Multi-response optimization of CO_2 laser welding process of austenitic stainless steel

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Abstract

Recently, laser welding of austenitic stainless steel has received great attention in industry, due to its wide spread application in petroleum refinement stations, power plant, pharmaceutical industry and households. Therefore, mechanical properties should be controlled to obtain good welded joints. The welding process should be optimized by the proper mathematical models. In this research, the tensile strength and impact strength along with the joint operating cost of laser welded butt joints made of AISI304 was investigated.

Design-expert software was used to establish the design matrix and to analyze the experimental data. The relationships between the laser welding parameters (laser power, welding speed and focal point position) and the three responses (tensile strength, impact strength and joint operating cost) were established. Also, the optimization capabilities in design-expert software were used to optimise the welding process.

The developed mathematical models were tested for adequacy using analysis of variance and other adequacy measures. In this investigation the optimal welding conditions were identified in order to increase the productivity and minimize the total operating cost. Overlay graphs were plotted by superimposing the contours for the various response surfaces. The process parameters effect was determined and the optimal welding combinations were tabulated.

Keywords: Optimization, Tensile strength, Impact strength, Joint cost, laser welding, AISI304, RSM.

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1. Introduction

The nature of the laser beam enables it to be focused on a small spot, allowing high power density to be achieved. This advantage is the main feature in representing its potential as a welding process. Besides that, the high production rate achievable with the laser beam welding is attractive for many applications [1]. In fact, stainless steels are often welded using laser beams in industrial processes. This technique produces good metallurgical properties, high production rate and increases automation possibilities [2, 3]. It is well known that whatever the welding method, fusion welding generally involves heating the two joined parts together which can cause modification with loss of material characteristics. In other words the properties of the area around the weld-bead (HAZ) would be affected with variation in hardness, reduction of tensile strength, toughness …etc.

The main challenge for the manufacturer is how to choose the process input parameters that would produce an excellent welded joint. Conventionally, to define the weld input parameters for new welded products to produce a welded joint with the required specifications is a time-consuming trial accompanied by error development effort, with weld input parameters chosen by the skill of the engineer or machine operator. Then the weld is inspected to determine whether it meets the specification or not. Eventually the chosen parameters would produce a welded joint close to the required specification. Also, what often not considered, or achieved are optimised welding parameters combinations. In other words, there are often alternative ideal welding parameters combinations, which can be used if they can only be determined.

In order to predict the welding parameters accurately without consuming time, materials and labour effort, there are various methods of obtaining the desired output variables through models development. In the last two decades, the use of Design of Experiment (DoE) has grown rapidly and been adapted for many applications in different areas. Responses Surface Methodology (RSM) is the best known type of DoE design; the concept of RSM was introduced in the early 1950’s by Box and Wilson [4]. Since then, many researchers have used the RSM procedures in different disciplines, for example physics, engineering and chemistry. Wang and Rasmussen [5] have investigated the inertia welding process of low carbon steels using RSM. Koichi et al. [6] studied the combination of welding conditions that produce maximum notched tensile strength of the friction welded joints of S4 5C carbon steel by means of RSM. Benyounis et al. [7] have proposed models using RSM to investigate the effect of welding parameters in

SAW on the impact strength. Optimization of friction welding of dissimilar materials using factorial design was studied by Murti and Sundaresan [8]. Olabi et al. [9] have applied RSM to investigate the effect of laser welding parameters on residual stress distribution over the depth, at three locations from the weld centre line of AISI304 butt joints. Benyounis et al. [10] have also reported the effect of CO_2 laser welding parameters on the impact strength and Notched Tensile Strength (NTS) of butt joints made of medium carbon steel plates. Benyounis et al. [11] have done another work to predict the residual stress near the weld seem for CO_2 laser butt-welding joints of AISI 304 plates. Control of distortion in robotic CO_2-shielded FCAW was investigated by Arya and Parmar [12] using fractional factorial technique.

It is important to investigate the mechanical properties of any weld joint in order to describe its performance. The tensile strength and the impact strength are among the most vital mechanical properties. In this study, the tensile and impact strength will be investigated. Furthermore, the weld joint operating cost was also considered in this investigation, for purpose of optimization. Therefore, this paper aims at first to employ RSM to relate the laser welding input parameters (laser power, welding speed and focal position) to the three responses (i.e. tensile strength, impact strength and operating cost). The second aim is to find the optimal welding combination that would maximize both tensile and impact strengths at a relatively low cost could be determined. The most important laser welding variables were considered in this investigation, because the utilized welding machine can control these variables only.

2. Methodology

2.1 Response Surface Methodology

Engineers often wish to determine the values of the process input parameters at which the responses reach their optimum. The optimum could be either a minimum or a maximum of a particular function in terms of the process input parameters. RSM is one of the optimization techniques currently in widespread use in describing the performance of the welding process and finding the optimum of the responses of interest.

RSM is a set of mathematical and statistical techniques that are useful for modelling and predicting the response of interest affected by a number of input variables with the aim of optimizing this response [13]. RSM also specifies the relationships among one or more measured responses and the essential controllable input factors [14]. When all independent variables are measurable, controllable and continuous in the experiments, with negligible error, the response surface can be expressed by:

$$y = f(x_1, x_2, \ldots x_k) \quad (1)$$

Where: k is the number of independent variables

To optimize the response "y", it is necessary to find an appropriate approximation for the true functional relationship between the independent variables and the response surface. Usually a second order polynomial Eq.2 is used in RSM.

$$y = b_o + \sum b_i \chi_i + \sum b_{ii} \chi_{ii}^2 + \sum b_{ij} \chi_i \chi_j + \varepsilon \quad (2)$$

2.2 Experimental design

The test was designed based on a three factors five levels central composite rotatable design with full replication [13]. The laser welding input variables are Laser power, travel speed and focus point position. In order to find the range of each process input parameter, trial weld runs were performed by changing one of the process parameters at a time. Absence of clear welding defects, full penetration, a smooth and uniform welded surface with sound face and root bead were the criteria of selecting the working ranges. Fig. 1 presents the bead shape and size of the selected samples. Table 1 shows the process variables, their coded and actual values. Statistical software Design-Expert V7 was used to code the variables and to establish the design matrix shown in Table 2. RSM was applied to the experimental data using the same software; polynomial Eq. 2 was fitted to the experimental data to obtain the regression equations for all responses. The statistical significance of the terms in each regression equation was examined using the sequential F-test, lack-of-fit test and other adequacy measures using the same software to obtain the best fit.

Table 1: Independent variable and experimental design levels used.

Variable	Notation	Unit	Limits				
			-1.682	-1	0	1	1.682
Laser power	P	[kW]	1.03	1.1	1.2	1.3	1.37
welding speed	S	[mm/s]	26.48	35	47.5	60	68.52
Focus position	F	[mm]	-1	-0.8	-0.5	-0.2	0

Table 2: Design matrix.

Experimental information					Results		
No	Run order	Parameters			Responses		
		P, kW	S, cm/min	F, mm	Average Tensile strength MPa	Average Impact strength J	Joint cost €/m
1	8	1.1	35	-0.8	666	37	0.3489
2	4	1.3	35	-0.8	614	43	0.3619
3	15	1.1	60	-0.8	643	35	0.2035
4	5	1.3	60	-0.8	632	38	0.2111
5	13	1.1	35	-0.2	652	43	0.3489
6	11	1.3	35	-0.2	640	47	0.3619
7	17	1.1	60	-0.2	536	39	0.2035
8	12	1.3	60	-0.2	621	42	0.2111
9	7	1.03	47.5	-0.5	546	27	0.2537
10	18	1.37	47.5	-0.5	529	41	0.2700
11	10	1.2	26.5	-0.5	666	45	0.4694
12	6	1.2	68.5	-0.5	637	37	0.1816
13	1	1.2	47.5	-1	658	41	0.2619
14	19	1.2	47.5	0	629	45	0.2619
15	2	1.2	47.5	-0.5	692	41	0.2619
16	3	1.2	47.5	-0.5	658	43	0.2619
17	16	1.2	47.5	-0.5	630	43	0.2619
18	14	1.2	47.5	-0.5	638	44	0.2619
19	9	1.2	47.5	-0.5	672	43	0.2619
20	20	1.2	47.5	-0.5	671	45	0.2619

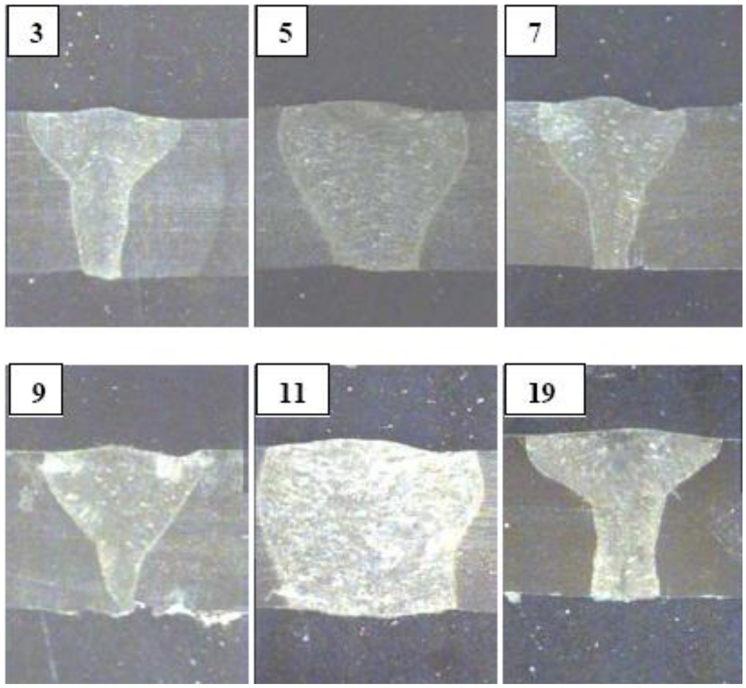

Fig. 1: Macrographs shows the bead shape, width and penetration of selected samples. The numbers on each macrograph indicates the sample number.

2.3 Desirability approach

There are many statistical techniques for solving multiple response problems like overlaying the contours plot for each response, constrained optimization problems and desirability approach. The desirability method is recommended due to its simplicity, availability in the software and provides flexibility in weighting and giving importance for individual response. Solving such multiple response optimization problems using this technique consists of using a technique for combining multiple responses into a dimensionless measure performance called as overall desirability function. The desirability approach consists of transforming each estimated response, Y_i, into a unitless utilities bounded by $0 < d_i < 1$, where a higher d_i value indicates that response value Y_i is more desirable, if $d_i = 0$ this means a completely undesired response or vice versa when $d_i = 1$ [15]. In the current work the individual desirability for each response d_i was calculated using Eqs. 3 to 6. The shape of the desirability function can be changed for each goal by the weight field 'wt_i'. Weights are used to give more emphasis to the upper/lower bounds or to emphasize the target value. Weights could be ranged between 0.1 and 10; a weight greater than one gives more emphasis to the goal, while weights less than one give less emphasis. When the weight value is equal to one, this will make the d_is vary from zero to one in a linear mode. In the desirability objective function (D), each response can be assigned an importance (r), relative to the other responses. Importance varies from the least important a value of 1(+), to the most important a value of 5(+++++). If the varying degrees of importance are assigned to the different responses, the overall objective function is shown in equation 7 below. Where n is the number of responses in the measure and T_i is the target value of i^{th} response [16].

For goal of maximum, the desirability will be defined by:

$$d_i = \begin{cases} 0 & , \quad Y_i \le Low_i \\ \left(\dfrac{Y_i - Low_i}{High_i - Low_i}\right)^{wt_i} & , \quad Low_i \langle Y_i \langle High_i \\ 1 & , \quad Y_i \ge High_i \end{cases} \tag{3}$$

For goal of minimum, the desirability will be defined by:

$$d_i = \begin{cases} 1 & , \quad Y_i \le Low_i \\ \left(\dfrac{High_i - Y_i}{High_i - Low_i}\right)^{wt_i} & , \quad Low_i \langle Y_i \langle High_i \\ 0 & , \quad Y_i \ge High_i \end{cases} \tag{4}$$

For goal as a target, the desirability will be defined by:

$$d_i = \begin{cases} \left(\dfrac{Y_i - Low_i}{T_i - Low_i}\right)^{wt_{1i}} & , \quad Low_i \langle Y_i \langle T_i \\ \left(\dfrac{Y_i - High_i}{T_i - High_i}\right)^{wt_{2i}} & , \quad T_i \langle Y_i \langle High_i \\ 0 & , \quad Otherwise \end{cases} \tag{5}$$

For goal within range, the desirability will be defined by:

$$d_i = \begin{cases} 1 \quad , \quad Low_i \langle Y_i \langle High_i \\ 0 \quad , \quad Otherwise \end{cases} \tag{6}$$

$$D = \left(\prod_{i=1}^{n} d_i^{r_i} \right)^{\frac{1}{\sum r_i}} \tag{7}$$

2.4 Optimization

The optimization part in Design-expert software V7 searches for a combination of factor levels that simultaneously satisfy the requirements placed (i.e. optimization criteria) on each one of the responses and process factors (i.e. multiple response optimization). Numerical and graphical optimization methods were used in this work by selecting the desired goals for each factor and response. As mentioned before the numerical optimization process involves combining the goals into an overall desirability function (D). The numerical optimization feature in the design expert package finds one point or more in the factors domain that would maximize this objective function. In a graphical optimization with multiple responses, the software defines regions where requirements simultaneously meet the proposed criteria. Also, superimposing or overlaying critical response contours can be defined on a contour plot. Then, a visual search for the best compromise becomes possible. In the case of dealing with many responses, it is recommended to run numerical optimization first; otherwise it could be impossible to find out 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 [16]. Fig. 2 shows flow chart of the optimization steps in the design-expert software.

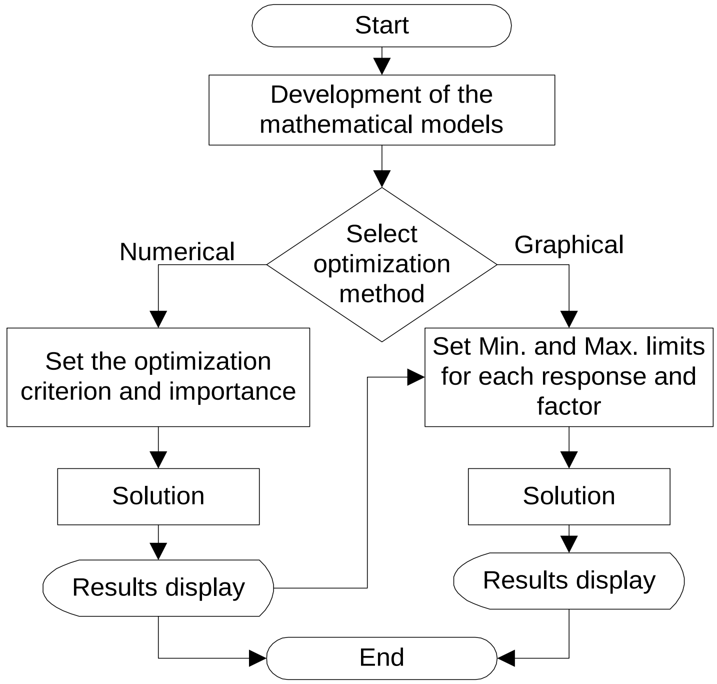

Fig. 2: Optimization steps.

3. Experimental work

3.1 Laser Welding

The base metal is AISI304 with has a microstructure of equiaxial austenitic grains and a chemical composition shown in Table 3 cold rolled in the form of plates with dimension of 160 mm x 80 mm x 3 mm were butt joined using a 1.5 kW CW CO_2 Rofin laser and a ZnSe focusing lens with focal length of 127 mm. Argon gas was used as a shielding gas with a constant flow rate of 5 l/min. The direction of the welding bead is perpendicular to the rolling direction of the stainless steel plates. During the laser welding operation, the plates were clamped rigidly to avoid any deformation caused by the thermal loading, which may affect the results. No special heat treatment was carried out either before or after the laser welding. However, the plate’s edges were prepared to ensure full contact along the weld line during the laser welding and cleaned by acetone to remove any remaining cutting fluid or dust. The welding operation was accomplished according to the design matrix Table 2 and in a random order to avoid any systematic error in the experiment.

3.2 Testing Specimens

Charpy impact strength subsize specimens of 55 x 10 x 3 mm and standard tensile strength specimens accordant to ASTM E 8M-01^{E2} [17] were cut from each welded sample by means of laser cutting. The impact strength samples were tested at room temperature of 20 ºC using a MAT21 universal pendulum impact tester. Tensile tests were performed in air using Instron universal electromechanical testing machine model 4202, with a gage length of 12.5 mm and a crosshead speed of 5 mm min^{-1}. The average of at least three results of both impact and tensile strength were calculated for each sample and presented in Table 2.

Table 3: Typical chemical compositions for the AISI304 used.

Element	Cr	Ni	C	Si	Mn	Mo	Fe
Wt.%	19.577	8.29	0.029	0.273	2.25	0.223	Balance

3.3 Operating Cost Calculation

Laser welding operating costs can be estimated per hour or per unit length of the weld if the application data is known. The welding system used in this work utilized CO_2 and uses a static volume of laser gases of approximately 7.5 litres every 72 hours. For this type of welding system with 1.5 kW maximum output power the operating costs can be divided into different categories as listed in Table 4. The operating cost calculation does not consider the unscheduled break down and maintenance, such as break down in the table motion controller or PC hard disc replacement. The total approximated operating cost per hour as a function of the output power can be given by 4.954 + 1.158*P. While the total approximated operating cost per unit length of the weld is given by Eq. 8 assuming 85% utilization. In this work, Eq. 8 was used to calculate the joint cost per metre for all the twenty samples as can be seen in Table 2.

Table 4: Operating costs break down.

Element of cost	Calculations	Welding cost €/h
Laser electrical power	(20.88 kVA)(0.8 pf¤)(€ 0.104/kWh)*(P/1.5)‡	1.158*P
Chiller electrical power	(11.52 kVA)(0.8 pf)(€ 0.104/kWh)	0.958
Motion controller power	(4.8 kVA)(0.8 pf)(€ 0.104/kWh)	0.399
Exhaust system power	(0.9 kWh)(€ 0.104/kWh)	0.094
Laser gas LASPUR208	{(€ 989.79/ bottle)/(1500liter/bottle)}x 7.5Liter/72h	0.069
Gas bottle rental	(€ 181.37/720h)	0.252
Chiller additives	(€ 284.80/year)/(8760 h/year)	0.033
Shielding gas (Argon)	(5liter/min)(60min/hr)(€8.62 x10^{-3}/Liter)	2.586
Nozzle tip	(€ 5.60/200h)	0.028
Exhaust system filters	(€ 5/100h)	0.05
Focus lens	(€184.51/lens)/(1000h)	0.185
Maintenance labour (with overhead)	(12 h/2000h operation)(€50/h)	0.30
Total approximated operating cost per hour		€4.954+1.158*P/h

¤ pf: power factor which converts from kVA to kWh.
‡ (P/1.5): The ratio of the utilized laser power to the maximum laser power achieved by the machine.

$$\text{Welding cost[Euro/m]} = \frac{4.954 + 1.158 \times P[\text{kW}]}{(0.85) \times S[\text{cm/min}][60\text{min/hr}][\text{m/100cm}]} \quad (8)$$

Where
P: used out put power in kW.
S: Welding speed in cm/min.

4. Results and Discussion

4.1 Development of mathematical models

The fit summary tab in the Design-Expert software suggests the highest order polynomial where the additional terms are significant and the model is not aliased. Selecting the step-wise regression method eliminates the insignificant model terms automatically. The sequential F-test for significance of both the regression model and the individual models terms along with the lack of fit test were carried out using Design- Expert V7 software. The ANOVA for the reduced quadratic models summarize the analysis of each response and show the significant model terms. Tables 5 to 7 show the ANOVA results for the tensile strength, impact strength and operating cost respectively. The same tables show also the other adequacy measures R^2, Adjusted R^2 and predicted R^2. All the adequacy measures are in logical agreement and indicate significant relationships. The adequate precision ratios in all cases are greater than 4 which indicate adequate models discrimination. The analysis of variance result for the tensile strength model shows that the main effect of the three laser welding parameters and the quadratic effect of the laser power along with the interaction effect of the three parameters are significant model terms; nevertheless the main effect of laser power was added to support hierarchy. However, the welding speed and the laser power are the factors that have the greatest effect on tensile strength. For the impact strength model the results indicate that the main effect of the three factors and the quadratic effect of the laser power are significant model terms. However, the laser power is the factor most associated with the impact strength. In the welding operation cost model, the analysis of variance results demonstrated that the main effect of the laser power and welding speed along with the quadratic effect of the welding speed are significant model terms. As mentioned earlier, the welding cost per metre can be calculated using Eq. 8. In this work, a mathematical model was developed to estimate the cost for optimization purpose. According to the obtained results the developed models are statistically accurate and can be used for further analysis. The final models in terms of coded and actual factors are shown below Eqs.9 to14.

Table 5: ANOVA analysis for the tensile strength model.

Source	Sum of Squares	DF	Mean squares	F Value	Prob > F	
Model	34184.45	7	4883.492	12.435	0.0001	Significant
P	21.32	1	21.317	0.054	0.8197	
S	2621.85	1	2621.851	6.676	0.0239	
F	1788.57	1	1788.575	4.554	0.0542	
PS	2400.60	1	2400.603	6.113	0.0294	
PF	2306.09	1	2306.085	5.872	0.0321	
SF	2102.52	1	2102.521	5.354	0.0392	
P^2	22943.49	1	22943.493	58.421	< 0.0001	
Residual	4712.75	12	392.729			
Lack of Fit	1964.24	7	280.606	0.510	0.7976	Not significant
Pure Error	2748.50	5	549.701			
Cor Total	38897.19	19				
R-Squared = 0.879				Adj. R-Squared = 0.808		
Pred. R-Squared = 0.643				Adeq. Precision = 10.963		

Table 6: ANOVA analysis for the impact strength model.

Source	Sum of Squares	DF	Mean squares	F Value	Prob > F	
Model	339.11	4	84.776	29.003	< 0.0001	Significant
P	107.51	1	107.511	36.781	< 0.0001	
S	61.13	1	61.130	20.914	0.0004	
F	44.77	1	44.771	15.317	0.0014	
P^2	125.69	1	125.693	43.002	< 0.0001	
Residual	43.84	15	2.923			
Lack of Fit	35.90	10	3.590	2.259	0.1906	Not significant
Pure Error	7.94	5	1.589			
Cor Total	382.95	19				
R-Squared = 0.886				Adj. R-Squared = 0.855		
Pred. R-Squared = 0.702				Adeq. Precision = 19.655		

Table 7: ANOVA analysis for the operating cost model.

Source	Sum of Squares	DF	Mean squares	F Value	Prob > F	
Model	0.092253	3	0.030751	995.25	< 0.0001	Significant
P	0.000343	1	0.000343	11.09	0.0042	
S	0.084825	1	0.084825	2745.4	< 0.0001	
S^2	0.007084	1	0.007084	229.3	< 0.0001	
Residual	0.000494	16	3.09E-05			
Cor Total	0.092747	19				
R-Squared = 0.995				Adj. R-Squared = 0.994		
Pred. R-Squared = 0.981				Adeq. Precision = 106.64		

$$\text{Tensile Strength} = 658.41 - 1.25*P - 13.86*S - 11.44*F + 17.32*PS + 16.98*PF - 16.21*SF - 39.54*P^2 \quad (9)$$

$$\text{Impact Strength} = 42.88 + 2.81*P - 2.12*S + 1.81*F - 2.93*P^2 \quad (10)$$

$$\text{Joint cost per metre} = 0.26 + 0.00501*P - 0.079*S + 0.022*S^2 \quad (11)$$

And the final models in terms of actual factors are shown below:

$$\text{Tensile Strength} = -4433.90 + 9102.06 * P - 19.9 * S - 511.93 * F + 13.86 * PS + 565.94136 * PF - 4.32 * SF - 3954.102 * P^2 \quad (12)$$

$$\text{Impact Strength} = -401.17 + 730.46 * P + 0.17 * S + 6.04 * F - 292.67 * P^2 \quad (13)$$

$$\text{Operating cost per metre} = 0.8177 + 0.0501 * P - 0.019664 * S + 0.000141 * S^2 \quad (14)$$

4.2 Effect of Process Parameters on the Responses

In the subsequent headings, whenever an interaction effect or a comparison between any two input parameters is being discussed the third parameter would be on its centre level.

4.2.1 Tensile strength

It is evidence form the results that all the process input parameters have a significant effect on tensile strength of a laser butt joint made of AISI304. However, Fig. 3 is a Perturbation plot which illustrates the effect of the laser welding parameters on the tensile strength and Fig. 4 is a contours graph showing the effect of the laser power and focal point position on the tensile strength.

It is evident from Fig. 3 that both the welding speed and the focal point position have a slightly negative effect on the impact strength. While, in the case of the laser power the result demonstrate that increasing the laser power until it reaches its centre value would result in improving the tensile strength, the tensile strength then starts to drop as the laser power tends to increase above the centre limit. Such behaviour could be attributable to one of the following reasons. Firstly, is that the size of the HAZ would affect the weld joint mechanical properties. The HAZ would be wider when applying high laser power, according to El-Batahgy [18, 19], which makes the tensile strength to decrease. Secondly, it could be due to the fact that the austenitic stainless steel has low thermal conductivity [3], the heat will be localized and as the laser beam is moved the localized heat is likely to take more time to conduct through the bulk metal, which would allow the grains to grow in the weld zone and in the HAZ, this would result in reducing the tensile strength as stated in [18]. Generally, as the results indicate neither too high laser power nor too low are recommended to weld with.

In terms of interaction effect between laser power and welding speed, it is evident that by using slow welding speeds and high laser power all weld bead parameters, such as penetration and weld bead width, tend to increase, as mentioned in [20]. The reasons that reduce the joint tensile strength can be summarized in the following points: 1) When using high laser power and slow welding speed undesirable tensile residual stresses would result as discussed in [4, 10].This would speed up the fracture as the joint is pre-stressed. 2) The increment in the heat input would be reflected in a wider HAZ and grain growth of the weld area is likely to happen and this would reduce the joint tensile strength as discussed earlier. On the other hand, welding with low laser power and high welding speed would also reduce the tensile strength of the welded joint due to a lack of full joining on a micro scale, especially at the back of the welded joint, i.e. the weld which does not encompass all the joint line is likely to occur because of inadequate back bead width. Therefore, based on the obtained results applying either high laser power with low welding speed or low laser power with high welding speed is not recommended. Fig. 5 shows the interaction effect between the laser power and the welding speed at a focus point position of -0.5 mm.

In relation to the interaction effect between the welding speed and focus point position, the results indicate that using either a focused or defocused laser beam with a slow welding speed has no significant effect on the tensile strength. On the other hand, the result indicates that by applying high welding speeds, the focus position should be set at its lowest limit of -0.8 mm to obtain slightly better tensile strength. This is because using a focused beam along with high welding speed would result in a poor joint and its consequences were discussed earlier. Fig. 6 is contours plot illustrating the interaction between the welding speed and focus position at a laser power of 1.2 kW.

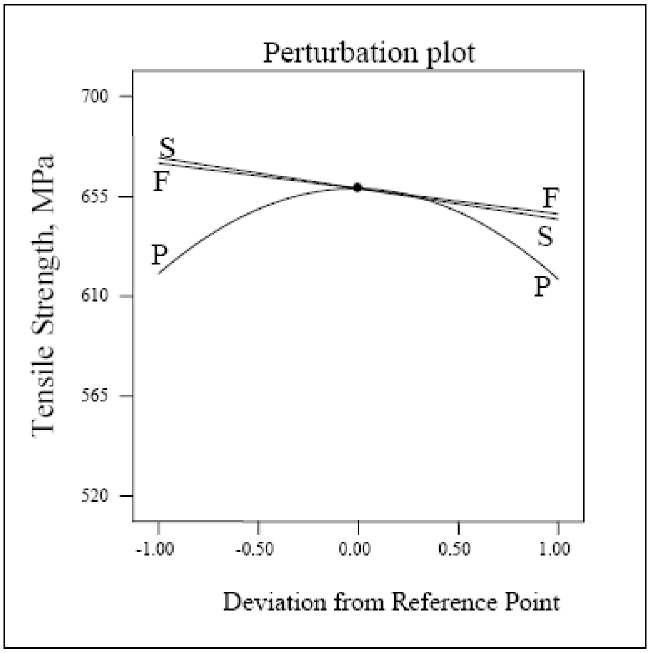

Fig. 3: Perturbation plot showing the effect of all factors on the tensile strength.

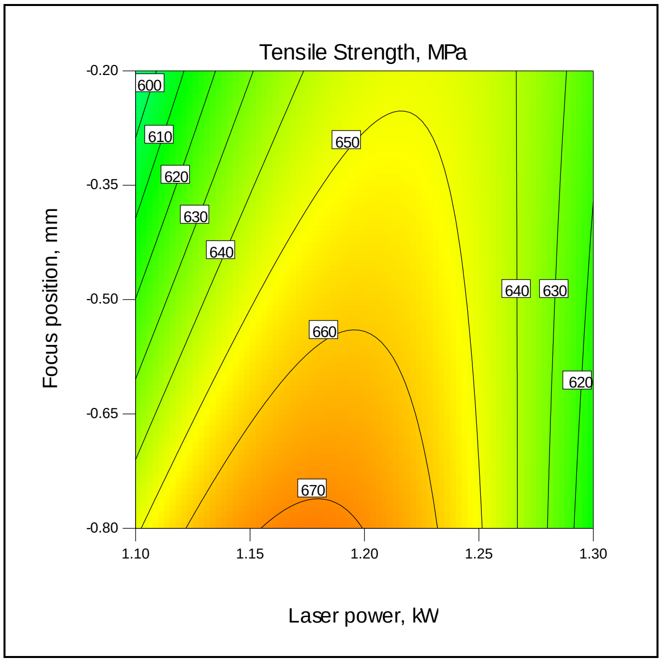

Fig. 4: Contours plot showing the effect of P and F on the tensile strength at S = 47.5 cm/min.

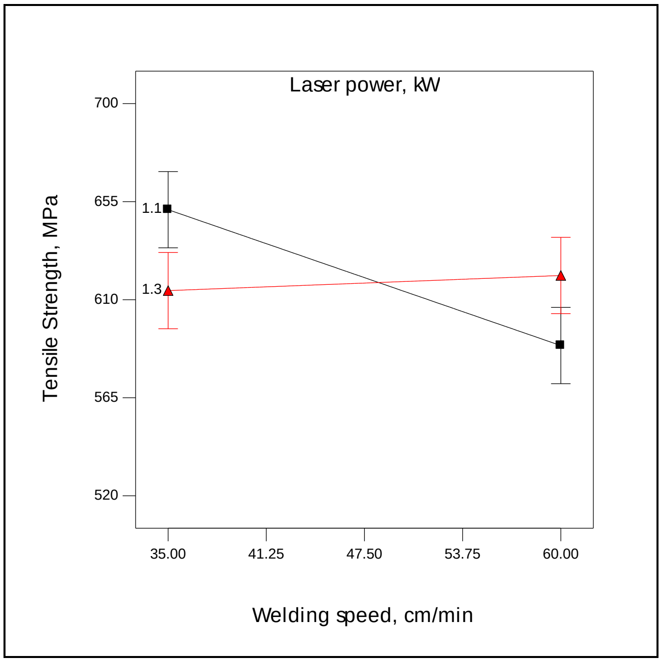

Fig. 5: Interaction effect between S and P on the tensile strength at F = - 0.5 mm.

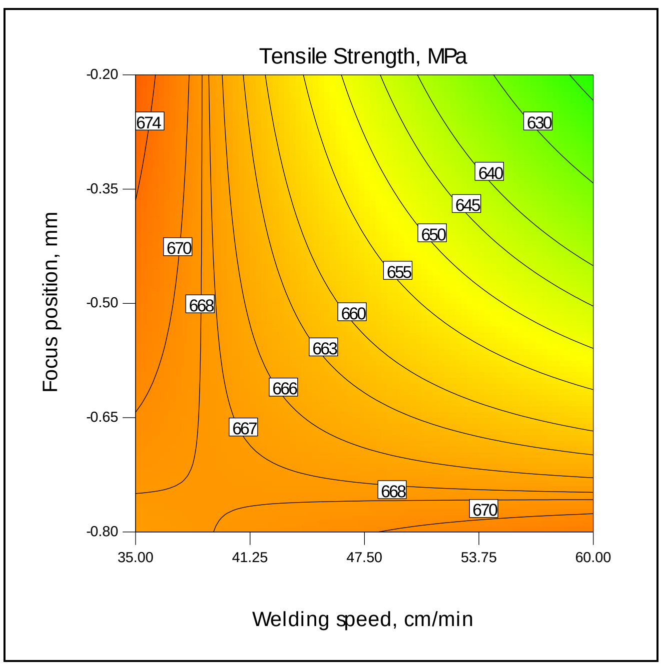

Fig. 6: Contours plot showing the effect of S and F on the tensile strength at P = 1.2 kW.

4.2.2 Impact strength

In the welding field, toughness is normally expressed as impact toughness, due to the fact that it is usually determined using the Charpy impact notch test. For that reason, the relationship between the laser welding input parameters and impact strength of the welds must be highlighted. The result demonstrates that all the input parameters have a significant effect on the impact strength of the welded joint. No significant interaction effect was found in the case of the impact strength model. Fig. 7 shows a perturbation plot to compare the effect of different welding factors at a particular point (midpoint by default) in the design space. From this figure, it can be noticed that the impact strength increases as the laser power increases, due to the high temperature achieved would lead to an annealing of the weld pool and the HAZ which would enhance their toughness. The result demonstrated that using a focused laser beam would improve the impact strength due to the improvement in toughness. Finally, the impact strength decreases as the welding speed increases due to the relatively smaller weld pool size obtained as a result of the high cooling rate which reduces the welds toughness and make them more brittle. Fig. 8 shows the effect of the laser power and welding speed on the impact strength at a focus position of -0.5 mm. Generally speaking the results indicate that as the tensile strength increases, the impact strength would be reduced. This is important in the optimization of the welding process.

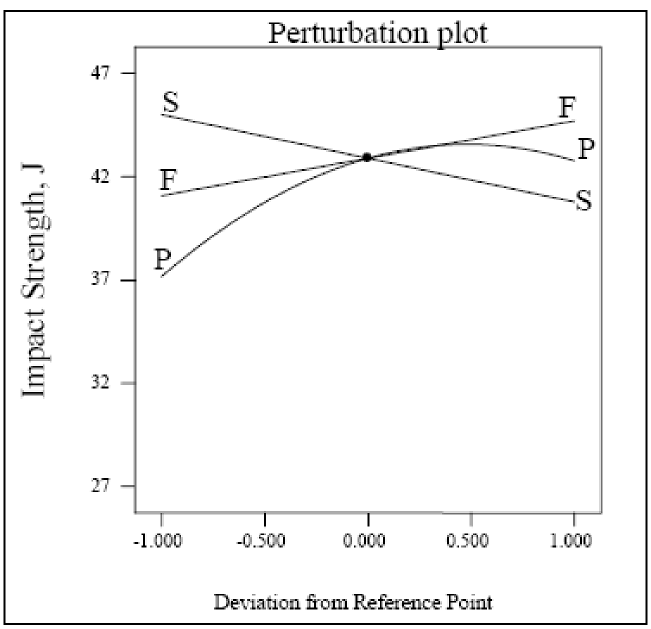

Fig. 7: Perturbation plot showing the effect of all factors on the impact strength.

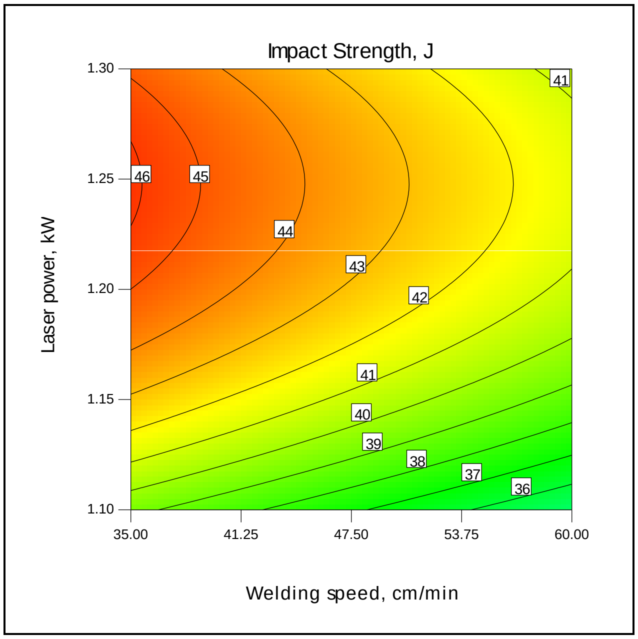

Fig. 8: Contours plot showing the effect of P and S on the impact strength at F = -0.5 mm.

4.3 Optimization

The issue of linking between the strength and toughness must be addressed as any increase in the strength is usually reflected in deteriorating the toughness as a consequence both strength and toughness are usually studied together. On balance, and based on the above discussion, it's better to run an optimization technique to find out the optimal welding condition at which the desirable mechanical properties of the welded joint can be achieved. In fact, once the models have been developed and checked for adequacy, the optimization criteria can be set to find out the optimum welding conditions. In this investigation two criteria were implemented to maximize both tensile and impact strengths. The first criterion is to reach maximum tensile strength and impact strength with no limitation on either the process parameters or the operating cost. While, in the second criterion, the goal was to reach maximum tensile and impact strength at relatively low operating cost by using maximum welding speed. However, Table 8 summarizes these two criteria. While Tables 9 and 10 present the optimal solution based on the two optimization criteria as determined by Design-expert software. The optimization results clearly demonstrate that, what ever the optimization criteria, the laser power has to be around its centre limit of 1.2 kW to achieve the maximum tensile and impact strength. This result support the discussion made earlier on the effect of laser power on the responses. Table 9 presents the optimal welding conditions according to the first criterion that would lead to maximum tensile and impact strength of about 677 MPa and 47 J respectively at high joint operating cost of about € 0.36 per metre. But if the joint cost is to be reduced much further with approximate percentage of 43.28 % with acceptable tensile and impact strength, the welding speed has to be maximized to its highest value and a focus position of -0.8 mm has to be used instead of -0.2 mm. In this case, the tensile and impact strength would be about 670 MPa and 39 J respectively as can be seen in Table 10. It is obvious that the graphical optimization allows visual selection of the optimum welding conditions according to certain criterion. The result of the graphical optimization are the overlay plots, these type of plots are extremely practical for quick technical use in the workshop to choose the values of the welding parameters that would achieve certain response value for this type of material. The green/shaded areas on the overlay plots Fig. 9 and 10 are the regions that meet the proposed criteria.

Table 8 Optimization criteria used in this study.

Parameter or Response	Limits		Importance	First criterion	Second criterion
	Lower	Upper			
Laser power, kW	1.1	1.3	3	is in range	is in range
Welding speed, cm/min	35	60	3	is in range	maximize
Focused position, mm	-0.8	-0.2	3	is in range	is in range
Tensile Strength, MPa	529	692	5	maximize	maximize
Impact Strength, J	27	46	5	maximize	maximize
Joint cost per meter, €/m	0.1816	0.4694	3	is in range	minimize

Table 9: Optimal solution as obtained by Design-Expert based on the first criterion.

Number	Laser power	Welding speed	Focused position	Tensile Strength	Impact Strength	Joint cost per meter	Desirability
1	1.2	35	-0.2	677.052	46.750	0.3617	0.9518
2	1.2	35	-0.21	676.966	46.719	0.3617	0.9515
3	1.21	35	-0.2	676.775	46.975	0.3621	0.9509
4	1.2	35	-0.22	676.755	46.697	0.3618	0.9509
5	1.2	35.19	-0.2	676.569	46.782	0.3599	0.9503
6	1.2	35.2	-0.2	676.562	46.723	0.3597	0.9502
7	1.19	35	-0.2	676.863	46.534	0.3613	0.9480
8	1.19	35.01	-0.2	676.751	46.479	0.3612	0.9463
9	1.23	35	-0.2	673.989	47.337	0.3631	0.9419
10	1.21	38.85	-0.2	667.482	46.500	0.3268	0.9166

Table 10: Optimal solution as obtained by Design-Expert based on the second criterion.

Number	Laser power	Welding speed	Focused position	Tensile Strength	Impact Strength	Joint cost per meter	Desirability
1	1.22	60	-0.8	670.433	39.401	0.2052	0.8144
2	1.22	60	-0.8	670.284	39.415	0.2052	0.8144
3	1.22	60	-0.8	670.556	39.389	0.2052	0.8144
4	1.22	60	-0.8	670.817	39.360	0.2051	0.8143
5	1.22	60	-0.8	669.933	39.444	0.2053	0.8143
6	1.22	60	-0.79	670.010	39.432	0.2052	0.8143
7	1.22	60	-0.79	669.517	39.474	0.2052	0.8142
8	1.22	60	-0.79	669.520	39.470	0.2052	0.8142
9	1.22	60	-0.8	669.607	39.468	0.2054	0.8141
10	1.22	59.94	-0.8	670.662	39.385	0.2053	0.8140

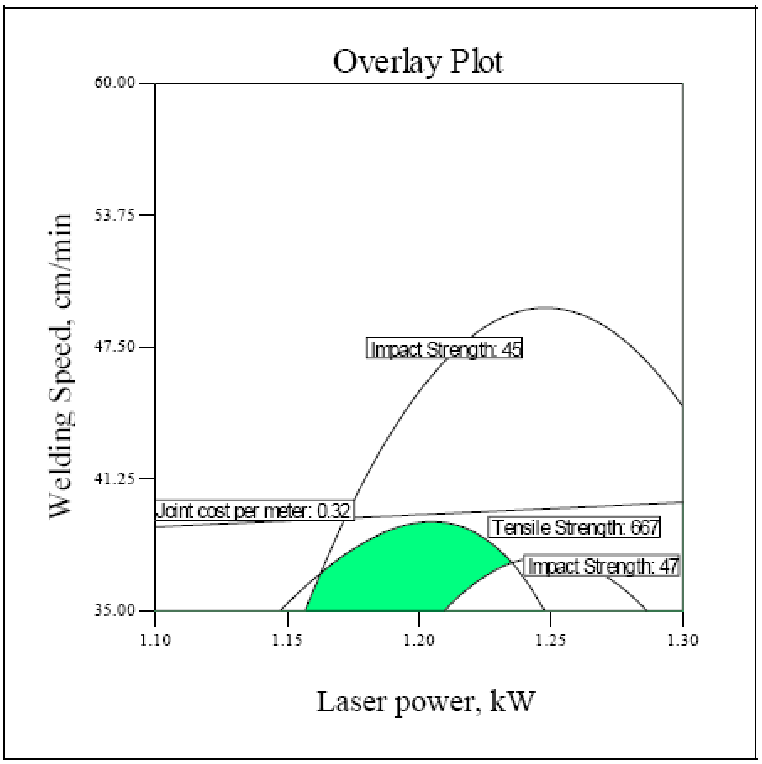

Fig. 9: Overlay plot shows the region of optimal welding condition based on the first criterion at F = -0.2 mm.

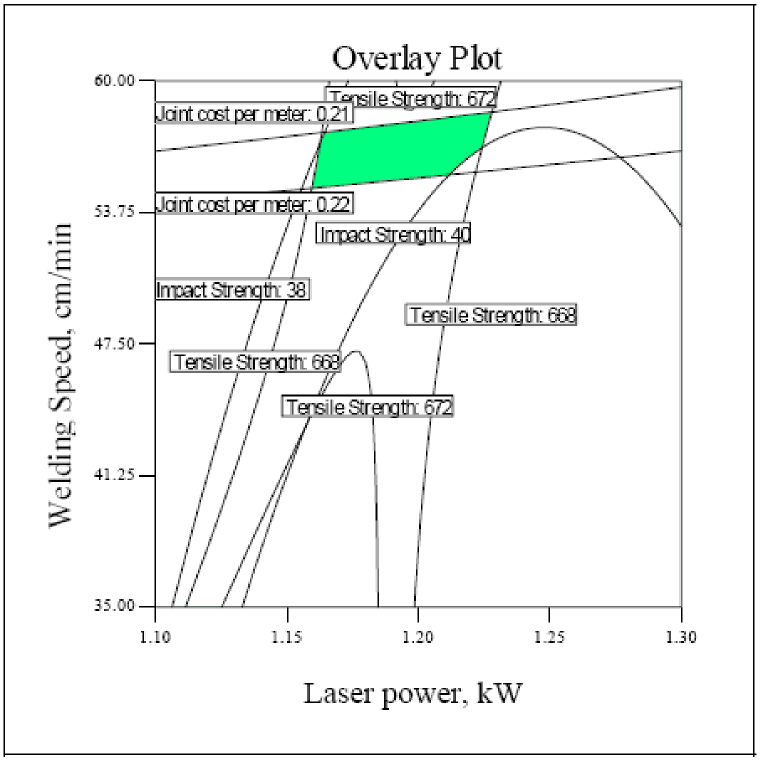

Fig. 10: Overlay plot shows the region of optimal welding condition based on the second criterion at F = -0.8 mm.

4.4 Validation of the developed models

In order to validate the developed models, three confirmation experiments were carried out with welding conditions chosen randomly from the optimization results. For the actual responses the average of three measured results was calculated. Table 11 summarizes the experiments condition, the average of actual experimental values, the predicted values and the percentages of error. The validation results demonstrated that the models developed are quite accurate as the percentages of error in prediction were in a good agreement

Table 11: Validation test results.

Exp. No.	P, kW	S, cm/min	F, mm		Tensile Strength MPa	Impact strength, J	Joint operating cost
1	1.2	35	-0.2	Actual	681	46	0.3554
				Predicted	677.0360	46.8081	0.3617
				Error %	0.509	-1.757	-1.80
2	1.22	60	-0.8	Actual	627	40	0.2081
				Predicted	670.4500	39.3996	0.2052
				Error %	-6.987	2.315	1.405
3	1.21	38.85	-0.2	Actual	710	47	0.3207
				Predicted	667.7540	46.4078	0.3268
				Error %	5.994	1.955	-1.831

5. Conclusion

Using the laser machine and within the limits of the laser parameters considered in this study the following points can be concluded:

1. RSM is an accurate technique to optimize the laser welding process in order to obtain the best mechanical properties of the welded component.
2. A laser power between 1.2 and 1.23 kW is an optimum input to obtain an excellent welded component produced from austenitic stainless steel AISI304.
3. The welding speed is the most effective welding parameter and its interaction with the focal point position should be monitored. Welding speed between 35 and 39 cm/min is compatible with F = -0.2 mm, while S = 60 cm/min is compatible with F = -0.8 mm.
4. Superior, efficient and economical welds could be achieved using the welding conditions drawn from the numerical optimization.
5. The graphical optimization results allows quicker search for the optimal welding settings.
6. The welding operating cost can be reduced by approximately 43% with acceptable mechanical properties if the optimal welding conditions are used.

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