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Comparison of Response Surface Methodology and Genetic Algorithm in Parameter Optimization of Laser Welding Process

K. Vijayan[1,*], *P. Ranjithkumar*[2] *and B. Shanmugarajan*[3]

[1] M.A.M. College of Engineering and Technology, Tamil Nadu, India-621105.
[2] M.A.M. School of Engineering, Tamil Nadu, India-621105.
[3] Welding Research Institute, Bharat Heavy Electrical Ltd., Tamil Nadu, India-620014.

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Abstract: This paper presents the comparative studies between Response Surface Methodology (RSM) and Genetic Algorithm (GA) in parameter optimization of laser welding process. Bead-on-plate weld was carried out on low carbon steel plate using diffusion cooled CO_2 laser welding system. Weld bead geometry and heat affected zone were modelled and optimized as function of three laser welding process parameters namely laser power, welding speed and focal position using RSM based historic data design. The effects of the various laser welding parameters on weld bead geometry and Heat Affected Zone (HAZ) were studied using contour plots. The interaction effect of process parameters on the responses were studied using analysis of variance. Optimum welding parameters to obtain desire quality of joint were determined by numerical optimization module in RSM. Thereafter, priori approach of GA was also applied to determine the optimum welding parameter. The predictive ability of both the methodologies was compared. RSM yield better result than GA.

Keywords: Genetic Algorithm; Laser Beam Welding; Optimization; Response Surface Methodology.

1 Introduction

Laser beam welding is recognized as an important advanced welding process by various manufacturing industries for joining a wide range of materials. This welding process is a radiant energy based process, in which laser beam with high energy is used for melting and joining of metals in any type of applications. This technique is widely used in various industries due to low heat input per unit volume, less HAZ, narrow and deep penetration, high aspect ratio, fine welding seam quality, defect-free and high speed welding [1].

Generally, weld quality is decided by the weld geometry like bead widths, height and depth of penetration. The geometry of the weld bead depends upon properties of materials and process variables such as laser power, welding speed, fiber diameter, focal position, shielding gas, etc. [2]. The proper selection and combination of laser welding process variables plays vital role in formation of the best bead geometry and mechanical properties [3]. Selection and controlling of laser welding process parameters are the main challenges for researchers and manufacturers. Conventionally, determination of welding parameters for a material with the required quality is a time consuming process, requires many trials involving error development effort and the skill of the engineers.

In recent years, computational techniques have been used to predict the welding parameters accurately with minimum number trials and also to develop mathematical model between welding process parameters and responses. Optimization of the welding process parameters is done using the mathematical model. Thereafter optimization techniques can be applied to determine the optimum welding condition. A comparative study of various techniques like RSM, GA, Artificial Neural Network (ANN), factorial technique and taguchi method was carried out. The authors proposed that the combination of two optimization techniques would reveal better result in determining the optimum welding

* Corresponding author e-mail: vijayan.mamcet@outlook.com

Table 1: Variable input parameters

Laser power	(P)	1500, 2500 and 3500 W
Welding speed	(S)	0.75 to 14 m/min
Focal position	(F)	−4, −2, 0, 2 and 4 mm.

condition [4]. Several studies conducted in laser welding processes are reported [5–9]. The review reveals a high level of interest in the adaptation of various modelling and optimization techniques like Kriging model, RSM, ANNs, FEM and GA to optimize the laser welding process.

In this research work the objectives are to minimize the weld bead widths & HAZ and to maximize the depth of penetration without compromising the quality of weld. Laser power, welding speed and focal position being considered as input process parameters. RSM based historic data design is used to develop the empirical relationship between input process parameters and output responses. Numerical optimization is used to determine the optimal welding condition. Then, GA is also used to optimize and determine the process parameter which results in the best bead dimensions and HAZ.

2 Experimental procedure

A diffusion cooled carbon dioxide laser welding system with a maximum power of 3.5 kW in Gaussian mode was used for conducting whole experiment. All experimental trials were carried out in bead-on-plate configuration on 7 mm thick low carbon steel plates of chemical composition C-0.003, P-0.013, S-0.005, Si-0.001, Mn-0.001, Al-0.04, N-0.01 and balance iron. Before welding, the surfaces of the plates were brushed and washed to get clean weld. The specimens were rigidly fixed on to a fully automated table. The working ranges of the input parameters were decided based on initial trials and expert opinions. The experiments were conducted in three stages using different values of laser power. At each stage, the welding speed and focal position were varied. During the experimental campaign helium at a flow rate 30 litres per minute was used as shielding gas. Laser power, welding speed and focal position were varied in accordance to Table 1

When laser power was too high and welding speed was low, an excessive melting of material occurs due to the addition of heat. On the other hand, the depth of penetration was very shallow while using high welding speed and low laser power [2]. So, twenty one experimental trail with depth of penetration greater than 1mm thickness were considered for investigation.

Macroscopic investigation of bead geometry and heat affected zone of the weld were carried out using stereo microscope. Two metallurgical specimens were cut away from each weldment. The metallurgical specimens were refined with abrasive wheels till surfaces displays mirror like finish. Thereafter, metallurgical specimens were exposed to etchant to reveal the weld bead geometry and HAZ. The measured (average) responses for twenty one successful combinations of input parameters are presented in Table 2.

3 Mathematical modelling

Mathematical models represent the empirical relationship between the input process parameters and output responses. The mathematical models are universally used to predict the output responses by conducting minimum number of experiments and reduce the time for selecting the right combinations of input process variables. Response surface methodology is a collection of mathematical and statistical techniques that are useful for modelling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response [11].

In this present work, the output responses such as depth of penetration, weld widths and HAZ were modelled via RSM based historical data design. The output responses are expressed in terms of the process variables such as laser power (P), focal position (F) and welding speed (S). The mathematical models in terms of coded factors and actual factors are shown in Eqs. 1–8. The output responses namely depth of penetration, weld widths and HAZ can be arrived by substituting the input process parameters (laser power, welding speed and focal position) in the equations shown in coded form.

Equations in coded form,

$$\text{Depth} = 1.71 + 1.44A - 2.58B + 0.03C \quad (1)$$

$$\text{Width-top} = 0.94 + 0.73A - 1.53B + 0.25C \quad (2)$$

$$\text{Width-middle} = 0.6409 + 0.3104A - 0.6125B - 0.2238C \quad (3)$$

$$\text{HAZ} = 0.39 + 0.29A - 0.39B - 0.065C \quad (4)$$

Equations in actual form,

$$\text{Depth} = 0.9896 + 1.436P - 0.3894S + 7.60E - 0.3F \quad (5)$$

$$\text{Width-top} = 0.8043 + 0.7346P - 0.2307S + 0.0615F \quad (6)$$

$$\text{Width-middle} = 0.5467 + 0.3104P - 0.0924S - 0.0559F \quad (7)$$

$$\text{HAZ} = 0.1069 + 0.2866P - 0.058238S - 0.01635F \quad (8)$$

4 Analysis of variance

Analysis of variance (ANOVA) test was executed to confirm the accuracy of the mathematical models and model terms. ANOVA test results for four response models are presented in Tables (3–6). These tables also display the other appropriate measures namely R^2,

Table 2: Input parameters and responses.

	Input parameters			Responses			
Std run	A: Power (kW)	B: Speed (m/min)	C: Focus (mm)	Depth (mm)	Width-top (mm)	Width-middle (mm)	HAZ
1	1.5	6	0	1.171	0.813	0.596	0.187
2	1.5	4	0	1.781	0.78	0.615	0.234
3	1.5	2	0	2.336	1.25	0.747	0.456
4	1.5	1	0	2.8	2.025	1.197	0.621
5	2.5	6	0	2.417	0.999	0.582	0.343
6	2.5	4	0	2.429	1.3	0.754	0.487
7	2.5	2	0	2.607	1.647	0.939	0.589
8	2.5	1	0	4.655	3.134	1.2	0.902
9	3.5	14	0	2.028	0.869	0.455	0.413
10	3.5	12	0	2.017	0.827	0.6	0.543
11	3.5	10	0	1.966	0.941	0.65	0.559
12	3.5	8	0	1.689	1.117	0.869	0.568
13	3.5	6	0	2.12	1.531	1.066	0.624
14	3.5	4	0	2.038	1.728	1.2	0.687
15	3.5	2	0	3.786	2.255	1.282	0.807
16	3.5	1	0	6.183	3.372	1.882	0.951
17	3.5	0.75	0	7	4.138	1.676	1.219
18	3.5	1	2	6.763	2.25	1.171	0.926
19	3.5	1	4	6.286	4.344	1.49	1.203
20	3.5	1	-2	6.545	3.302	1.71	1.225
21	3.5	1	-4	6.319	3.203	1.78	1.217

Table 3: ANOVA analysis for Depth

Source	Sum of Squares	df	Mean Square	F-Value	p-value Prob $> F$	Remark
Model	62.11	3	20.7	16.24	< 0.0001	significant
A-Power	26.29	1	26.29	20.63	0.0003	
B-Speed	46.03	1	46.03	36.11	< 0.0001	
C-Focus	2.31E-03	1	2.31E-03	1.81E-03	0.9665	
Residual	21.67	17	1.27			
Cor Total	83.78	20				

$R^2 = 0.74$; Adjusted $R^2 = 0.69$;
Predicted $R^2 = 0.60$; Adequate Precision = 10.47

Table 4: ANOVA analysis for Top-width

Source	Sum of Squares	df	Mean Square	F-Value	p-value Prob $> F$	Remark
Model	20.12	3	6.71	18.08	< 0.0001	significant
A-Power	6.88	1	6.88	18.54	0.0005	
B-Speed	16.15	1	16.15	43.54	< 0.0001	
C-Focus	0.15	1	0.15	0.41	0.5316	
Residual	6.31	17	0.37			
Cor Total	26.43	20				

$R^2 = 0.76$; Adjusted $R^2 = 0.71$;
Predicted $R^2 = 0.54$; Adequate Precision = 12.2

Table 5: ANOVA analysis for Middle-width

Source	Sum of Squares	df	Mean Square	F-Value	p-value Prob $> F$	Remark
Model	3.42	3	1.14	38.68	< 0.0001	significant
A-Power	1.22	1	1.22	41.59	¡ 0.0001	
B-Speed	2.59	1	2.59	87.84	¡ 0.0001	
C-Focus	0.12	1	0.12	4.24	0.0551	
Residual	0.50	17	0.029			
Cor Total	3.93	20				

$R^2 = 0.87$; Adjusted $R^2 = 0.84$;
Predicted R^2 =0.79; Adequate Precision = 19.11

adjusted R^2, predicted R^2 and desirability ratio. When the calculated value of F is greater than 4, the model terms are substantial. The model terms are statistically substantial, if the obtained probability value (p-value) is smaller amount than 0.05 [10]. In this case 95% confidence level was considered. It can be observed that the models are substantial as the p-values are less than 0.05. The value of adequate precision ratio over 4 shows the model is substantial. The models are substantial when the other adequacy measures R^2 and adjusted R^2 are in fair agreement with each other.

5 Effect of process parameters

5.1 Depth

The combined effects of input process parameters on depth of penetration is shown in perturbation plot (Fig. 1(a)), it is very clear that depth of penetration increases and decreases significantly with increase in laser power and decrease in welding speed respectively, whereas a slight decrease in depth of penetration is observed with increase in focal position. The increase in laser power leads to increase the energy density input causing more metal to melt and consequently, more depth of penetration is achieved. However, the reverse occurrence is witnessed for welding speed, as increased

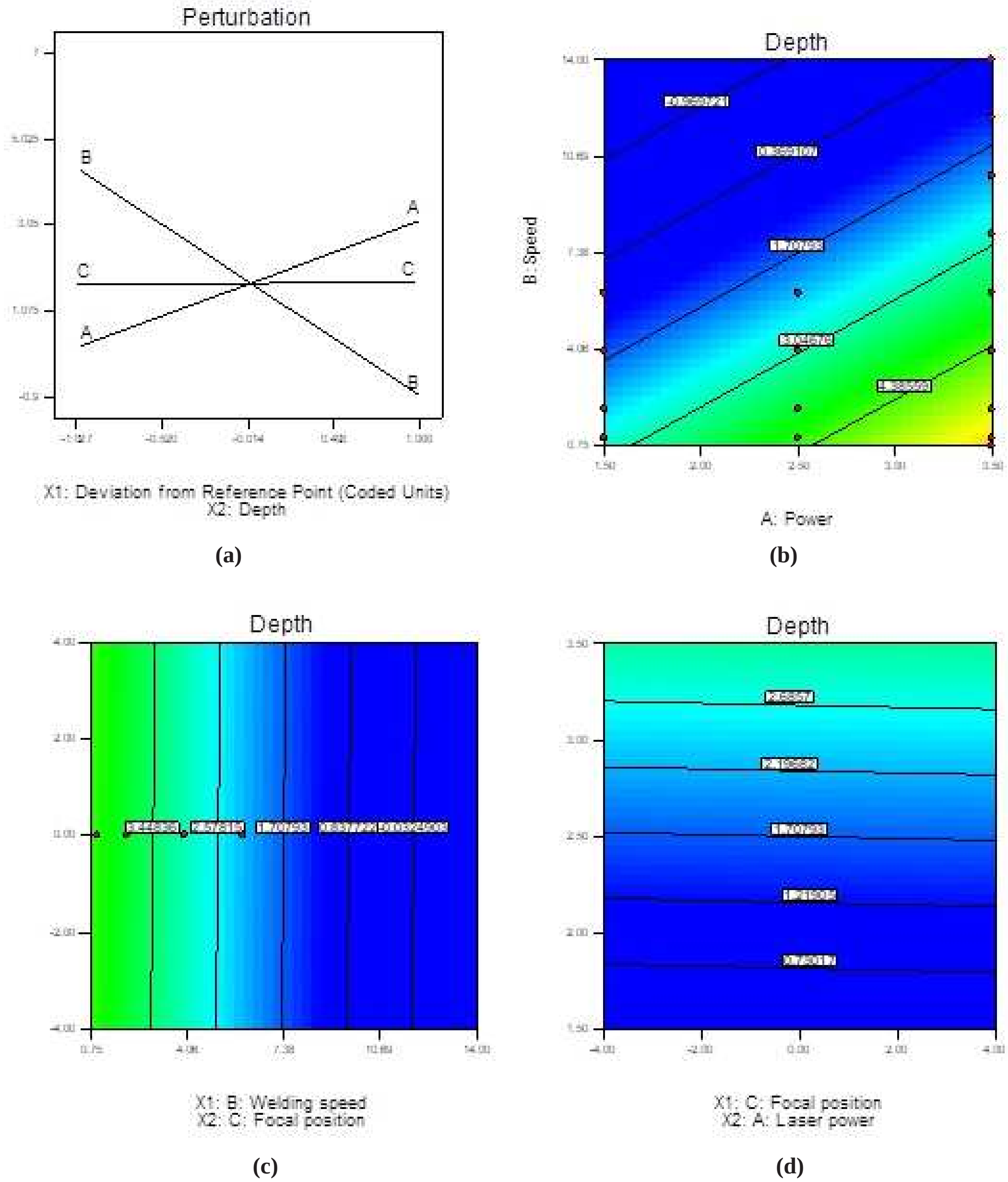

Fig. 1: (a) Perturbation graph represents the effect of various factors on depth of penetration (A: laser power, B: welding speed, C: focal position), (b) Contours plot illustrates the effects of laser power and welding speed on depth of penetration, for focal position = 0 mm, (c) Contours plot illustrates the effects of welding speed and focal position on depth of penetration, for laser power = 2500 W, and (d) Contours plot illustrates the effects of laser power and focal position on depth of penetration, for welding speed = 7.38 m/min

welding speed reduces the interaction duration and hence less time is available for the heat energy to flow deep into the specimen.

The contour graphs are presented in Figs. 1(b)–(d), show the combined effects between the process parameters on penetration depth obtained from the experimental results. Of the three two-factor interactions, the combined effect of laser power-welding speed is utmost significant. Moreover, it is obvious that various combinations of the input process parameters are possible to obtain the desired depth of penetration. It can be concluded that a combination of greater laser power, lesser welding speed and medium focal position needs to be chosen within the specified range to obtain deeper penetration.

Table 6: ANOVA analysis for HAZ

Source	Sum of Squares	df	Mean Square	F-Value	p-value Prob $> F$	Remark
Model	1.78	3	0.59	30.24	< 0.0001	significant
A-Power	1.05	1	1.05	53.38	< 0.0001	
B-Speed	1.03	1	1.03	52.47	< 0.0001	
C-Focus	0.011	1	0.011	0.55	0.4704	
Residual	0.33	17	0.02			
Cor Total	2.11	20				

$R^2 = 0.84$; Adjusted $R^2 = 0.81$;
Predicted $R^2 = 0.70$; Adequate Precision $= 15.21$

5.2 Top-width

Fig. 2(a) shows the perturbation graph illustrating the effects of individual laser welding parameters on top-width, whereas Figs. 2(b)–(d) are the contour plots presenting the combined effects of two-factor on top-width. From perturbation graph, it is witnessed that welding speed is the utmost significant parameter affecting the top-width; also the result shows that laser power contributes a secondary effect on top-width. An increase in laser power and a decrease in welding speed results in wider top-width due to increased energy density input. Because, heat input is directly proportionated with laser power and inversely proportionated with welding speed, similar result was obtained from an experimental study reported in [10]. Large amount of material is melted at this stage, which results wider width at the top.

Fig. 2(c) illustrates the effect of welding speed and focal position on top-width; it is observed that top-width increases with decrease in welding speed. Again this is due to the addition of more heat input at slow welding speed. The focal position has little effect on top-width. The optimum value of top-width can be obtained by appropriate combination of input process parameters. The contour graph for interaction of laser power and focal position is illustrated in Fig. 2(d). It is evident that top-width tends to increase with laser power and while focal position kept above the surface of specimen. Also, when the focal position is kept above the surface of specimen; the area of interaction increases due to defocused beam. Wide area of the material is melted due to wide spread of defocused laser beam at the weld interface, results a wider top-width.

5.3 Middle-width

The combination effects of input parameters on middle-width is shown in perturbation graph (Fig. 3(a)), it is obvious that middle-width increases and decreases significantly with increase in laser power and decrease in welding speed respectively, whereas a slight increase in middle-width is observed when focal position kept below the surface of specimen. The contour graphs Figs. 3(b)–(d) show the effects of two-factor interactions on middle-width. The interaction effect of laser power and welding speed is shown in Fig. 3(b); it is observed that higher laser power with lower welding speed results in wider middle-width. Large amount of material is melted at this stage, results in wider middle-width of weldbead.

This is because of the fact that more heat input is obtained at greater laser power and smaller welding speed. Fig. 3(c) presents the contour plot for interaction between welding speed and focal position. Middle-width increases with decrease in welding speed and while focal position is kept below the surface of the specimen as stated early. Similarly the combination effect between laser power and focal position is shown in Fig. 3(d), middle-width increases with laser power and while focal position is kept below the surface of the specimen. When the focal position is kept under the surface of specimen, power density in metal inside is more than that on the outer side of the specimen.

5.4 HAZ

Fig. 4(a) represents the interaction effect of the laser power, welding speed and focal position on HAZ; it is observed that HAZ increases with an increase in laser power and a decrease in welding speed, similar trend was observed from an experimental study reported in [10]. Whereas a slight increase in HAZ is observed when focal position kept below the surface of the specimen. Contour graph Fig. 4(b) shows the two-factor combination effect of laser power and welding speed on HAZ. It is clear that laser power and welding speed are the utmost significant input process parameters affecting HAZ.

An increase in laser power and a decrease in welding speed results in wider HAZ, due to the addition of more heat input. Because, heat input is directly proportional to laser power and inversely proportional to welding speed. The interaction effect of welding speed and focal position on HAZ is shown in Fig. 4(c). The HAZ increases with laser power whereas focal position has little effect. Similarly, the interaction effect between laser power and focal position is shown Fig. 4(d); HAZ increases while decreasing the welding speed and the focal position has very little effect.

6 Numerical Optimization

Determination of optimized process parameters is very essential elements in all type welding processes. RSM was used to analyze the effect of each parameter on the bead geometry and HAZ, and also to predict the optimal choice for each welding parameter such as laser power, welding speed and focal position. Optimization aims at obtaining the best combination of the laser power, welding speed and focal position that has the maximum influence on the bead geometry and HAZ.

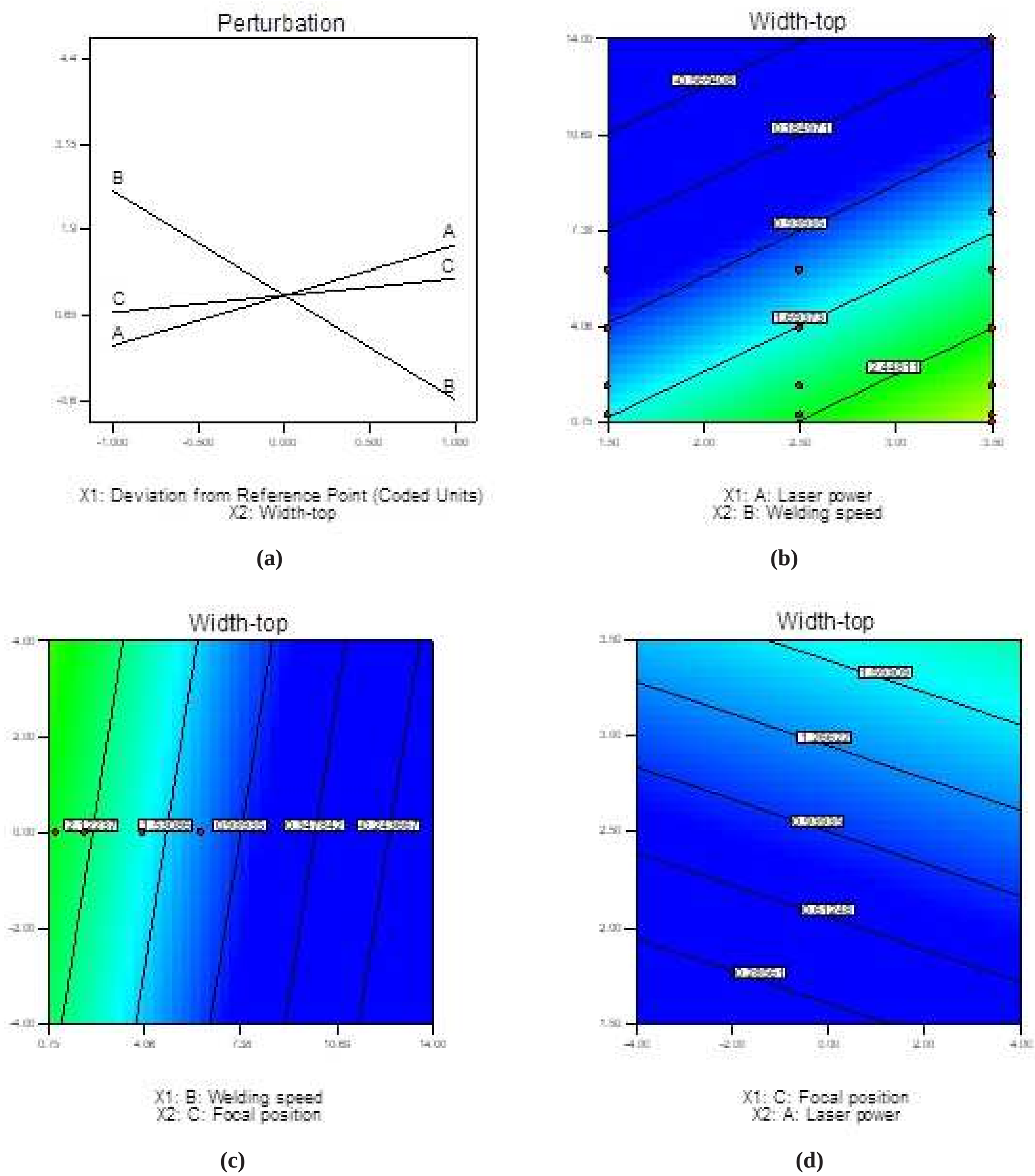

Fig. 2: (a) Perturbation graph represents the effect of various factors on top-width (A: laser power, B: welding speed, C: focal position), (b) Contours plot illustrates the effects of laser power and welding speed on top -width, for focal position = 0 mm, (c) Contours plot illustrates the effects of welding speed and focal position on top-width, for laser power = 2.5 kW, and (d) Contours plot illustrates the effects of focal position and laser power on top-width for welding speed = 7.38 mm/min

Numerical optimization module provided in design-expert software v7 is used to find the right combination of laser power, welding speed and focal position that instantaneously satisfy the minimum weld widths and HAZ and maximum depth of penetration. The goal was to obtain maximum depth with no limitations on either process parameters or responses, by giving different importance to all the responses. Table 7, illustrates the goals, limits and importance of each factor on the responses. The optimal solution of the criteria is presented in Table 8 According to the criteria, optimal parameters were determined as laser power 3.5 kW, welding speed 0.75 m/min. and focal position-4 mm (below the surface of the specimen).

The solution with highest desirability value is considered as optimum and the corresponding parametric

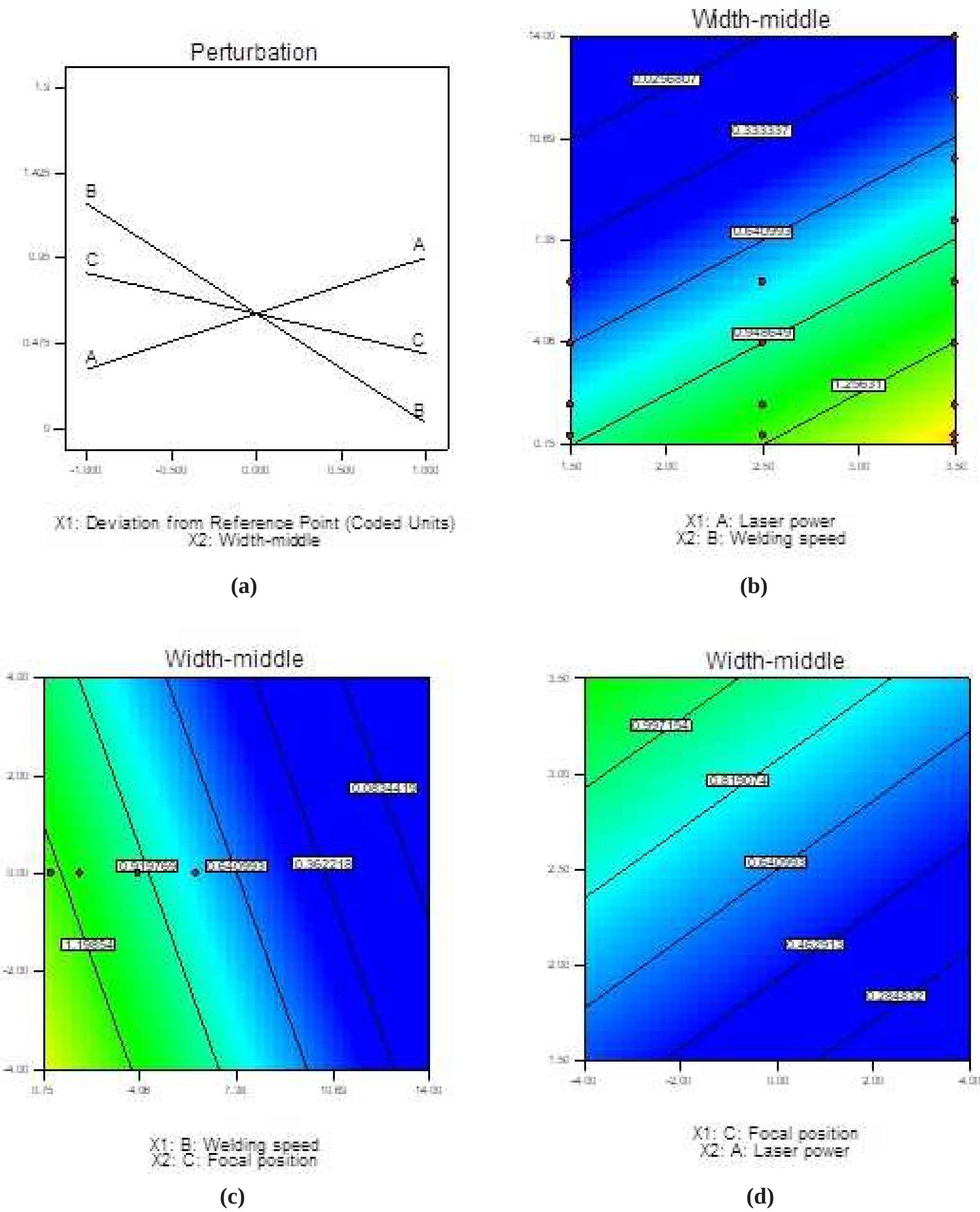

Fig. 3: (a) Perturbation graph represents the effect of various factors on middle- width (A: laser power, B: welding speed, C: focal position), (b) Contours plot illustrates the effects of laser power and welding speed on middle- width, for focal position = 0 mm, (c) Contours plot illustrates the effects of welding speed and focal position on middle-width, for laser power = 2.5 kW, and (d) Contours plot illustrates the effects of focal position and laser power on middle-width for welding speed = 7.38mm/min

values are considered as optimal welding conditions [11]. In this study the highest desirability value 0.851 is obtained.

7 Genetic Algorithm

Genetic Algorithm (GA) was introduced by Professor John Holland, University of Michigan in 1976. GA is a computerized search and optimization algorithm based on the mechanics of natural genetics and natural selection, works well in both continuous and discrete search space.

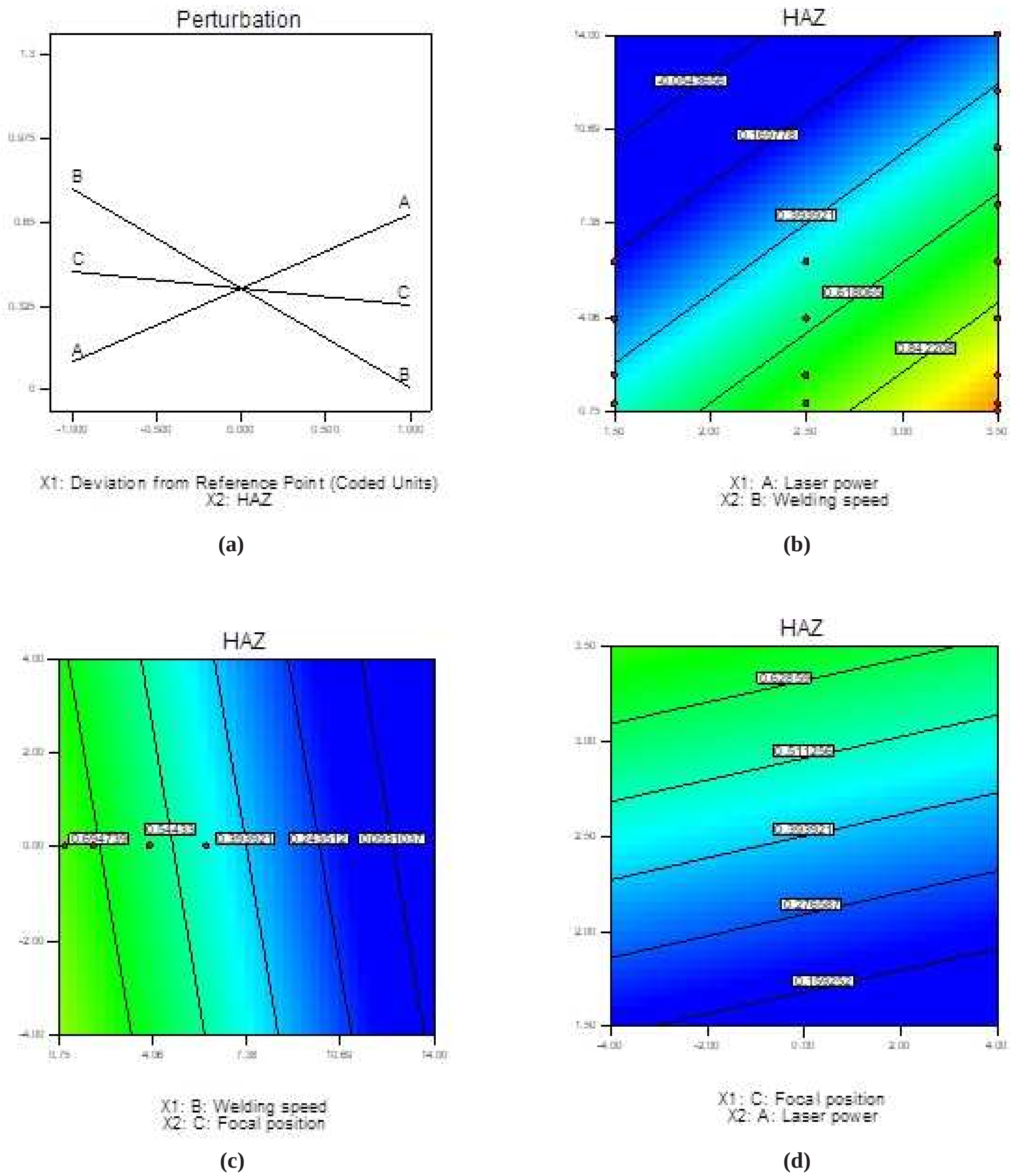

Fig. 4: (a) Perturbation graph showing the effect of various factors on HAZ (A: laser power, B: welding speed, C: focal position), (b) Contours plot illustrates the effects of laser power and welding speed on HAZ, for focal position = 0 mm, (c Contours plot illustrates the effects of welding speed and focal position on HAZ, for laser power = 2.5 kW, and (d) Contours plot illustrates the effects of focal position and laser power on HAZ for welding speed = 7.38 mm/min

Operation of GA starts with a population of random strings representing design variable. The fitness function of string is defined; then strings are evaluated, compared with the best value, and modified according to the requirement. In this technique the population is operated by three operators namely selection, crossover and mutation to develop a new population. Then, the new population is further assessed and tested for termination criteria. The operators are iteratively operated to meet the termination criteria. In GA terminology one cycle of operation is referred as a generation. The laser beam welding input parameters namely laser power, welding speed and focal position has very strong influence on depth of penetration, weld widths and HAZ. Objectives of

Table 7: Criteria for numerical optimization

Parameters	Goal	Lower limit	Upper limit	Importance
Laser power (kW)	Range	1.5	3.5	3
Welding speed (m/min)	Range	0.75	14	3
Focal position (mm)	Range	−4	0	3
Depth (mm)	max.	1.171	7	5
Top width (mm)	Range	0.78	4.344	3
Middle width (mm)	Range	0.455	1.882	3
HAZ (mm)	Range	0.134	0.548	5

Table 8: Optimal solutions of the criteria

No	Power (kW)	Speed (m/min)	Focal position (mm)	Depth (mm)	Width top (mm)	Width middle (mm)	HAZ	Desirability
1	3.50	0.75	−4.00	5.694	2.956	1.787	1.131	0.851
2	3.50	0.75	−3.99	5.694	2.957	1.787	1.131	0.851
3	3.50	0.75	−3.97	5.694	2.958	1.786	1.131	0.851
4	3.50	0.75	−4.00	5.690	2.954	1.786	1.130	0.851
5	3.50	0.77	−4.00	5.687	2.952	1.786	1.130	0.850

this study are to maximize the depth of penetration and middle-width and to minimize the top-width and HAZ by changing the combination of input process parameters. The objectives are combined to single objective function (COF) by assigning different weightage to every response [13]. The normalized COF is shown in Eq. 9.

$$\begin{aligned} \mathrm{COF} = {} & (0.4/7 \times \text{Depth}) + (0.2/1.882 \times \text{Middle width}) \\ & (0.2/4.344 \times \text{Top width}) - (0.2/1.225 \times \text{HAZ}) \end{aligned} \quad (9)$$

Steps in GA

(i) Evaluate the fitness of every individual in the population.
(ii) Select the best and fittest parents from the given population.
(iii) Perform crossover operation by recombining the individuals from parents to form children (new generation).
(iv) Mutate the new generation.
(v) If termination condition is not reached, go back to step 2, else terminate the operation, and return the best individual in the current population.

In the present investigation, GA coding is done using Microsoft Visual Studio 2008 as Front end, MS ACCESS 2007 as the back end and is run on Intel (R) Core i3-2350M [14]. The following are the GA-parameters, Population size = 100, Probability of mutation = 0.8, Maximum number of generation = 200, Selection operator = Tournament method, Crossover operator = Single point operator, Crossover probability = 0.8 and fitness parameter depth, top-width, middle-width and HAZ. A test of 20 runs was conducted for the selected population size. GA was run for 200 generations as the result remained stagnant after 30 generations. The optimum input process parameters are predicted as laser power 3.5 kW, welding speed 0.75 m/min and focal position −3.94 mm.

Table 9: Comparison of results

Optimal solution	Numerical optimization	Genetic algorithm	Deviation
Laser power (kW)	3.50	3.50	0
Welding speed (m/min)	0.75	0.75	0
Focal position (mm)	−4	−3.94	0.06
Depth (mm)	5.694	5.431	0.53
Top width (mm)	2.956	3.255	0.29
Middle width (mm)	1.787	1.508	0.279
HAZ (mm)	1.131	1.244	0.069

8 Results and Discussion

The optimum welding conditions were determined using different optimization techniques. Table 9 presents the optimum welding parameters predicted by RSM that would result to maximum depth of penetration of about 5.694 mm, which is superior to that attained with priori approach of GA. According to the RSM, the optimum value of the laser power has to be 3.5 kW, welding speed has to be 0.75 m/min and focal position −4 mm. On the other hand, while putting the priori approach of GA, the laser power is has to be kept at 3.5 kW, welding speed has to reach a value of 0.75 m/min, when the focal position is set around the −3.94 mm. Using GA, the maximum depth of penetration achieved is 5.431 mm and the minimum attainable top-width is 3.255 mm, as can be seen in Table 9. Both the methods are equally good, the parameter combinations with RSM is best according to objectives of investigation, which can be selected as the optimum laser welding conditions.

9 Conclusions

A comparative study between RSM and GA for parameter optimization of laser welding process was carried out. Bead-on-plate configuration was adopted for welding of low carbon steel plates. The influence of the various laser welding parameters such as laser power, welding speed and focal position on weld bead geometry and heat affected zone was investigated. Response surface methodology was used for developing the mathematical models between laser welding parameters and responses. Optimization problem was developed to minimize weld widths & HAZ and to maximize depth of penetration. The optimum welding parameters were determined by RSM and GA. The parameters combination obtained by RSM is better than GA.

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K. Vijayan received the B.E. in Mechanical Engineering from Bharathidasan University, Tamil Nadu, India, in 1998, and M.E. in Manufacturing Engineering from Anna University, Tamil Nadu, India, in 2007. Currently, he is working as associate professor in M.A.M College of Engineering and Technology, Tamil Nadu, India. His research interests include Welding, Material science and Engineering optimization.

P. Ranjithkumar received the Ph.D. in Manufacturing Engineering from National Institute of Technology, Trichy, Tamil Nadu, India in 2010. Currently, he is working as professor at M.A.M. School of Engineering, Tamil Nadu, India. His research interest includes Micro-machining, Manufacturing Engineering and Materials Science.

B. Shanmugharajan received the Ph.D. in Welding Technology from National Institute of Technology, Trichy, Tamil Nadu, India in 2017. Currently, he is working as Senior Manager in Welding Research Institute, Bharat Heavy Electrical Ltd., Tamil Nadu, India. His research interest includes Materials Science, Welding and Engineering optimization.