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Assessment and Minimization of the Residual Stress in Dissimilar Laser Welding

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Abstract. Establishing the relationship between process parameters and the magnitude of residual stresses is essential to determine the life of welded components. It is the aim of this paper to develop mathematical models to assess residual stresses in the heat-affected zone of dissimilar butt jointed welds of AISI304 and AISI1016. These models determine the effect of process parameters on maximum residual stress. Laser power, travel speed and focal position are the process input parameters. Plates of 3 mm thick of both materials were laser welded using a 1.5 kW CW CO_2 Rofin laser as a welding source. Hole-drilling method was used to compute the maximum principal stress in and around the HAZ of both sides of the joint.

The experiment was designed based on a three factors five levels full central composite design (CCD). Twenty different welding runs were performed in a random order, 6 of them were centre point replicates and the maximum residual stresses were calculated for each sample. Design-expert software was used to fit the experiential data to a second order polynomial. Sequential F test and other adequacy measures were used to check the model's performance. The results show that the developed models explain the residual stress successfully. Using the developed models, the main and interaction effect of the process input variables on the residual stresses at either side of the weld were investigated. It is found that all the investigated laser parameters are affecting the performance of the residual stress significantly.

Introduction

Welding of dissimilar metals is a challenging work due to the variation in physical and chemical properties of both materials. Dissimilar laser welding, which is a high power density and low heat input process offers clarifications to a wide range of problems usually encountered with the normal welding methods. Due to the difference in the thermal properties of the two metals that forming the dissimilar joint, a large difference in the cooling rates could occur, which may result in variation in the residual stresses in the welded joint [1]. Controlling the residual stress is essential since tensile residual stresses are not beneficial for many applications as they can lead to crack initiation and growth with significant reduction in the fatigue life of the welded joint [2].

In the past two decades, the application of Response Surface Methodology (RSM) to predict a certain feature of the welds output parameters and to optimize different welding processes was the interest of lots of researchers [3-6]. Therefore, this paper firstly aims to employ RSM to relate the laser welding input parameters to two responses (i.e. principal residual stresses on both sides of the weld joint). The second aim is to determine the optimal welding combination that minimizes both responses. The laser welding parameters used in this study- laser power, welding speed and focus position- were selected as they are the only parameters which can be controlled on the welding machine used.

Experimental procedure

Laser welding. Dissimilar laser butt-welding of AISI304 and AISI1016 was performed using a 1.5 kW CW CO_2 laser welding and a lens with a focal length of 127 mm. Pilot experiments were carried out using one factor at a time to identify the factor ranges. The lack of visible welding defects and full depth of penetration were the criteria for choosing the ranges of each factor. Table 1 presents the process factors, their limits and coded values. A three factor, five level full CCD was used in order to develop the design matrix for this experiment as shown in Table 2 [7]. The welding operation was performed according to the design matrix, in a random order. Argon was used as the shielding gas at constant flow rate of 5 l/min. During the laser butt-welding, the plates with dimensions of 180 x 80 x 3 mm were clamped rigidly to avoid any deformation that might take place due to the thermal loading. No special heat treatments were carried out either before or after the laser welding. However, the plate's edges were machined to ensure a full contact along the welding line.

Residual stress measurements. The hole-drilling method was used to measure the maximum residual stress. The basic test procedure described in Measurement Group TN-502-5 and ASTM 837 was followed. However, the surface was prepared using the recommended sandpaper and the degreaser as mentioned in the test procedure [8, 9]. A strain gauge rosette used was of type CEA-06-062UM-120, which allows measurement of the residual stresses close to the weld-bead, to ensure that the hole is located in the HAZ. Commercially available milling guide apparatus (model RS-200) with an ultra-high speed air turbine and a carbide cutter of diameter 1.6 mm were used to drill a hole in the centre of the strain gauge rosette of 2.052 mm in depth as recommended in the guides [8, 10]. Calibration coefficients $\overline{a}$, $\overline{b}$ and material properties of both materials were used to transform the micro-strains data into stress using the blind-hole analysis described in [8, 9]. The holes were drilled at two locations one on the centre of each side and as close as possible to the weld seam to ensure the holes are located in the HAZ.

Results and Discussion

Analysis of variance. The lack-of-fit test, the sequential F-test for the significance of both the regression models and the individual model terms were performed using Design-Expert statistical software. Selecting the stepwise regression method allows elimination of the insignificant model terms automatically. The analyses of variance for the reduced quadratic models for both responses were abstracted and presented in Table 3. For both models the 'Prob. > F' value does not exceed 0.05, which indicates that the models are statistically significant. Also the terms in these models have a significant effect on the responses being investigated. The two empirical models in terms of actual values are shown in Eqs. 1 and 2. To confirm the adequacy of the two models developed, the predicted values and actual experimental measured values were presented in Table 4. It is evident that all the actual and predicted responses are in excellent agreement. To check the models developed in mid-points, two confirmation tests were performed using new welding settings which selected randomly, but still within the experiment range [11]. These new conditions are: for the first test P = 1.352 kW, S = 7.645 mm/s and F= - 0.2 mm and for the second test P = 1.14 kW, S = 10.833 mm/s and F = - 0.8 mm. The results of these confirmation tests are listed in Table 5. It is clear that the models successfully explained the responses within the variables domain, as the maximum error in prediction for both responses in both tests are in good agreement. Accordingly the models developed are adequate and can be used to predict the responses within the factors domain.

Table 1: Independent variable and experimental design levels.

Variable	Notation	Unit	Standardized/actual levels				
			-1.682	-1	0	1	1.682
Laser power	P	[kW]	1.06	1.13	1.24	1.35	1.42
Welding speed	S	[mm/s]	4.128	5.833	8.333	10.833	12.538
Focus position	F	[mm]	-1	-0.8	-0.5	-0.2	0

Table 2: Design matrix of the experiment.

No	Laser power	Welding speed	Focus position	No	Laser power	Welding speed	Focus position
1	1.13	5.833	-0.8	**11**	1.24	4.128	-0.5
2	1.35	5.833	-0.8	**12**	1.24	12.538	-0.5
3	1.13	10.833	-0.8	**13**	1.24	8.333	-1
4	1.35	10.833	-0.8	**14**	1.24	8.333	0
5	1.13	5.833	-0.2	**15**	1.24	8.333	-0.5
6	1.35	5.833	-0.2	**16**	1.24	8.333	-0.5
7	1.13	10.833	-0.2	**17**	1.24	8.333	-0.5
8	1.35	10.833	-0.2	**18**	1.24	8.333	-0.5
9	1.06	8.333	-0.5	**19**	1.24	8.333	-0.5
10	1.42	8.333	-0.5	**20**	1.24	8.333	-0.5

Table 3: Abstracted ANOVA table for the reduced quadratic models of the two responses.

Source	$\sigma_{AISI304}$, MPa				$\sigma_{AISI1016}$, MPa			
	SS	df	F-value	p-value	SS	df	F-value	p-value
Model	944.02	7	14.28	<0.0001	324.67	6	17.97	<0.0001
Lack-of-fit	111.03	7	34.01	0.0006	34.32	8	4.45	0.0583
Residual	113.36	12			39.14	13		

Table 4: Actual and predicted residual stress on HAZ for the two responses.

No.	$\sigma_{AISI304}$, MPa					$\sigma_{AISI1016}$, MPa					
	Act.	Pred.	No.	Act.	Pred.	No.	Act.	Pred.	No.	Act.	Pred.
1	87.46	88.88	**11**	103.56	101.03	**1**	92.81	93.34	**11**	99.08	99.55
2	90.76	96.31	**12**	80.68	82.50	**2**	97.59	95.99	**12**	83.05	85.80
3	65.47	70.07	**13**	84.43	79.97	**3**	87.33	85.17	**13**	87.69	89.29
4	78.78	77.50	**14**	91.18	90.74	**4**	89.13	87.81	**14**	92.60	94.22
5	88.93	91.93	**15**	92.58	91.77	**5**	97.25	96.28	**15**	90.30	88.86
6	89.88	90.48	**16**	93.32	91.77	**6**	99.54	98.93	**16**	87.90	88.86
7	89.05	88.70	**17**	91.83	91.77	**7**	90.30	88.10	**17**	87.78	88.86
8	86.96	87.25	**18**	91.52	91.77	**8**	91.55	90.75	**18**	89.25	88.86
9	83.96	80.47	**19**	92.79	91.77	**9**	87.18	88.93	**19**	88.90	88.86
10	86.90	85.50	**20**	91.90	91.77	**10**	91.91	93.39	**20**	89.61	88.86

Table 5: Confirmation tests for residual stress of dissimilar welding.

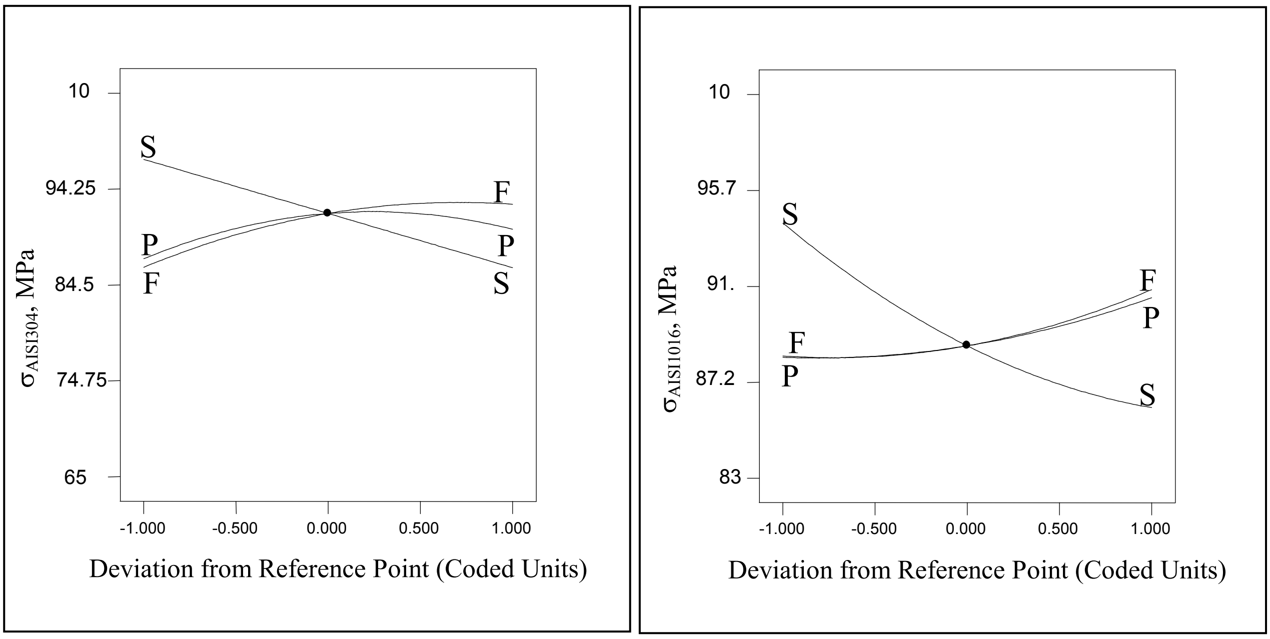
No.	$\sigma_{AISI304}$			$\sigma_{AISI1016}$		
	Act., MPa	Pred., MPa	Error %	Act., MPa	Pred., MPa	Error %
First test	89.31	84.63	5.46	94.72	90.85	4.08
Second test	70.95	72.76	-2.55	85.14	81.59	4.18

$$\sigma_{AISI304} = -282.24 + 616.45\,P + 0.393\,S + 25.62F - 67.27\,PF + 5.19\,SF - 256.65\,P^2 - 25.18F^2 \qquad (1)$$

$$\sigma_{AISI1016} = 211.01 - 154.37\,P - 5.23\,S + 16.26\,F + 67.1\,P^2 + 0.216\,S^2 + 11.36\,F^2 \qquad (2)$$

Effect of Process Parameters on the responses.

As the results indicate, the main effect of all the parameters, some of the interaction effects and most of the quadratic effects are significant terms in the two models. It is notable that in both cases, the interaction effect between the laser power and welding speed is not significant. Fig. 1 shows the effect of the process parameters on the responses. These kinds of plots help to show how sensitive the responses are to the process parameters. From this figure, it is demonstrated that as the laser welding process parameters are increased, from their lowest limit to their highest limit, the residual stress component $\sigma_{AISI304}$ and $\sigma_{AISI1016}$ would be influenced as follow: For the welding speed an decrease in the residual stress components of 11.33% and 8.67% respectively, for the laser power, an increase of about 3.43% and 3.00% respectively and for the focal position, an increase of around 7.42% and 3.32% respectively. It is clearly shown that the two responses are more sensitive to the welding speed and less sensitive to the focal position and laser power. The most hazardous welding condition at which the welded component is considered unsafe is that which introduce undesirable tensile stress, which would reduce the serving life of this welded component. The most dangerous condition is slow welding speed, high laser power and focused beam (i.e. F = 0 mm) which tends to increase the unwanted residual stress.



(a) (b)

Fig. 1: Perturbation plot showing the effect of all parameters on (a) $\sigma_{AISI304}$ and (b) $\sigma_{AISI1016}$.

Numerical Optimization.

The numerical optimization feature in the design expert software package finds a point or more in the factors domain that would maximize the objective functions based on the desirability approach. The desirability approach consists of transforming of each estimated response, Y_i, into a dimensionless utility bounded by $0 < d_i < 1$, where a higher d_i value indicates that the response value Y_i is more desirable, if $d_i = 0$ this means a completely undesired response or vice versa when $d_i = 1$ [12].The objective of the numerical optimization criterion is to produce welds with minimum residual stress. Therefore, and as the results demonstrated, the welding speed has to be maximized and both the laser power and focal position have to be minimized. According, to this criterion the safe welding condition would be as presented in Table 6. However, these conditions are optimized purely from a residual stress point of view, and do not consider other performance criteria, for example, the impact strength needs to be above a certain value. Therefore, a general optimization model should be run to determine the welding settings which satisfy all the requirements for all mechanical properties of interest [11].

Table 6: Selection of optimal welding settings based on the criterion for dissimilar welding.

No.	P	S	F	$\sigma_{AISI304}$	$\sigma_{AISI1016}$	Desirability
1	1.130	10.833	-0.800	70.073	85.165	0.936
2	1.130	10.832	-0.797	70.229	85.160	0.935
3	1.131	10.833	-0.800	70.146	85.163	0.934
4	1.130	10.812	-0.800	70.151	85.177	0.934
5	1.130	10.833	-0.791	70.478	85.149	0.933
6	1.130	10.786	-0.800	70.251	85.192	0.932
7	1.130	10.833	-0.787	70.683	85.142	0.932
8	1.133	10.833	-0.800	70.316	85.158	0.931
9	1.130	10.766	-0.800	70.324	85.203	0.930
10	1.130	10.833	-0.780	70.968	85.132	0.930

Conclusion

The following conclusions were drawn from the results obtained and are applicable only for the materials investigated in this work: The developed mathematical models and the optimal welding setting are valid in the welding parameters ranges that were used for developing the mathematical models. Extrapolation over those limits would limit the applicability of the found solutions.

1. RSM provides benefit in the applications where immediate predictions are needed and computationally intensive predictions, such as finite element method, are too slow. This technique allows the determination of the optimal welding setting combinations, and prevents loss of materials.

2. Both responses decrease as the welding speed increases, but both increase as either laser power or focus position increase.

3. In order to minimize the residual stress generated, the optimal welding settings are: laser power of 1.13 kW, focus position of - 0.8 mm and welding speed of 10.833 mm/s.

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