 m³/h and focal position of –1 mm.
3. Both the welding speed and the side blowing gas flow have significant effects on the welding quality by affecting the welding heat input supplied to the welding zone. Their effects on the welding quality are quite different.

References
[1] Farrokhi F, Endelt B and Kristiansen M 2019 Optics & Laser Technology 111 671
[2] Prabakaran M P and Kannan G R 2017 Ferroelectrics 519 223
[3] Moradi M, Arabi H and Shamsborhan M 2020 Optik 202 163619
[4] Yuce C, Tutar M, Karpat F, Yavuz N and Tekin G 2017 Strojniški Vestnik 63 510
[5] Yaakob K I, Ishak M, Quazi M M and Salleh M N M 2019 Measurement 135 452
[6] Prabakaran M P and Kannan G R 2019 Optics & Laser Technology 112 314
[7] Ai Y, Shao X, Jiang P, Li P, Liu Y and Liu W 2016 Optics and Lasers in Engineering 86 62
[8] Casalino G, Facchini F, Mortello M and Mummallo G 2016 IFAC-PapersOnLine 49 378
[9] Marwan K O H and Kaçar R 2018 Materials Testing 60 40
[10] Fang K T, Lin D K, Winker P and Zhang Y 2000 Technometrics 42 237
[11] Zdravecká E and Slota J 2019 Metals 9 91
[12] Vedrtnam A, Singh G and Kumar A 2018 Defence Technology 14 204
[13] Vyas M, Jain M, Pareek K and Garg A 2019 Measurement 148 106904
[14] Leardi R 2009 Analytica Chimica Acta 652 161
[15] Shihab S K 2018 Arabian Journal for Science and Engineering 43 5017
[16] Kumar S S, Murugan N and Ramachandran K K 2019 Measurement 137 257
[17] Xu K and Zhang SQ 2018 Key Engineering Materials 765 204
[18] Gu X, Liu Y, Li W, Han Y and Zheng K 2019 Materials 12 4207
[19] Sada S O 2020 Cogent Engineering 7 1741310
[20] Kumar S and Singh R 2019 Measurement 148 106924

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