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Optimizing the CO_2 laser welding process for dissimilar materials

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ABSTRACT

A dissimilar full-depth laser-butt welding of low carbon steel and austenitic steel AISI316 was investigated using CW 1.5 kW CO_2 laser. The effect of laser power, welding speed and focal point position on mechanical properties (i.e., ultimate tensile strength, UTS and impact strength, IS) and on the operating cost C was investigated using response surface methodology (RSM). The experimental plan was based on Box–Behnken design; linear and quadratic polynomial equations for predicting the mechanical properties were developed. The results indicate that the proposed models predict the responses adequately within the limits of welding parameters being used. The optimum welding conditions were found.

1. Introduction

Welding of dissimilar materials 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].

The application of response surface methodology (RSM) in many areas to predict a certain feature and to optimize different processes was the interest of lots of researchers. Eltawahni et al. [2,3] have applied RSM in optimizing laser cutting for different materials. Anawa and Olabi [4] utilized Taguchi in optimization the process parameters of laser welding of dissimilar materials and Olabi et al. [5] have implemented RSM in laser welding. A comprehensive literature review on the application of such techniques has been carried out by Benyounis and Olabi [6]. Melhem et al. [7] have studied the three-dimensional consideration of jet impingement onto the kerf in relation to laser cutting process, they havealso investigated the effect of jet velocity on heat transfer rates. Yilbas et al. [8] investigated the Laser cutting of sharp edge and the effect of thermal stress analysis. Anawa and Olabi [9] studied how to control of welding residual stress for dissimilar laser welding material using Taguchi method. Benyounis et al. [10] purposed a multi-response optimization of CO_2 laser welding process of austenitic steel, using RSM and including results about costs too. Benyounis et al. [11] have also evaluated and minimized the residual stresses of the dissimilar laser welding process. Benyounis et al. [12] also have reported on the mechanical properties, weld bead and cost for CO_2 laser welding process optimisation. Yilbas et al. [13] presented an investigation on the Laser cutting of holes in thick sheet metals: development of stress field.

This paper first aims to use RSM to relate the laser welding input parameters (laser power, welding speed and focal position) to the main mechanical properties (ultimate tensile strength and impact strength). The second aim is to find the optimal conditions maximize the mechanical properties, keeping the cost relatively low.

2. Methodology

2.1. Experimental design

The experiment was designed based on a three level Box–Behnken design [14] with 5 centre points. Laser power, welding speed and focal point position represent the laser independent input variables. The Box–Behnken design was chosen because it avoids all the corner points, and the star points, where the combination of extreme value of laser power, welding speed and focal point position (corner points), or the extreme value of these factors (star point), could generate defects in the weld joint (lack of penetration, drop out, undercut).

Although, the twelve unique combinations represent less than one-half of all possible combinations for three factors with the same

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number of levels, they offer enough information to fit the Eq. (1), especially in the middle of the process design space. In order to find the limitation of the process input parameters and so to individuate the centre point of the process design space, preliminary trial simulation runs were carried out. Factors have been stated between a range of values useful to have an acceptable quality of the welded joint.

Table 1 shows the laser input variables and experimental design levels used. RSM was applied to the experimental data using statistical software design-expert V7. Linear and second order polynomials were fitted to the experimental data to obtain the regression equations. The sequential *F*-test, lack-of-fit test and other adequacy measures were used in order to select the best models. A step-wise regression method was used to fit the second order polynomial Eq. (1) to the experimental data and to identify the relevant model terms [15]. With the same statistical software, it was able to generate the statistical and response plots.

$$y = b_o + \sum b_i \chi_i + \sum b_{ii} \chi_{ii}^2 + \sum b_{ij} \chi_i \chi_j + \varepsilon \quad (1)$$

2.2. Laser welded

The dissimilar joining metals used are AISI316 and low-carbon steel with chemical composition as shown in Table 2. Both metals was cut into plates of 160 × 80 × 3 mm which were butt joined using a 1.5 kW CW CO_2 Rofin laser and a ZnSe focusing lens with a focal length of 127 mm. Argon gas was used as shielding gas with constant flow rate of 5 l/min. Soon after the welding three charpy impact strength subsize specimens of 55 × 10 × 3 mm and three standard tensile strength specimens accordant to ASTM E 8M-01^{E2} [16] were cut from each welded sample by means of laser cutting. The impact strength samples were tested at room temperature of 20 °C using a MAT21 universal pendulum impact tester. Tensile tests were performed in air using the pneumatic jaws-testing machine Zwick Roell

Table 1
Independent variables and experimental design levels used.

Variable	−1	0	1
Laser power, A (kW)	1.1	1.263	1.43
Welding speed, B (cm/min)	25	50	75
Focal point position, C (mm)	−0.8	−0.5	−0.2

Table 2
Chemical composition for the low carbon steel used.

Element	C	P	S	Si	Mn	Al	N
Wt(%)	0.003	0.013	0.005	0.001	0.001	0.04	0.01

Table 4
ANOVA table for ultimate tensile strength model.

Source	Sum of squares	*df*	Mean squares	*F*-value	Prob > *F*	
Model	173.556	5	34.711	14.568	0.0002	Significant
A	10.125	1	10.125	4.249	0.0637	
B	141.681	1	141.681	59.463	< 0.0001	
C	0.500	1	0.500	0.210	0.6558	
AB	12.250	1	12.250	5.141	0.0445	
BC	9.000	1	9.000	3.777	0.0780	
Residual	26.209	11	2.383			
Lack of fit	10.076	7	1.439	0.357	0.8889	Not significant
Pure error	16.133	4	4.033			

R^2=0.86; adjusted R^2=0.90; predicted R^2=0.75; adequate precision=13.68.

Table 5
ANOVA table for impact strength reduced quadratic model.

Source	Sum of squares	*df*	Mean squares	*F*-value	Prob > *F*	
Model	1111.250	6	185.208	13.836	0.0003	Significant
A	360.014	1	360.014	26.895	0.0004	
B	36.125	1	36.125	2.699	0.1315	
C	56.889	1	56.889	4.250	0.0662	
AC	160.444	1	160.444	11.986	0.0061	
BC	256.000	1	256.000	19.124	0.0014	
C^2	241.778	1	241.778	18.062	0.0017	
Residual	133.861	10	13.386			
Lack of fit	116.217	6	19.369	4.391	0.0868	Not significant
Pure error	17.644	4	4.411			
Cor total	1245.111	16				

R^2=0.89; adjusted R^2=0.83; predicted R^2=0.60; adequate precision=12.42.

Table 3
Design matrix, experimental measured responses and operating cost.

Std	Run	Laser power (kW)	Welding speed (cm/min)	Focal point position (mm)	Ultimate Tensile strength (MPa)			Impact strength (J)			Operating cost (€/m)
					UTS1	UTS2	UTS3	IS1	IS2	IS3	
17	1	1.263	50	−0.5	362	362	362	68	68	67	0.252
1	2	1.1	25	−0.5	369	369	369	60	59	59	0.488
11	3	1.263	25	−0.2	364	364	363	59	60	58	0.503
13	4	1.263	50	−0.5	359	358	361	72	72	72	0.252
15	5	1.263	50	−0.5	362	362	363	61	71	70	0.252
5	6	1.1	50	−0.8	362	362	364	58	57	61	0.244
3	7	1.1	75	−0.5	357	355	357	62	49	56	0.163
6	8	1.43	50	−0.8	361	360	361	62	59	59	0.259
9	9	1.263	25	−0.8	366	367	367	60	71	64	0.503
4	10	1.43	75	−0.5	357	355	357	68	70	71	0.173
8	11	1.43	50	−0.2	361	361	360	72	72	76	0.259
10	12	1.263	75	−0.8	357	357	354	43	44	42	0.168
7	13	1.1	50	−0.2	362	361	359	39	47	54	0.244
16	14	1.263	50	−0.5	364	365	366	72	70	71	0.252
14	15	1.263	50	−0.5	362	363	362	61	72	72	0.252
12	16	1.263	75	−0.2	359	360	358	69	65	73	0.168
2	17	1.43	25	−0.5	361	362	363	72	70	71	0.518