Experimental Study on Laser Welding of AISI 304 Steel with Design of Experiments Approach

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Abstract. Austenitic stainless steels find extensive applications in engineering and structural parts requiring inherent corrosion resistance. The main objective of this study is to achieve good quality butt joint in 2.5-mm thick 304 grade Stainless Steel. The joint quality is quantified in terms of weld-bead dimensions. The main issue that manufacturers face is controlling the input process parameters, to get a good quality joint, with required weld bead geometry under controlled thermal distortion. The objective of this work is to select proper input process parameters that would result in desirable weld-bead profiles with minimal heat input. The critical process parameters influencing laser-welding were found using response surface methodology technique. The results proved that the developed model could efficiently predict the responses. The criteria demonstrated a possible reduction in top width of weld bead with enhanced depth of penetration, which automatically envisaged an increase in aspect ratio. A two-factor five-level criteria design was used for predicting the optimized parameters by performing multi-response optimization. Among them, the third criterion has shown a significant decrease in heat input and it was chosen as the best-optimized parameter.

1. Introduction
Laser welding is a high power density and low heat input process that results in a high depth of penetration. Laser welding, especially, keyhole welding, being a fast cooling process, results in sudden shrinkage during solidification. Heat input is one of the major factors that adversely affect the quality of the joint. The main problem in keyhole laser welding is the high amount of heat generation due to a decrease in reflectivity caused by the formation of narrow vapor channel, which traps the laser beam inside the channel. This beam entrapment maximizes the depth of penetration. Sometimes unnecessary heat generation leads to an increase in weld bead dimensions, which results in an increase in top width.

The heat affected zone (HAZ) would be wider when applying high laser power, and the strength of the joint decreases. Also, the fact that the austenitic stainless steel has low thermal conductivity, implies that the heat will be localized. When the laser beam is moved, the localized heat will take more time to conduct through the bulk metal. This increases the top width, simultaneously pushing the HAZ to wider areas. This would allow the grains to grow in the weld zone and in the HAZ, reducing the joint strength. Generally, very high or very low laser power is not recommended.
It creates surface defects as well as spoils the aesthetic appearance of the weld bead. Unnecessary heat generation results in the large molten zone. Faster cooling rates of laser welding, creates thermal distortion, due to sudden shrinkage of the wider molten area. This study aims at minimization of heat input without compromising aspect ratio, to get desirable weld bead geometry. The minimal heat input results in minimal shrinkage, minimal distortion of the workpiece, small heat affected zone, narrow weld beads with good aesthetic appearance.

2. Literature Survey
Research suggests that an optimal heat input must be used to reduce thermal distortion and eliminate unnecessary detrimental metallurgical effects. Giridharan et al., [4] predicted optimum pulsed gas tungsten arc welding process parameters to obtain optimum weld bead geometry with full penetration in welding of 3 mm thick stainless steel sheets of 3 mm thickness. Benyounis et al., [3] investigated laser-welded butt joints made of AISI304 and related the laser-welding parameters with tensile strength, impact strength and joint-operating cost and optimized the process. Ruggiero et al., [13] developed regression equations for weld bead geometry of dissimilar full depth laser-butt welding of low carbon steel and austenitic steel AISI 316 and used it to find optimum welding conditions. Olabi et al., [9] developed a mathematical model relating laser welding parameters and the magnitude of the residual stress at different locations using response surface methodology for laser butt-welding of AISI304 plates joints using a 1.5 kW continuous wave CO₂ Rofin laser.

Padmanaban et al., [10] developed an empirical relationship to predict the tensile strength of laser beam welded AZ31B magnesium alloy by incorporating process parameters such as laser power, welding speed, and focal position. Nagesh et al., [8] developed multiple linear regression models and back-propagation neural network for weld bead shape parameters of the TIG welding process and optimized the process parameters applying genetic algorithmic approach. Pan et al., [11] used Taguchi technique to optimize welding parameters of an Nd: YAG laser for thin plate magnesium alloy butt welding. Sathya et al., [14] applied Taguchi technique, grey relational analysis, and the desirability approach to optimize the parameters for laser welding of 904 L super austenitic stainless steel. Abilash et al., [1] investigated hybrid laser-arc welding process based on the relative position of the laser and the arc and, the effects of welding parameters on the weld bead. Mei et al., [7] presented influence of laser power, welding speed, focal position, shielding gas and zinc vaporization on the quality of deep-penetration laser welds of high-strength galvanized steel sheets.

In the present work, RSM is employed to relate the laser welding input parameters (laser power, welding speed) to the four responses (i.e. top weld width, depth of penetration, heat input, aspect ratio). The optimal welding process parameters that minimize both the heat input and top weld bead width are determined while maintaining good aspect ratio.

3. Methodology
The material used for the present study is 2.5 mm thick Austenitic Stainless Steel 304 grade. The bead on plate trials were carried out on the workpieces of 100 mm × 80 mm × 2.5 mm dimensions.

Figure 1. Macrograph of weld bead (2.5 KW, WS = 5 m/min)
The samples were ground to remove sharp edges. The specimens were cleaned with SS wire brush, followed by acetone. The matrix of experimental trials was performed using a 1.0-mm diameter laser spot of 3.5 kW Continuous Wave Carbon dioxide (CO\textsubscript{2}) laser, as shown in table 1. A two-factor, five-level central composite design shown in table 1 was used to explore the effects of the CO\textsubscript{2} laser welding parameters on the depth of penetration, top bead width, heat input and aspect ratio. The working ranges selected were based on the quality of weld beads, which was based on penetration and absence of visible defects in weldments.

| Sl. No. | Power (W) | Speed (m/min) | TW (µm) | DP (µm) | HI (J/m) | AR  |
|---------|-----------|---------------|---------|---------|----------|-----|
| 1       | 1000      | 2.50          | 966.7   | 1940.0  | 21600    | 2.00|
| 2       | 2500      | 2.50          | 1110.3  | 2450.0  | 54000    | 2.20|
| 3       | 1000      | 7.50          | 640.0   | 546.6   | 7200     | 0.85|
| 4       | 2500      | 7.50          | 741.7   | 1920.0  | 18000    | 2.58|
| 5       | 0689      | 5.00          | 540.0   | 526.7   | 7452     | 0.97|
| 6       | 2811      | 5.00          | 826.7   | 2450.0  | 30240    | 2.96|
| 7       | 1750      | 1.46          | 1340.0  | 2450.0  | 64726    | 1.82|
| 8       | 1750      | 8.53          | 750.0   | 1020.0  | 11078    | 1.36|
| 9       | 1750      | 5.00          | 813.3   | 2086.7  | 18900    | 2.56|
| 10      | 1750      | 5.00          | 740.0   | 1853.3  | 18900    | 2.50|
| 11      | 1750      | 5.00          | 800.0   | 1960.0  | 18900    | 2.45|
| 12      | 1750      | 5.00          | 860.0   | 2006.7  | 18900    | 2.33|
| 13      | 1750      | 5.00          | 740.0   | 1853.3  | 18900    | 2.50|

Where TW is Top Width, DP is Depth of Penetration, HI is Heat Input and AR is the Aspect ratio.

The systematic error was avoided by conducting experimental trials in a random order. The molten pool obtained during welding process was shielded using a flow of Argon gas maintained at 25 L/min. Specimens were cut along the transverse direction of each weldment for characterization. An optical microscope was used to measure the width and depth of the bead. The bead on plate macrograph for a specimen processed with a power of 2.5 kW and a welding speed of 5 m/min is shown in figure 1. The measured width and depth of bead profiles for all the experimental trials conducted are provided in table 1.

### 4. Model Development

RSM was used to develop the mathematical models. The step-wise regression method was used to eliminate the unnecessary terms of the model. Sequential F-test and lack of fit test were carried out for finding the significance of the developed models and terms in each model. ANOVA results are given in table 2. The models were developed in terms of actual factors and the empirical models are given in equation (1) to equation (4).

\[
\text{Top Width} = 1151.98 + 0.469591 \times \text{power} - 270.355 \times \text{speed} - 0.00559867 \\
\times \text{power} \times \text{speed} - 0.0000951831 \times \text{power}^2 + 20.3667 \times \text{speed}^2
\]
Depth of Penetration
= 1173.99 + 1.46986 × power − 275.495 × speed + 0.108444 × power × speed − 0.00349924 × power² + −11.76 × speed²

Heat Input
= 37955.2 + 26.9712 × power − 15376.7 × speed − 2.88 × power × speed + 1410.32 × speed²

Aspect Ratio
= 0.313949 + 0.00121916 × power + 0.240041 × speed + 0.000204267 × power × speed − 4.13556e−007 × power² − 0.0669 × speed²

The R² and R² adj values of the equations developed for the parameters are given in table 3. The higher values of R² and R² adj indicate the adequacy of the model [5; 12; 15]. Other statistical tests like F-Test, lack of fit test were also conducted to access the adequacy of the model. The results indicate that the model is functional to navigate within the design space applicable.

| Parameter           | R²     | R² adj  |
|---------------------|--------|---------|
| Top Width           | 0.9683 | 0.946   |
| Depth of Penetration| 0.9724 | 0.9527  |
| Heat Input          | 0.9654 | 0.948   |
| Aspect Ratio        | 0.9650 | 0.9401  |

4.1. Optimization by Desirability approach

The desirability method is used for solving multiple response problems because of its accessibility, simplicity, and flexibility in weighting and giving importance to individual response. In the desirability approach, multiple responses are combined into a dimensionless degree of overall performance referred to as the overall desirability function

5. Results and Discussion

The effect of the input parameters on the bead top width (TW) is shown in figure 2 (a) and figure 2 (b). It is observed that the welding speed (S) is the most affecting factor, which significantly influences the top width of the weld bead. Increase in welding speed (S) decreased the top width of the bead. This can be attributed to reduced laser interaction time at the joint line. As a result, the heat input per unit length decreased leading to less amount of the base metal being melted. Due to this, the top width of the weld bead decreased. On the other hand, an increase in laser power (P) increases bead top width dimensions, as a direct consequence of power density [6].

The effect of the process parameters on the depth of penetration (DOP) is shown in figure 2 (c) and figure 2 (d). The results indicate that both the power and welding speed significantly affect the depth of penetration. An increase in laser power for a given welding speed, increased the heat input, enhancing heat transfer along the thickness. Thus more DOP will be achieved. However, the effect is opposite in the case of welding speed. With increased welding speed the heat input per unit length decreased [1; 2]. This resulted in poor heat transfer in the vertical direction and decreased DOP. To achieve maximum DOP the laser power should be maximum, while welding speed has to be minimum. The heat input (HI) is directly related to the welding speed, laser power and welding efficiency by the expression given below in equation (5).
Heat Input = \frac{\text{Laser Power}}{\text{Welding Speed}} \times \eta \quad (5)

where \( \eta \) is the welding efficiency.
From figure 2 (e) and figure 2 (f), it is evident that as the power increases and welding speed decreases, the heat input increases. When using higher laser power and slow welding speed undesirable residual stresses are induced as discussed in [7]. From figure 2 (g) and figure 2 (h), it is evident that the aspect ratio increases as power increases. But as the welding speed increases, the aspect ratio is increasing initially then after reaching a maximum point it starts to decrease. Thus laser power influences more on aspect ratio than the welding speed.

**Table 3.** Dependent process variables and their goals

| Response            | Notation | Units | Goals       |
|---------------------|----------|-------|-------------|
| Top Width           | TW       | µm    | Minimize    |
| Depth Of Penetration| DOP      | µm    | Maximize    |
| Heat input          | HI       | J/m   | Minimize    |
| Aspect Ratio        | AR       | No units | Maximize or Target |

The numerical optimization determines a point or more than maximizing this function. Numerical methods were used in this study. The chosen goals for each process parameter and output are shown in table 3 and table 4. Four optimization criteria were chosen for numerically optimizing the input process parameters with the output.

### 5.1. Optimization Criteria

The numerical optimization would find a point or more points that maximize the desirability function. In the numerical optimization, four criteria were implemented, as presented in table 4. The First criteria is to set constraints on the process parameters, so the goal is to reach the minimum value of both top width and heat input, maximizing the DOP as well as aspect ratio, giving more importance to the main factors, minimizing laser power and maximizing welding speed by keeping default weight (1) and default importance (+++) for all parameters. The main aim is to decrease the heat input, without compromising on the aspect ratio. Based on the first criteria, optimized values are achieved with a desirability of 0.692 and an aspect ratio of 2.25. The optimized aspect ratio value from the first criteria is kept as a target for the second criteria. More importance (++++) is given to minimizing heat input, with the aspect ratio set to a target value of 2.25.
Table 4. Optimization criteria and results using multi-response optimization

| Welding Parameters | Responses |
|--------------------|-----------|
| Power (W)          | Speed (m/min) | TW (µm) | DOP (µm) | HI (J/m) | AR | Desirability |
| Min                | Max        | Min     | Max      | Min      | Max or Target |

| Criteri a          | W  | I* | W  | I* | W  | I* | W  | I* | W  | I* | W  | I* |
|--------------------|----|----|----|----|----|----|----|----|----|----|----|----|
| First              | ++ | +  | ++ | +  | ++ | +  | ++ | +  | +++| 1  | +++|
| Result             | 1683.059 | 6.148 | 729.556 | 1682.898 | 12860.163 | 2.255(max) | 0.692 |
| Second             | ++ | +  | ++ | +  | ++ | +  | ++ | +  | +++| 1  | +++|
| Result             | 1690.357 | 6.181 | 729.400 | 1681.832 | 12833.648 | 2.255(tar) | 0.774 |
| Third              | ++ | +  | ++ | +  | ++ | +  | ++ | +  | +++| 1  | +++|
| Result             | 1659.348 | 6.199 | 725.265 | 1647.69 | 12501.5 | 2.218(tar) | 0.755 |
| Fourth             | ++ | +  | ++ | +  | ++ | +  | ++ | +  | +++| 2  | +++|
| Result             | 1700.8  | 6.248 | 728.694 | 1675.5  | 12745.226 | 2.250(tar) | 0.757 |

There is a slight increase in power (from 1683 W to 1690 W) and speed (from 6.14-m/min to 6.181-m/min) from the obtained optimized values. But there is a considerable decrease in heat input (i.e., it was decreased from 12860 J/m to 12833 J/m), which matches with the target value of 2.25 for the aspect ratio. In third criteria also target value for the aspect ratio has been kept as 2.25, but medium importance (+++)) is given to the aspect ratio while maximum importance is given to heat input, and all other conditions are set as being followed in second criteria.

Figure 3. Overlay plot of the top width
There is a significant decrease in heat input (i.e., it was decreased from 12833 J/m to 12501 J/m), but a slight reduction in aspect ratio (2.218). In the fourth criteria, everything kept as same as being followed in second criteria except more weight (2) is given to heat input, aspect ratio. There is an increase in heat input compared to third criteria (i.e., it got increased from 12501 J/m to 12745 J/m). The optimized values of Heat input, aspect ratio are individually shown in table 4 based on different criteria. Among four criteria, third criteria resulted in a significant decrease in heat input with a slight decrease in aspect ratio. As a result, third criteria appear the best-optimized parameter for the butt welding of SS304 of 2.5 mm thick plates. Figure 3 gives the optimized values for third criteria i.e., top width as 725.358, DOP as 1648.42, heat input as 12501.9 in the yellow region with corresponding input parameters (1660 W, 6.18 m/min) which is the feasible response according to given proposed criteria.

6. Conclusion

The objective of this study was to examine the effect of power and welding speed on the depth of penetration, weld width, aspect ratio and heat input in CO₂ laser welding of AISI304 steel. Laser welding experiments were conducted by varying power and welding speed based on central composite design. The model equations developed using RSM were used are to explore the effect of process parameters on weld characteristics and the desirability approach is used to determine the optimal laser-welding parameters. Four criteria were used for predicting the optimized parameters by performing multi-response optimization. The following results are obtained

- Laser power has a small effect in weld profile and top width
- Laser power has greater influence in penetration depth than weld profile and top width.
- Welding speed is the most important parameter during CO₂ laser welding.
- A higher welding speed results in a considerable decrease in the aspect ratio, leading to an unacceptable weld profile indicating the dependence of aspect ratio on welding speed. Increasing the power increases the aspect ratio.
- Among the four criteria, the third criterion has shown a significant decrease in heat input and has been chosen as a best-optimized solution.
- The optimized parameters are power = 1659 W and welding speed = 6.18 m/min.

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