Optimising the laser-welded butt-joints of medium carbon steel using RSM

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Abstract

The optimization capabilities in design-expert software were used to optimise the keyhole parameters (i.e. maximize penetration (P) and minimise the heat input, width of welded zone, (W) and width of heat affected zone (W_{HAZ})) in CW CO_2 laser butt-welding of medium carbon steel. The previous developed mathematical models to predict the keyhole parameters in terms of the process factors namely; laser power (LP), welding speed (S) and focused position (F) were used to optimize the welding process. The goal was to set the process factors at optimum values to reach the desirable weld bead quality and to increase the production rate. Numerical and graphical optimization techniques were used. In fact, two optimization criteria were taken into account. In this investigation optimal solutions were found that would improve the weld quality, increase the productivity and minimize the total operation cost. In addition to that, superimposing the contours for the various response surfaces produced overlay plots.

Keywords: Laser welding; RSM; Optimization, Keyhole parameters;

1. Introduction

Laser welding with high power density high degree of automation and high production rate is extremely advantageous in automotive application [1]. But the point is how to express the weld bead parameters in terms of process input factors to determine the optimum welding conditions. Considering that welding is usually done with the aim of producing a good joint at low cost. However it is impossible to achieve low cost welding and good junction without optimization. Trial and error methods were previously used to determine the optimal process conditions for the required weld joint quality [2,3]. Optimization of the weld bead volume 'minimize' in SAW was studied [4]. Also, optimization of the impact strength of spiral-welded pipes in SAW at different serving temperatures was investigated [5]. Despite, the different optimization techniques used in the previous studies, the goals were reached and optimal welding conditions were identified to achieve the desirable weld quality with minimum cost [4,5]. For a strong weld, bead penetration should be maximized and the heat input, bead width of fusion zone as well as bead width of HAZ should be minimized.

Minimizing the heat input would result in reducing the welding cost through reduced energy consumption and increased welding productivity through high welding speed. By utilizing the above advantages, the weld bead profile could be optimised. The objective of this study is to optimize the autogenous laser welded joints subjected to maximize penetration and minimize both the fusion zone width and HAZ width. In order to achieve these objectives mathematical models were developed to relate the important weld bead parameters and the laser welding input variables [6].

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The mathematical models developed and optimised for the weld bead profile are very useful to identify the correct and optimal combination of the laser welding input variables, in order to obtain superior weld quality at relatively low cost.

2. Experimental work

Medium carbon steel with chemical composition in weight percent of 0.46 % C, 0.2% Si, 0.7% Mn and Fe Balance was used as work piece material. The size of each plate was 180 mm long x 80 mm width with thickness of 5 mm. Trial samples of butt-joints were performed by varying one of the process variables to determine the working range of each variable. Absent of visible welding defects and at least half depth penetration were the criteria of choosing the working ranges. The experiment was carried out according to the design matrix in a random order to avoid any systematic error in the experiment using a CW 1.5 kW CO_2 Rofin laser provided by Mechtronic Industries Ltd. Argon gas was used as shielding gas with constant flow rate of 5 l/min. Two transverse specimens were cut from each weldment. Standard metallographic procedures were made for each transverse specimen. The bead profile parameters 'responses' were measured using an optical microscope with digital micrometers attached to it with accuracy of 0.001 mm, which allow to measure in X-axes and y-axes. The average of two measured weld profile parameters was recorded for each response.

3. Optimization

The optimization module in Design-expert searches for a combination of factor levels that simultaneously satisfy the requirements placed (i.e. optimization criteria) on each of the responses and process factors (i.e. multiple response optimization). Numerical and graphical optimization methods were used in this work by choosing the desired goals for each factor and response. The optimization process involved combining the goals into an overall desirability function. The numerical optimization finds a point or more that maximize this function. While, in the graphical optimization with multiple responses you need to define regions where requirements simultaneously meet the proposed criteria. Superimposing or overlaying critical response contours on a contour plot. Then, visual search for the best compromise becomes possible. In case of dealing with many responses, it is recommended to do numerical optimization first otherwise you may find it impossible to uncover a feasible region. The graphical optimization displays the area of feasible response values in the factor space. Regions that do not fit the optimization criteria are shaded [7]. Figure 1, flow chart shows the optimization steps.

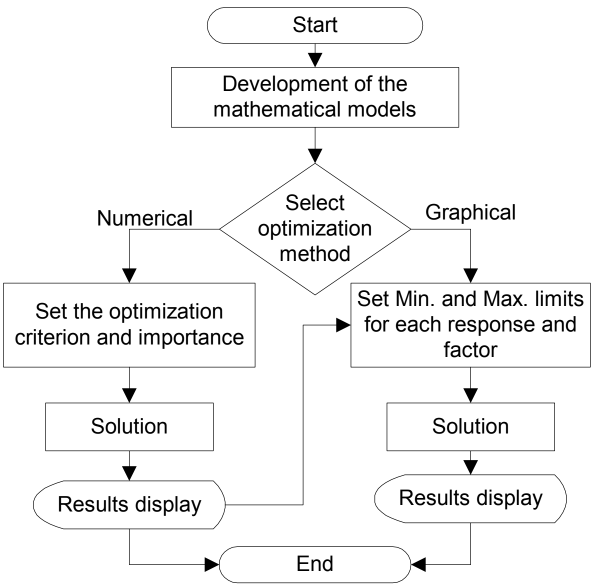

Fig. 1. Optimization steps

3.1. Development of mathematical models

The mathematical models were developed and presented previously [6]. Box-Behnken design was used to develop the models. Table 1 presents the selected process control parameters with their limits and units. The adequate final mathematical models in terms of coded factors are listed below:

Table 1.
Independent process variables and experimental design levels used.

Variables	Code	Unit	-1	0	+1
Laser power	LP	kW	1.2	1.3125	1.425
Welding speed	S	cm/min	30	50	70
Focused position	F	mm	-2.5	-1.25	0

$$\text{Heat input} = 1260 + 118.29 * LP - 600 * S + 240 * S^2 - 51.43 * LP * S \quad (1)$$

$$P = 3.68 + 0.46 * LP - 0.53 * S + 0.54 * F \quad (2)$$

$$W = 2.42 + 0.26 * LP - 0.56 * S - 0.38 * F - 0.31 * S^2 + 0.30 * F^2 + 0.23 * S * F \quad (3)$$

$$W_{HAZ} = 0.53 + 0.06 * LP - 0.16 * S + 0.03 * F - 0.08 * LP * S \quad (4)$$

3.2 Optimization method

3.2.1 Numerical optimization

Two criteria were introduced in this numerical optimization. The first criterion is to reach full depth penetration and to minimize the following: heat input, width of the fusion zone and width of HAZ. In other words, to reach full depth penetration at relatively low welding cost by reducing the laser power and increasing the welding speed as well as to obtain excellent joints. While, in the second criterion the goal was to reach half depth penetration (i.e. $P \approx 2.5$ mm) and to minimize the following: heat input, width of the fusion zone and width of HAZ. However, the joint type will be double-sided butt joint to obtain superior junction. Tables 2 and 3 illustrate the goal, lower and upper limits as well as the importance for each response and factor in the first and second criteria respectively.

3.2.2 Graphical method

For each response the limits lower and/or upper have been chosen according to the numerical optimization results. The same two criteria, which are proposed in the numerical optimization, were introduced in the graphical optimization. In the first criterion the lower and upper limits for the laser power, welding speed and focused position are (1.38–1.41kW), (30.48–35.21 cm/min) and (-0.43 to 0) respectively. While for the second criterion the limits are (1.2-1.24 kW), (69.77-70 cm/min) and (-2.03 to –1.71 mm) respectively.

Table 2.
The first criterion of numerical optimization.

Name	Goal	Lower Limit	Upper Limit	Importance
Laser power	Minimize	1.2	1.425	4
Welding speed	Maximize	30	70	4
Focused position	Is in range	-2.5	0	3
Heat input	Minimize	822.857	2280	5
Penetration	Is target = 5	4.99	5	5
Width	Minimize	1.342	3.681	2
Width HAZ	Minimize	0.375	0.872	2

Table 3.
The second criterion of numerical optimization.

Name	Goal	Lower Limit	Upper Limit	Importance
Laser power	Minimize	1.2	1.425	4
Welding speed	Maximize	30	70	4
Focused position	Is in range	-2.5	0	3
Heat input	Minimize	822.857	2280	5
Penetration	Is target = 2.5	2.499	2.5	5
Width	Minimize	1.342	3.681	2
Width HAZ	Minimize	0.375	0.872	2

4. Results and discussion

The result of the numerical optimization table 4 shows the welding conditions, which lead to full depth penetration at relatively low welding cost. It is evident that to achieve full depth penetration, the optimal working range for the laser power has to be between (1.38-1.42 kW) and the welding speed has to be between (30.48-35.55 cm/min) using a focused position spanning from (-0.43 to 0 mm. However, the full depth penetration achievement has a negative effect on both the bead width of WZ and HAZ, due to the high laser power and slow welding speed used. Table 5 presents the results of the second criterion in the numerical optimization. It is clear that to achieve half depth penetration, the optimal laser power ranges between (1.2 – 1.24 kW), the welding speed ranges between (69.77 – 70 cm/min) and the focused position spanning from (-1.71 to –2.03), because of half depth penetration the welding has to be double-sided butt-welding to obtain excellent welded joints. In this case, the heat introduced twice, which would make the total heat input for the two passes to be around 1700 J/cm but it is still less than the minimum heat input of 1960 J/cm in the first optimization criterion. The reduction in the heat input results in less distortion and improve the weld quality. As the welding speed was doubled, the welding cost will be less resulting in improving the process productivity. Also, the bead width of welded zone and HAZ are significantly less in the second criterion. The graphical optimization results allow visual inspection to choose the optimum welding condition. The shaded areas on the overlay plots figures 2 and 3 are the regions that do not meet the proposed criteria.

Table 4.
Optimal welding condition based on the first criterion.

No.	Laser power	Welding speed	Focused position	Heat input	Penetration	Width	Width HAZ	Desirability
1	1.41	35.21	-0.00	1967.11	4.99984	2.62583	0.778076	0.243
2	1.41	35.08	-0.00	1972.52	4.99972	2.62288	0.778613	0.243
3	1.40	33.57	-0.00	2035.54	4.99999	2.58837	0.784574	0.234
4	1.41	34.41	-0.04	2006.33	4.99999	2.61728	0.78523	0.230
5	1.39	32.87	-0.00	2065.7	5.00000	2.57212	0.787292	0.224
6	1.42	35.55	-0.05	1960.78	4.99999	2.64371	0.781039	0.223
7	1.39	32.28	-0.00	2090.83	4.99999	2.55602	0.788761	0.213
8	1.38	30.52	-0.00	2166.54	4.99441	2.50473	0.79157	0.128
9	1.41	30.73	-0.32	2210.56	4.99999	2.61339	0.827088	0.106
10	1.42	30.48	-0.43	2238.7	4.99682	2.64875	0.838873	0.059

Table 5.
Optimal welding condition based on the second criterion.

No.	Laser power	Welding speed	Focused position	Heat input	Penetration	Width	Width HAZ	Desirability
1	1.20	69.77	-1.71	833.96	2.49964	1.40749	0.383966	0.991
2	1.20	70.00	-1.71	834.653	2.49988	1.40172	0.382422	0.990
3	1.20	69.31	-1.73	835.792	2.499	1.44525	0.385042	0.986
4	1.21	70.00	-1.75	836.94	2.5	1.42156	0.380906	0.985
5	1.20	68.48	-1.78	839.744	2.5	1.51241	0.387102	0.976
6	1.22	70.00	-1.84	842.912	2.5	1.47593	0.37693	0.971
7	1.22	70.00	-1.89	845.724	2.49903	1.50353	0.375005	0.964
8	1.22	70.00	-1.92	847.305	2.499	1.51897	0.373951	0.960
9	1.23	70.00	-1.94	848.642	2.49922	1.532	0.373073	0.957
10	1.24	70.00	-2.03	855.035	2.49971	1.59706	0.368844	0.940

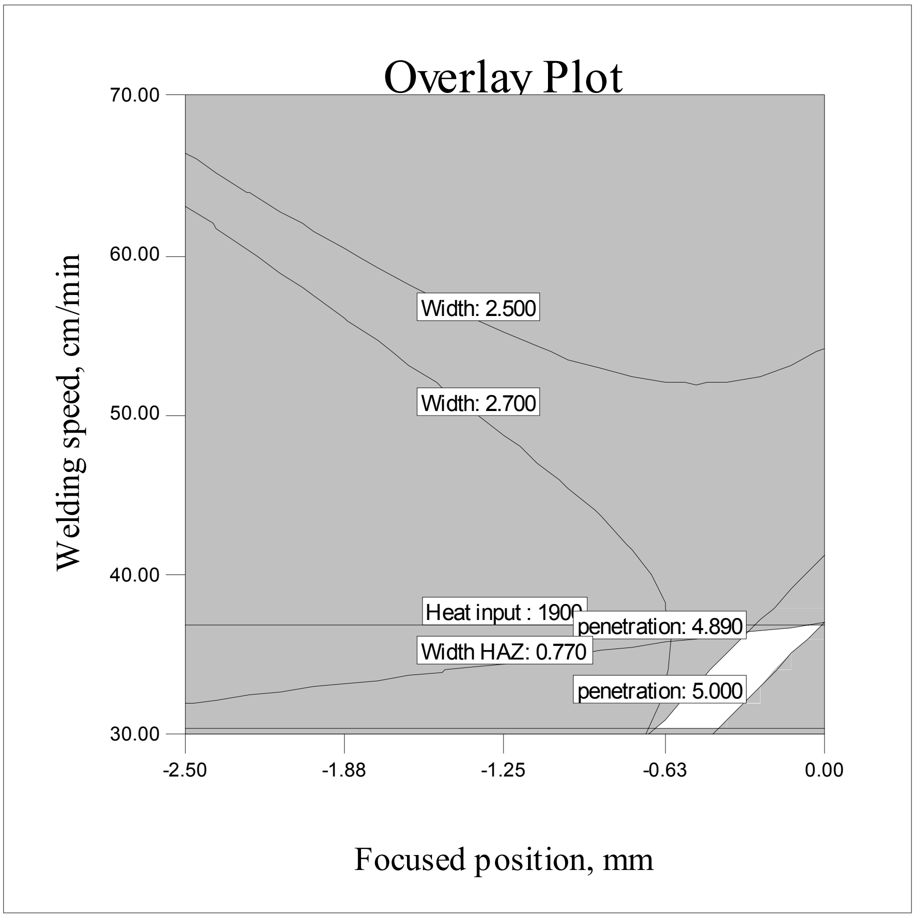

Fig. 2. Overlay plot shows the reign of the optimal working condition
based on the first criterion at LP = 1.42 kW.

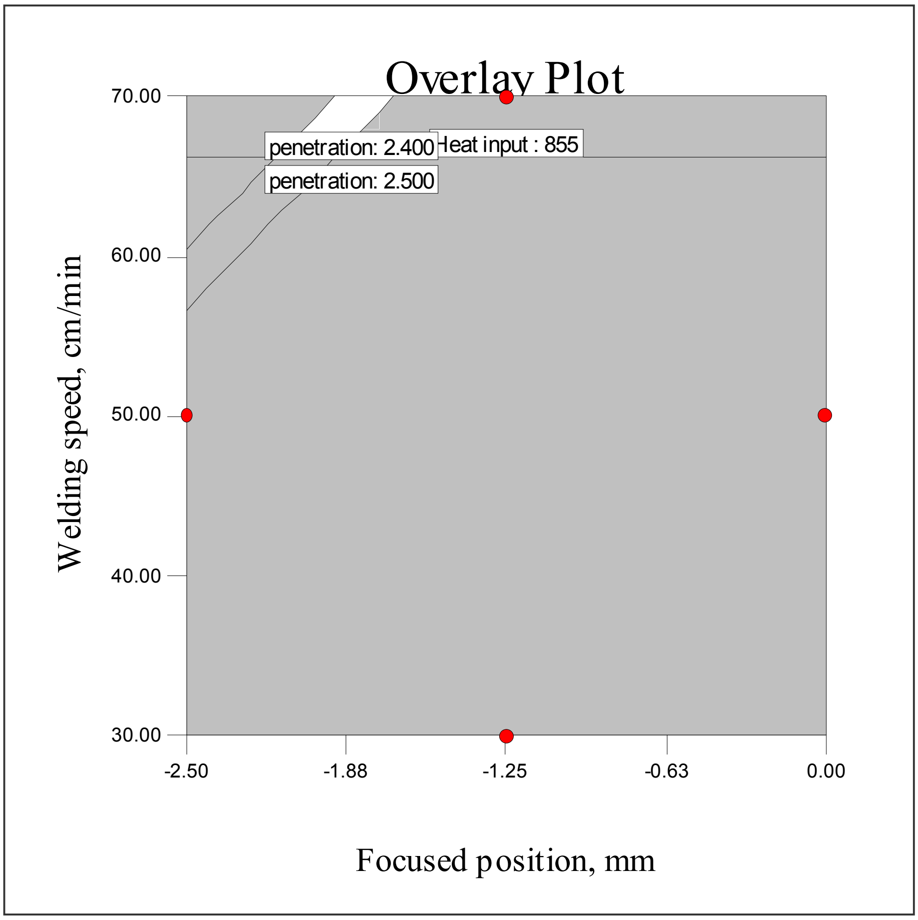

Fig. 3. Overlay plot shows the reign of the optimal working condition based on the second criterion at LP = 1.2 kW

5 Conclusions

The following points were concluded from this investigation among the factors limits considered.

1. Design expert software can be used for optimising the weld bead parameters and finding the corresponding optimum process factors.
2. Full depth penetration has a strong effect on the other bead parameters investigated.
3. Strong, efficient and low cost weld joints could be achieved using the optimum welding conditions.

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