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Evaluation of the Mechanical Properties by Computational and Experimental Techniques in High Power Laser Welding of Dissimilar Materials

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Abstract: In most recent times, joining of dissimilar materials by laser technique has become relatively phenomenon and a challenging task in engineering industries. This has been due to the technicalities and economical importance attached to it. The consideration of dissimilar-metals being combined to a greater extent, provide possibilities for benefiting from the mechanical properties of each material in a functional way. In this study, high power CO2 laser was employed to investigate the cost and the weld properties of dissimilar metals (316L stainless steel and AISI1016 carbon steel) in its proper prospective. In this paper, the effect of different levels of laser powers, namely (1, 1.25 and 1.5 KW), specimen scanning speeds (500,750 and 1000mm/min) and focal point positions of (-1, -0.5 and 0) on the cost, toughness, tensile strength, heat input and weld bead geometry (weld pool area and weld pool width) are all presented. As software, the Design of Experiment (DOE) was applied through L9 Taguchi method in the development of the experimental layout. The results identify the optimal combinations of the laser welding input variables to obtain economic laser weld joint with an excellent mechanical properties. Development of linear and quadratic polynomial equations was deduced in predicting the response parameters for the joint zone. However, the results showed that the proposed models predict that the responses adequately fall due within the limits of welding parameters being investigated.

Keywords: Mechanical properties, computational and experimental techniques, laser welding, dissimilar materials

Introduction

Dissimilar joint in metals with different physical properties such as; thermal conductivity, heat capacity, thermal expansion coefficient, melting temperature; etc are generally characterized to be challenging task in engineering industries.[1-5]. Although this difference can be referred to as or otherwise reveal many of the problems, the demands for dissimilar joint are in progress due to the improved performance and cost reduction. Among the available materials, the ferritic low carbon steel and austenitic stainless steel (F/A) joints have received huge attention in chemical, petrochemical, power generations and automotive industries [6,7]. Generally, laser metal interaction is considered to progressively be used in a large scale of welding industry due to advantageous aspects own to them and this in otherwise, are compared to other welding process as different[8]. Depending on the focused beam properties attached to it, high power density permits welding based on the keyhole concept as idealized [9]. In the present work, 1.5 KW Rofin CO_2 laser was used to construct the welding between AISI 1016 mild steel and AISI 316L stainless steel such that the mechanical properties of a high standard must be used so as to withstand the operational service circumstance required. For desired weld quality to be in place; the cost, weld bead geometry and the mechanical properties are normally examined and considered a yardstick as these relate to the weld input parameters needed (laser power, welding speed and focal point position).

Such input–output relation can be considered in the form of operational statistical models [10]. Design of experiment (DOE) , a set of mathematical and statistical methods, can be used efficiently for predicting and optimizing the responses in a way that is expected to produce overall better performance for the welding process [11], which is affected by several input parameters [12]. Among the other techniques, the L9-Taguchi method has been used to improve productivities and reduce the time required for the experimental investigation. Further to this, it employs a special design of orthogonal arrays that allows studying the entire process parameter space depending on relatively limited number of experiments [13]. Therefore, it is possible to obtain the optimal process parameters insensitive to the variation of the circumstances and other noise factors [14]. The accurate control of the laser Power, welding speed and focal position with respect to the joint interface are fundamental to achieve a sound weld. From another point of view, Laser dissimilar welding can be seen as a multi-input and multi-output process; there are many factors and their interactions which affect the process. Thus, an in-depth optimization is required [15]. In the present work, the optimization has been considered to investigate the optimal welding conditions at which the desirable mechanical properties of the welded joint can be estimated.

Once the models have been developed and checked for adequacy, certain optimization criteria can be set to investigate the optimum welding conditions. Restricted and non restricted criteria were carried out to maximize the joint impact and tensile strength, minimize the operating welding cost and enhance the bead geometry. The importance is assigned for each parameter in any of the criteria due to the industrial request. In other words, the cost in some cases tends to take the priority of importance on the expense of the other experimental parameters. It seems that the cost is more important than ever before, especially in the current economic climate. The selection of the type of the laser active medium which is a mixture of gases with a known mixing percentage is essential to minimize the welding cost by increasing the welding speed [16,17]. On the other hand the results also indicated that increasing the laser welding speed leads to decrease the impact and the tensile resistance, whereas the change in the beam focusing has no influence on the operating cost. However, optimization criteria were implemented to achieve sound welds at a competitive cost whilst the analysis investigated that the joint under the welding conditions was completely adequate. The laser input parameters are represented by laser power (P), welding speed (S) and focused position (F) and the responses are welding operating cost (OC), heat input (HI), weld pool width (W) and weld bead area (A), impact strength (IS), tensile strength (TS).

Experimental Work

Laser Welding: In the current work, 2mm thick sheets of AISI316L austenitic stainless steel and AISA1016 mild steel cold rolled in the form of plates with dimension of 160 mm x 80 mm x 2 mm were butt joined using a 1.5 kW CWCO$_2$ Rofin laser and a ZnSe focusing lens with focal length of 127mm. Trial samples of butt-welding were performed by varying one of the process variables to determine the working range of each variable. Absence of visible welding defects and full penetration are the criteria of selecting the working range of each factor. 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 both 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 1 and in a random order to avoid any systematic error in the experiment. Three transverse specimens were cut from each specimen. Standard metallographic was made for each transverse specimen. The bead profile parameters 'responses' were measured using an optical microscope with digital micrometers attached to it with an accuracy of 0.001 mm, which allow to measure in x-axes and y-axes. The bead area was measured using image-analyzer software called Enterprise. The image of the entire weld-pool was captured first by using the MEIJI, EMZ-TR series optical microscope, and then the image was exported to the image-analyzer software for calibrating the image dimensions and area calculation. The average of at least three results of each weld-bead parameter was calculated for each sample for all materials and recorded for further analysis. The analysis of the chemical composition of the investigated steels; AISA 1016 carbon steel and AISI 316L stainless steel are listed in table 2.

Table 1: Design Matrix

Exp. No.	Run	Power (W)	Welding Speed (mm/s)	Focusing (mm)	Heat input (J/cm)	Area (mm2)	Width (mm)	Impact strength J/m2	Tensile strength (MPa)	Cost (€ /h)
1	3	1000	500	-1	960	2.525	3.166	38	427	0.39
2	1	1000	750	-0.5	640	2.012	2.370	32	436	0.26
3	2	1000	1000	0	480	1.487	1.575	26	420	0.2
4	6	1250	500	0	1200	2.431	2.664	39	511	0.4
5	7	1250	750	-1	800	2.242	2.581	35	450	0.3
6	9	1250	1000	-0.5	600	1.717	1.786	29	430	0.22
7	8	1500	500	-1	1440	2.753	3.312	43	511	0.42
8	4	1500	750	-0.5	960	2.242	2.317	36	496	0.32
9	5	1500	1000	0	720	1.731	1.522	30	472	0.23

Table 2: Chemical Composition

Material type	Percentage%								
Element	C	Si	Mn	Mo	Ni	Cr	P	S	Fe
AISI1016	0.14	0.049	0.317	0.04	0.03	0.1	0.005	0.009	Bal
AISI316L	0.018	0.5	1.3	2	10.199	18.6	0.001	0.001	Bal

Impact and Tensile Testing

The steel specimens were cut precisely to ideally meet the requirements of Charpy impact test and standard tensile test according to ASTM E 8M-01E2 [18, 19]. The impact test was carried out at the room temperature of 25ºC using a MAT21 universal pendulum impact tester. After welding, the weld quality was visually assessed, then, only the specimens free of surface defects were employed in the tensile test. The tensile test was resulted in using Instron universal electromechanical testing machine model 4202 whereas; the strain gauge length was of 12.5mm and the crosshead speed of 5mm/min. In order to obtain accurate values, the average of at least three results of both impact and tensile strength was evaluated for each sample. The impact and tensile test values of the responding metals are shown in table 1.

Operating Cost Estimating

Cost estimating is a well-formulated prediction of the desired laser joint construction of specific mechanical properties needed. Optimizing of the laser dissimilar welding process demands accurate calculations for the operating cost as well. In the present work, a static volume of laser gases of approximately 7.5 l every 72 h was utilized, so as the operating cost generally falls within the classification listed in table 3. However, the operating cost calculation does not involve the unscheduled breakdown and preventive maintenance, such as a breakdown in the table motion controller or PC hard disc damage. The total operating cost per unit length per hour of the laser welding as a function of laser power and electric power cost per KW is given by 8.337+1.792P. Successful total cost estimation can be investigated using the mathematical equation below, as the values of the operating cost for all the specimens are listed in table 3.

$$\text{Operating cost}\left[\frac{\text{EURO}}{\text{M}}\right] = \frac{8.337 + 1.729\text{P}}{(0.85)\times \text{S}\left[\frac{\text{cm}}{\text{min}}\right]\left[60\frac{\text{min}}{\text{h}}\right]\left[\frac{\text{m}}{100\,\text{cm}}\right]} \quad (1)$$

$$= \frac{8.337 + 1.729\text{P}}{0.51\times \text{S}} \quad (2)$$

Table 3: Operating Cost Breakdown

Element of cost	Calculations	Welding cost (€ /h)
Laser electrical power	(20.88 kVA)(0.8 pfa)(€ 0.161 /kWh) *(P/1.5)b	1.792 *P
Chiller electrical power	(11.52 kVA)(0.8 pf)(€ 0.161/kWh)	1.483
Motion controller power	(4.8 kVA)(0.8 pf)(€ 0.161/kWh)	0.618
Exhaust system power	(0.9 kWh)(€ 0.161/ kWh)	0.144
Laser gas LASPUR208	{(€ 1043.93/bottle)/(1500 liter/bottle)} ×7.5 liter/72 h	0.072
Gas bottle rental	(€ 181.37/720 h)	0.252
Chiller additives	(€ 284.80/year)/(8760 h/year	
Shielding gas (Argon)	(5 liter/min)(60 min/ h)(€ 17.3×10^{-3}/liter)	5.196
Nozzle tip	(€ 5.60/200 h)	0.028
Exhaust system filters	(€ 5/100h)	0.05
Focus lens	(€ 184.51/lens)/(1000h)	0.186
Maintenance labor (with overhead)	(12 h/2000h operation)(€ 50/h)	0.3
Total approximated operating cost per hour		€ 8.337+1.792*P/h

Experimental Design

In the present study, the Experiments were developed by the Taguchi method using L-9 orthogonal array that was compromised of three columns and nine rows. The applied orthogonal array was identified in terms of the degree of freedom such that, the degree of freedom for the orthogonal array should be greater than or at least equal to those for the process factors. Basically, DOE was selected based on the three welding parameters with three levels each. The typical welding parameters for this study are: Laser power (1 – 1.5 KW), welding scanning speed (500 – 1000 mm/min) and focused position (- 1 to 0 mm) being the laser welding input variables. Table 1 shows the selected laser input variables and experiment design Levels as well. Taguchi method was employed for the experimental data using statistical software ''Design-expert 7''. Evidently, the optimum process parameters resulted from this method are insensitive to the variation of environmental conditions and other noise factors [20] such that, the test runs were resulted in at random to avoid a systematic error creeping into the experimental procedure [21,22]. Furthermore, the number of experiments which may cause to increase the time and cost can be reduced by using the designed orthogonal array. Obviously, for investigating the range of each process input factor, trial weld runs were performed by changing one of the process factors at a time for each dissimilar material joint. Pilot experiments of laser welding were performed to determine the practical operating range of each individual laser welding parameter in order to produce qualified and economic dissimilar joint. Once the Taguchi method was applied to the experimental results using the statistical package (Design expert 7), series equation (1) was fitted to the experimental data to determine the regression equations for all responses. The significance of the terms in each regression equation was examined using an F-test, lack-of-fit test and or other adequacy measure using the same software to achieve the best fit [23]:

$$y = b_0 + \sum b_i x_i + \sum b_{ii} x_{ii}^2 + \sum b_{ij} x_i x_j + \epsilon \qquad (3)$$

Results and Discussion

Analysis of Variance (ANOVA). The main objective of the ANOVA is to extract from the results and how much each factor causes relative to the total variation to be observed in the results were shown cased. In this study, the investigations for welding process parameters were carried out using ANOVA firstly, to identify the parameter that significantly affected the welding quality. Thereon, the significance of the regression models test, the significance of the individual model coefficients test as well as the lack of- fit test were all carried out using the Design Expert 7 software. By this selection; of the step-wise regression method, the insignificant model terms were illuminated automatically as a result. The resulting ANOVA Tables 4–9 demonstrate the analysis of variance of each response and show the significant model terms that resulted. Furthermore, in the same vein, the tables show the adequacy measures R2, adjusted R2, adequacy precision R2 and predicted R2 for each response. This goes to prove that, the value of the entire adequacy measures were closed to 1, which in other words, it shows an alignment of considerable agreement and therefore indicate adequate models. The adequate precision compares the range of the predicted value at the design points to the average prediction error. However, the value of adequate precision is dramatically greater than 4 as well as the adequate model being obtained when the ratio of adequate precision is greater than 4. Regarding the experimental responses, it can be observed that, for the heat input model the welding speed (S), with an F value (92.748) can be observed as a prominent factor in this study. Of course, different scanning speeds, therefore, represent different effect that will be exerted on the heat input response, such that higher welding speed leads to low heat input while, on the other hand, the laser power (P) is considered to be of the second strongest effect on the heat input, whilst the influence for focal position on the heat input (H) model will not be noticed. The analysis of variance result of the heat input, weld pool area, weld pool width, impact strength, and cost models show that the highest effect of the three laser welding parameters was the welding speed of F values (92.748), (20585.15),(447.836), (1333.89),(399.038) respectively. From all cases consideration as analyzed, the laser power parameter has a more significant influence in the case of tensile strength model with an F value of (149.692). Further into the impact and tensile strength results as being analyzed; laser power, welding speed and the focusing parameters have been observed as significant model terms. In addition, two level interactions of the laser power and welding speed (PS) were obtained as a significant model term associated with the tensile strength as well. The final mathematical models in terms of the actual factors as determined by the design expert software are further shown in equations (4), (5), (6), (7), (8) and (9) below.

Final equations in terms of actual factors :

Heat input = 900 + 0.69333P - 1.2 S (4)

Area = 2.65978 + 4.68000E - 004P -1.63422E - 003S - 0.21511F (5)

Width = 3.84564 - 2.31919E-003S - 0.51951F (6)

Impact Strength = 38.94444 + 8.66667 E-003P - 0.021778S - 1.55556F (7)

Tensile Strength = 288.07758+0.22367P+0.036337 S + 34.66689F - 1.24004E - 004PS (8)

Joint Cost =0.48867+7.80000E-005P-3.75333E-004S (9)

Influence of the Process Parameter on the Response

Heat input (HI). The heat input; response parameter is a function of the input factors (laser power and welding speed). The heat input value can be evaluated as, heat input = (LP/S) ×η, where η is the welding efficiency. The welding efficiency is 80% [23]. As is shown in Fig.1 and Fig.2 welding speed has the greatest influence on the heat input. High welding speed results in a smaller value of heat input as the Laser power has a significant effect on the heat input as well. Consequently, with laser power decreasing the heat input reduces as shown in Fig. 3, describes the relationship between the laser power and the keyhole shape due to the dissipated heat input value. The results concluded also, the change in beam focusing on the heat input is entirely negligible.

Table 4: ANOVA for the Heat Input Model

Source	Sum of Squares	df	Mean Squares	F Value	p-value Prob > F	
Model	720266.67	2	360133.333	61.855	< 0.0001	Significant
A-P	180266.67	1	180266.667	30.962	0.0014	
B-S	5400000	1	540000	92.748	< 0.0001	
Residual	34933.333	6	5822.222			
Cor Total	7552000	8				

R2=0.9537 Adj R 2=0.9383

Pred R2 = 0.8818 Adeq Precision= 21.489

Table 5: ANOVA for the Fusion Area Model

Source	Sum of Squares	df	Mean Squares	F Value	p-value Prob > F	
Model	1.416704	3	0.472	12941.87	< 0.0001	Significant
A-P	0.082134	1	0.082	2250.932	< 0.0001	
B-S	0.751129	1	0.751	20585.15	< 0.0001	
C-F	0.052057	1	0.052	1426.65	< 0.0001	
Residual	1.428E-004	5	3.649E-005			

R2=0.9899 Adj R 2=0.9876

Pred R2 =0.9840 Adeq Precision= 114.424

Table 6: ANOVA for the Welding Pool Width Model

Source	Sum of Squares	df	Mean Squares	F Value	p-value Prob > F	
Model	3.325	2	1.663	492.237	< 0.0001	Significant
B-S	1.513	1	1.513	447.836	< 0.0001	
C-F	0.304	1	0.304	89.885	< 0.0001	
Residual	0.020	6	0.003			
Cor Total	3.346	8				

R2=0.9939 Adj R 2=0.9919

Pred R2 =0.9844 Adeq Precision= 50.04

Table 7: ANOVA for the Impact Strength Model

Source	Sum of Squares	df	Mean Squares	F Value	p-value Prob > F	
Model	235.06	3	78.35	783.52	< 0.0001	Significant
A-P	28.17	1	28.17	281.67	< 0.0001	
B-S	133.39	1	133.39	1333.89	< 0.0001	
C-F	2.72	1	2.72	27.22	0.0034	
Residual	0.50	5	0.10			
Cor Total	235.56	8				

R2 = 0.9979 Adj R2=0.9966

Pred R2 = 0.9924 Adeq Precision= 79.584

Table 8: ANOVA for the Tensile Strength Model

Source	Sumof Squares	df	Mean Square	F Value	p-value Prob > F	
Model	10641.253	4	2660.313	62.194	0.0007	Significant
A-P	6402.928	1	6402.928	149.692	0.0003	
B-S	3960.559	1	3960.559	92.592	0.0007	
C-F	1352.017	1	1352.017	31.608	0.0049	
AB	240.266	1	240.266	5.617	0.0768	
Residual	171.097	4	42.774			
Cor Total	10812.349	8				

R2= 0.9842 Adj R2= 0.9684
Pred R2 = 0.8670 Adeq Precision =18.463

Table 9: ANOVA for the Cost Model

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	0.05511	2	0.027555	208.136	< 0.0001	Significant
A-P	0.002282	1	0.002282	17.233	0.0060	
B-S	0.052828	1	0.052828	399.038	< 0.0001	
Residual	0.000794	6	0.000132			
Cor Total	0.055904	8				

R2= 0.9858 Adj R2= 0.9811
Pred R2 = 0.9690 Adeq Precision = 34.121

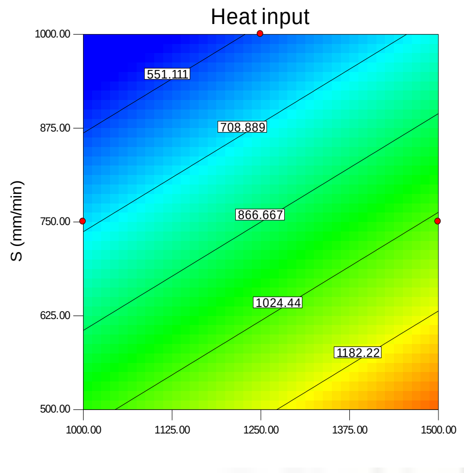


Figure 1. Contour graph shows the effect of the laser power and welding speed on the heat input.

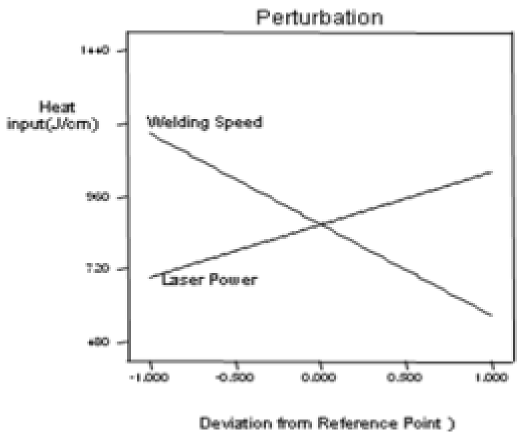
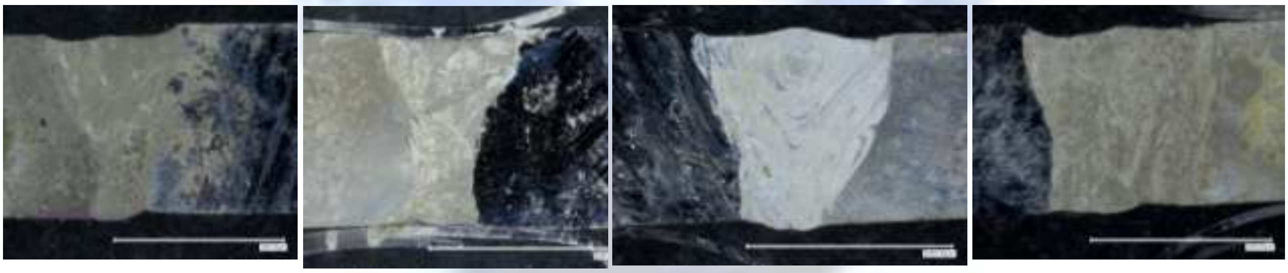


Figure 2. Perturbation plot shows the effect of the laser power and welding speed on the heat input.

Fusion area (A). Generally, the weld zone area 'A' of dissimilar joints between stainless-steel and mild steel was measured and drown in the contour graph as presented in Fig.4. Together with the perturbation plot in Fig.5, it is clear that thethree parameters are significantly affecting the fusion area. Basically, increasing the applied laser power leads to enlarge the fusion area.This effect is due to the fact that, increasing the power leads to an increase in the heat input. Therefore; more molten metal, more penetration and consequently more fusion area can be investigated. Often, the concept is reversed in the case of welding speed (S) effect, since the welding speed (S) matches an opposite with the heat input. In other word, whenwelding speed reaches the maximum value at 1000 mm/min, presented in Table 3, the fusion area is minimal and equals 1.487mm2 which explain the best obtained results. On the other hand, the fusion area tends to increase up to its highest value of(2.753mm2) at laser power equals to (1.5 KW). Compared with the welding speed and laser power, the results also indicate that, the beam focusing contributes less effecting in the fusion area dimensions.



a b c d

Figure 3. Macrographs shows the bead shapeas a function to the heat input: a. HI (480J/cm), b. HI (600J/cm), c. HI (960J/cm), d. HI (1440J/cm).

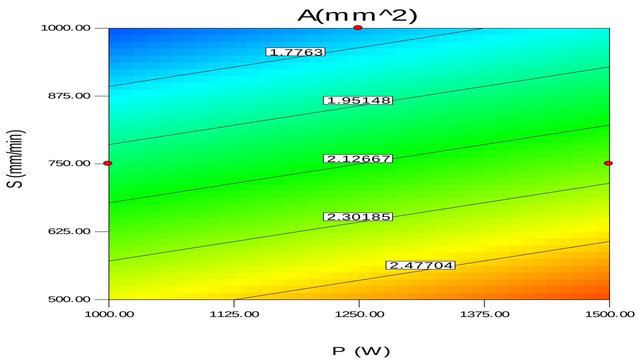


Figure 4 Contour graph shows the effect of S and F on the weld zone area

Welding zone width (W). Figures 5 and 6 predict that, welding speed (S) and focused position (F) are considered as the most powerful factors affecting the weld pool width (W). This is due to the increase in S results leading to a reduction in Width, W. The above analysis is in accordance with the fact that, laser beam travels at high speed over the welding line when (S) is increased as well as the heat input decreases, thereby leading to lesser volume of the melt metal to occur and again leads to the width of the welded zone being reduced. Further to these, defocused beam which is otherwise considered as divergent laser beam will relatively leads to spread the laser power onto wide area. In essence, the wide area of the base metal melts, leading to an increase in (W) retrospectively or vice versa as the case may be. However, narrower weld width of this size (1.522mm) will be obtained at lowest welding scanning speed of (1000mm/min) as the laser power of (1.5 KW) is applied.

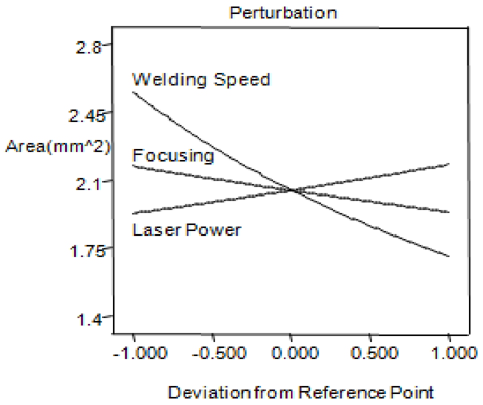


Figure 5 Perturbation plot shows the effect of S and F factors on the weld zone area

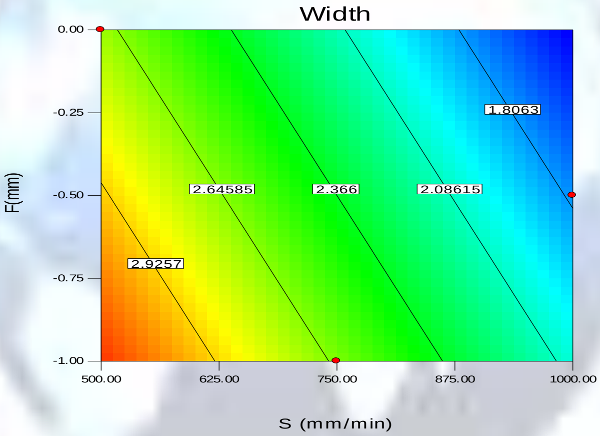


Figure 4 Contour graph shows the effect of S and F on the weld zone area

Impact Strength (IS). Generally, the data obtained from the Charpy impact testing are defined as a result of the effect of the processing parameters. The synopsis of these parameters can lead to different thermal behavior for the joint formation through welding and invariably results in a change in the microstructure and the mechanical properties of the welded materials. In view of these changes in the weld formation, the joints, then become sensitive to the service temperature. Therefore, the welded parts become very tough when the ambient temperature decreases or vice versa. Among the common important mechanical properties; impact strength found to have a significant effect on the failure of welded components in service. Therefore, the relationship between the laser welding input parameters and impact strength of the welds must be highlighted accordingly. Further to the process parameters, the results indicated that the welding speed is the most significant factor associated with impact response as shown in Fig.7 and Fig.8 The reduction in welding speed from its highest value to the lowest value would result in increasing the impact response by 43%. This because when the welding speed decreases more heat will introduce to the fusion zone; consequently more penetration is achieved leading to excellent joint. In addition, the results indicate that the laser power is a significant welding parameter in affecting the joint toughness characteristics. In this case, the maximum value of the laser power (P) at 1.5 KW leads to enhance the impact strength significantly. This result is justified due to the linear relationship between the power density and the heat input. Slight change in the impact strength value can be investigated due to the different focal point position being used.

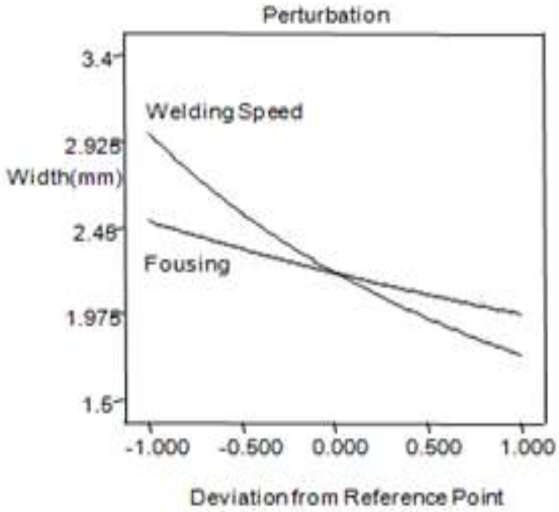


Figure 7 Perturbation plot shows the effect of S and F factors on the weld zone width

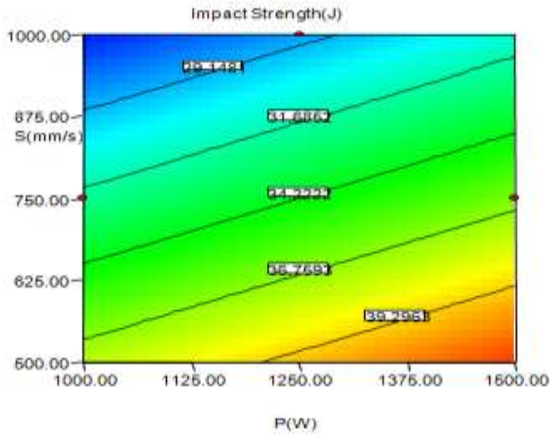


Figure 8 Contour graph shows the effect of S and F on the impact strength

Tensile Strength (TS). The experiments in the case of tensile strength test were carried out according to the design matrix given in Table 2. These were performed randomly to avoid any systematic error and as shown in the figures 9 and 10, it is observed that the influence of welding speed parameter on the tensile is not similar to that of the impact strength. Ironically, laser power has the most prominent effect on the tensile strength properties, hence the results demonstrated shown that the laser power has a positive effect on the tensile strength. High welding speed is thought to introduce less penetrated heat into the metal that makes the welded zone harder and, brittle when a high cooling rate is used. The results imply also, the laser power and the focusing are significant welding parameters in affecting the tensile strength characteristics.

Increase both of laser power and the focusing parameters would lead to enhance the tensile strength property. Basically, the focus position within the focal distance can achieve more fusion penetration in the form of butt joint laser weld, since maximum power density can be obtained in the focusing position. However, it is observed that the change in the focal point position is of less effect relative to other influential parameters. Fig.9 states the interaction between the laser power and the welding speed, as the interaction between any two input parameters is being analyzed the third parameter would be on its center level. Obviously, with slow welding speeds and high laser power all weld bead parameters including the tensile strength tend to increase, as observed in [24,25]. On the other hand the joint tensile strength can be reduced due to the undesirable induced tensile stresses as a result to the excessive laser power with low welding speed.

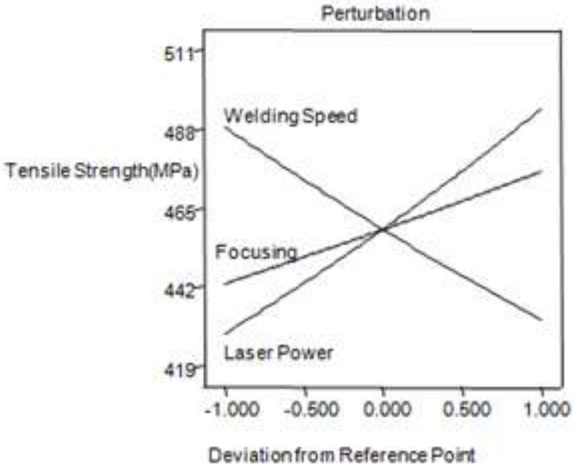


Figure 9: Perturbation shows the effect of S and F on the tensile strength

Generally, the graphical optimization otherwise considered as the overlay plots, allows visual selection of the optimum welding conditions as the criteria are performed. These are usually utilized in practice for quick technique use so as to select the welding parameter values that would result in certain response value. However, the same two criteria, proposed in the numerical optimization are used again. In the graphical optimization approach, basically the upper and lower limits for the responses can be chosen and fixed, and the software can identify a region which meets the proposed criteria. Invariably, the overlay plot tends to exhibits the area of feasible response values in the factor space. Fig.10 and Fig.11 indicate the overlay plots for the bead geometry, heat input and the cost for the first and second criteria respectively. Whilst, Fig.12 and Fig.13 represent the overlay plot for the impact, tensile strength and the cost of restricted and non restricted criteria respectively.

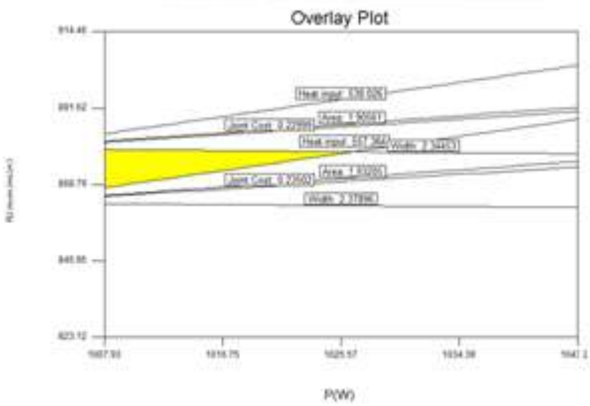


Figure10. Overlay plot shows the region of optimal welding condition based on the first criterion at F = -1 mm.

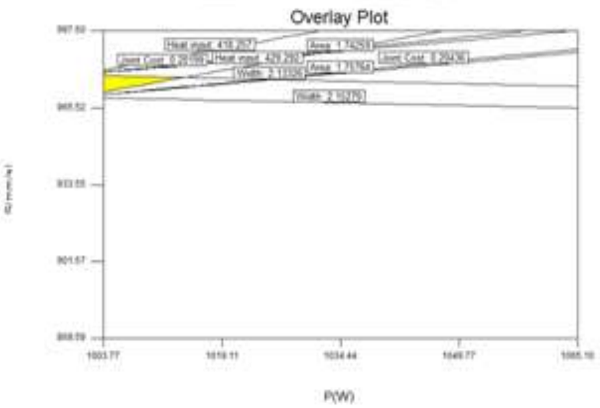


Figure 11. Overlay plot shows the region of optimal welding conditions basedon the first criterion at F= -1 mm.

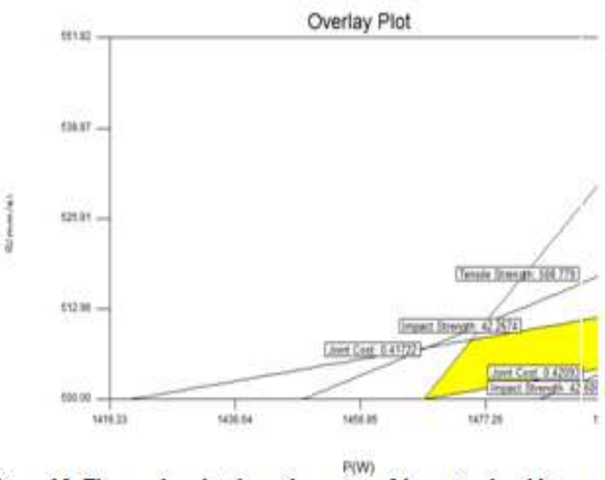


Figure 12. The overlay plot shows the region of the optimal welding condition based on the first criterion at = -1 mm.

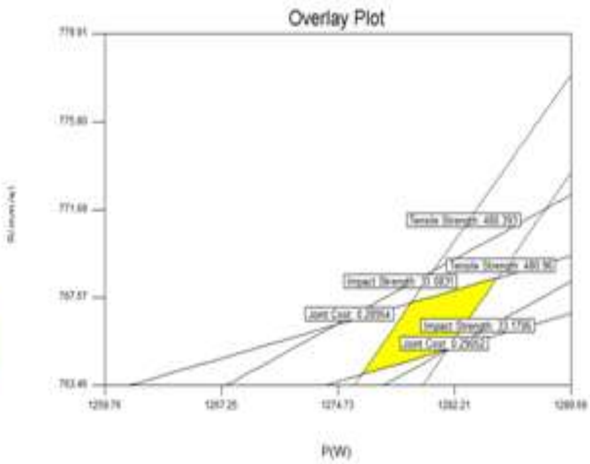


Figure 13. The overlay plot shows the region of the optimal welding condition based on the first criterion at F = -1 mm.

Conclusions

Laser dissimilar metal joints have been experimentally studied and statistically optimized using L9 Taguchi method, numerical optimization and graphical optimization as idealized. The following points were concluded from the study among the limits herein.

The statistical software using L9 Taguchi method can be used for optimizing the effect of welding parameters on the dissimilar metals joint and investigating the corresponding optimum input factors.

The value of the entire adequacy measures was close to 1, which in other words, it shows an alignment of considerable agreement and therefore indicate adequate models.

ANOVA results for the impact strength and cost models showed that the highest effect of the three laser welding parameters was the welding speed with F values (1333.89) and (399.038) respectively.

In the case of tensile test model, laser power has the most prominent effect on the tensile strength properties; hence the demonstrated results show that the laser power has a positive effect on the tensile strength with an F value (149.962).

Further to the optimization been analyzed, it is recommended to employ the numerical optimization approach at the start, so as to have the graphical optimization for the process parameters being utilized later, otherwise it may be difficult to discover a feasible region.

Restricted and non restricted numerical criteria were performed so as to achieve less heat input, enhanced bead geometry and lowest operating cost. The numerical optimization reveals the reduction percentages for the responses was around; HI (23%), OC (13%), A (9%), W (9%).

Maximum impact strength, tensile strength and lowest operating cost were obtained due to the optimization criteria, as the second criterion was applied. It stated that, the reduction percentages for the responses were around; (31%), IS (12%) and TS (6%).

The overlay plots in the graphical criteria allow visual search for the optimal welding conditions as it is used to assist the technicians and machine operator to find out the optimal setting quickly.

The welding speed in its maximum value, or nearly to its maximum value, in all optimization criteria leads to an increase in the production rate and a reduction in the operating cost.

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