Proceedings of the International Conference on Applied Mechanical Engineering Research(IC-AMER2019)
NIT Warangal, India – May 02-05, 2019
Paper No. XXX (The number assigned when the papaer is accepted)

Experimental Investigation on Laser Beam Welded Joints of Dissimilar Metals and Optimization of Process Parameters using Firefly Algorithm

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Abstract – Laser Beam Welding (LBW) is extensively being used in modern industry for joining of metals and alloys due to its advantages of controlled heating, narrow weld bead, low Heat Affected Zone (HAZ) and its ability to weld a wide range of metals, and dissimilar metals. With a new generation of high power lasers LBW makes the process a possibility for industrial applications dealing with thick metals for welding in ship building, offshore structures, pipelines, power plants and other industries. Further, LBW is suitable for joining at high process speed, low heat input to achieve high productivity, leading to reduced process costs. Therefore, an attempt is made in the present paper with an objective to investigate mechanical properties of dissimilar metal joints of AISI 4130 and AISI 316 steels. Experiments are conducted with LBW considering 2 mm thick dissimilar metals by varying Laser Beam Power, Welding Speed, Beam Incident Angle, Focal Point Position and Focal Length. The experimental output results measured are Ultimate Tensile Strength and Impact Strength. ANOVA is carriedout to obtain the influence of process parameters and statistical validation of the results. The Firefly Optimization Algorithm is used to determine the best combination of the process parameters of LBW.

***Keywords*:** Laser Beam Welding (LBW), Mechanical Properties, Analysis of Variance, Firefly Algorithm.

1. Introduction

AISI 316 Stainless Steel (SS) is the second most commonly used metal after 304 Austenitic Stainless steel. The marine grade SS 316L usually contains Cr, Ni and Mo ratio in marine grade 316L steel. Since it increases the corrosion resistance especially in coloride environments. AISI 316 SS is used in various industries such as oil, gas, petrochemical, pharmaceutical, food industries, etc., for manufacturing of pipes and sheets but it is more costlier in comparison to with 304 SS. AISI 4130 steel is a medium carbon steel consisting of Cr, Mo and Mn. It is used in oil industry and power plants, due to its very good strength at high temperatures dependent heat exchangers and generators. Further, it is also used in normalized, quenched and tempered states.

Welded joints of dissimilar SS and low alloy steel with high strength has plenty of applications in a variety of industries, oil, gas, petrochemical, thermal power plants and food industry. In many of said industries, the fluid transfer tube lines and nozzles are made of SS. Whereas the tanks and under pressure parts of the systems are made of low alloy steels by the conventional welding methods to join. In view of the extensive applications of dissimilar steel metal joints, optimizing the properties of such joint has always been the critical case. In past, some research has been presented concerning the joints of 4130 and 316 steel plates. But to overcome some of the drawbacks conventional processes, LBW offers significant advantages due its ability to Weld complex geometries with close tolerances, high strength and narrow HAZ, with high quality joining [1, 2].

2. Literature Review

In any welding process of dissimilar metals, it is important to use optimal parameters. Optimal parameters, can be obtained by scientific optimisation techniques. In the present work, Taguchi based orthogonal array is chosen to conduct experiments. Quite a good number of published literature shows the usability of optimisation techniques for both non-fusion and fusion welding including LBW of different materials. A brief literature is presented in the following:

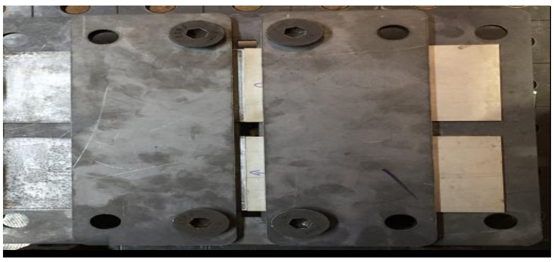
Mechanical behavior joints of AISI 4130 steel obtained by TIG and LBW are studied by comparing each other process. It is shown that the LBW is more suitable for mechanical characterization, Souza Netoa et al., [3]. GTAW method is used for investigating the properties of dissimilar joints of AISI 4130 & AISI 316 steels by Mostaan et al., [4] and analysed the interface structure SEM with EDS. Experimental study on the hardness and corrosion resistance by joining similar metals (304) and dissimilar metals (304/A36) have shown that the welding speed and corrosion resistance influence quality of the welding Mahmoud et al., [5]. The joint obtained by EBW is found to be having better tensile strength over the joints obtained by GTAW and FSW over the joints obtained by dissimilar metals (304/4130), Arivazhagan, et al., [6]. The recent publication on evolutionary algorithm Firefly Algorithm (FA) based on nature is found to be a good optimization tool and multi objective optimization problem [7]. Further, it is also shown that the FA can perform better than PS optimization algorithm particularly in the case noisy nonlinear optimisation problems at higher level of noises [8]. Lateron, the recent advantages and applications of FA are represented in a Yang et al., [9]. Though the literature shows that the joint properties of the LBW of dissimilar of steels are affected by Power (W), Speed (m/min) Beam Angle, Focal Point Position (mm) and Focal Length (mm), but they are limited to one or two input parameters are studied limited to indusial parameter. thereas, experiments have been carried-out with various levels of process parameters.

2.2. Objective of Research Paper

The objective of the present research work is to conduct experiments so as to investigate the effect of process parameters on the joints of dissimilar metals by LBW. Then the outputs mechanical properties are analysed by ANOVA followed by the optimization of process parameters by apply of FA.

3. Experimental Procedure

To achieve the objective, experiments are conducted by preparation of samples by joining of two plates of dissimilar metals. Samples of two plates of base metals (AISI 316 and AISI 4130) with dimensions of 2×80×280 mm are cut to size and used for welding. Fig. 1(a), shows the arrangements of sample pieces as AWS standard. The pieces are cleaned with acetone in order to prevent formation of any defects.

(a) 

(b) 

Fig. 1. LBW work pieces: (a) position of work pieces (b) welded joints

3.1. Welding process

Experiments are conducted with a CO_2 LBW system of 4kW (Trump Model). Experiments are conducted by keeping the average power of the CO_2 LBW constant at 4 KW throughout.

However, the pulse repetition (frequency) and focal length of 16 mm is used. Welding parameters consists of Power-A (1400, 1600, 1800, 2000, 2200 W), Welding Speed-B (1.2, 1.4, 1.6, 1.8, 2.0 m/min), Beam Angle-C (88, 89, 90, 91, 92 degrees), Focal Point Position - D (-0.2, -0.1, 0.0, 0.1, 0.2 mm), and Focal Length-E (16, 17, 18, 19, 20 mm). Taguchi approach consisting of experiments L_{25} (25) Orthogonal Array for five levels of these parameters is selected. Different combinations of parameters to weld specimens for the five levels and five factors are shown in Table 1. Experiments are conducted to obtain 25 joints, but a sample of 5 joints are shown in fig. 1(b).

3.2. Mechanical Properties Measurements

Test Specimens are prepared by using CNC wire cut EDM machine as per standard UTS of ASTM E 8M-01 and IS of ASTM E23 and the tested specimens for tensile test (FIE UTM) are shown fig. 2(a). followed by the specimens for Charpy Impact in fig. 2(b). The test results joint of each joint sample are presented in Table 1 (Columns UTS and IS).

(a) (b)

Fig. 2. Testing specimens as per ASTM: (a) Tensile test and (b) Impact test.

4. Analysis of Variance

Statistical analysis is conducted on the experimental results by ANOVA for UTS and is shown in Table 2 and IS results in Table 3 consisting of Degrees of Freedom, SS^2, adj SS, adj MS and percentage of contribution each parameters (% C). Similarly, the columns in Table 3 show the results ANOVA for IS with same parameters and symbols.

Percentage of contribution of each parameter for UTS is shown in Table 2. It is clear from the experimentation, that the percentage of contribution for Laser Power is 31.33%, Welding speed 15.96%, Beam angle 14.53%, Focal point position 10.38% and Focal length 11.17% respectively. It can be seen that the Laser Power has greater influence on UTS. R^2 = 83.4% confirms the reliability of experimentation. Since, the ANOVA is a parametric based optimization design, from the results it is clear that the Laser Power is the major factor with 31.33%, which is to be selected effectively to obtain better UTS. Similarly, the percentage of contribution of each parameter for IS is shown Table 3. It is clear from the results, that the percentage of contribution by laser power is 18.22%, welding speed 15.70%, Beam angle 21.18%, Focal point position 9.78% and Focal length 19.72%, respectively. It is observed that the Beam angle has the major influence on UTS. R^2 = 84.6% confirms the reliability of experiments. It is also clear from the results that the beam angle is the major factor (21.18%), which is to be selected to obtain better IS.

5. Optimisation using Firefly Algorithm

FA is a nature-inspired metaheuristic algorithm introduced in 2008 by Yang to solve optimisation problems. The algorithm is based on the social flashing behavior of fireflies in nature. Fireflies or lightning bugs belong to a family of insects that are capable to produce natural light to attract a mate or prey. Whereas Firefly Algorithm Regression equations of UTS and IS are shown in the following eq. (1) and eq. (2). The objective functions are converted into multi-objective function by weighted sum approaches. The approach to solve multi-objective optimization is to assign a weight W_i to each objective function. The single objective problem with a scalar objective function is shown in eq. (3). The weight are considered for $w_j = 0.5$. The multi-objective function is shown in eq. (4). Which converts the minimisation function to maximization by using eq. (5).

$$z_1 = 1447 - 0.008\,A + 16\,B - 7.7C + 61\,D - 12.3E \quad (1)$$
$$Z_2 = 27.8 + 0.0078\,A + 0.5\,B - 0.12\,C - 7.4\,D - 0.46\,E \quad (2)$$
$$Z = w_1 z_1 + w_2 z_2 \quad (3)$$
$$Min\,Z = 737.4 - 0.0001A + 8.25B - 3.91C + 26.8D - 6.38E \quad (4)$$
$$Max\,Z = -1(-Zmin) \quad (5)$$
$$Max\,Z = -1(-737.4 + 0.0001A - 8.25B + 3.91C - 26.8D + 6.38E) \quad (6)$$

The maximization of multi objective regression eq. (6) used and then for optimization by the application of FA and the optimal combination of process parameters. As shown in table 4.

6. Conclusions

Conclusions based on the experimental results present research are shown in the following:

- Sound welds are obtained by joining of dissimilar AISI 316 & AISI 4130 steels by LBW.
- LBW is suitable for welding AISI 316 with AISI 4130 steels for industrial applications owing to high welding speed and highest UTS 731.54 MPa and IS 28J as obtained for the experimental joints.
- ANOVA results show that the power 31.33% is the major influencing process parameter on UTS, whereas Beam angle 21.18% on IS.
- The multi-optimal combination of processes parameters obtained by the application of FA are: Power 1568.1 W, Speed 1.9 m/min, Angle 88.6 degrees, Focal Point Position 0.1 mm, Focal Length 16.3 mm at the UTS 588.24 MPa and Impact Strength 22.11 J.

Acknowledgement

The authors are grateful acknowledge Welding of Magod Laser Machining Pvt. Ltd., Bangaluru-560105, India, for permitting to conduct the experiments.

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Table. 1. LBW process parameters combination and mechanical properties of joints.

S. NO	Input Process Parameters					UTS (MPa)	IS (J)
	A	B	C	D	E		
1	1400	1.2	88	-0.2	16	513.85	26
2	1400	1.4	89	-0.1	17	519.23	22
3	1400	1.6	90	0.0	18	177.69	4
4	1400	1.8	91	0.1	19	341.54	25
5	1400	2.0	92	0.2	20	610.00	24
6	1600	1.2	89	0.0	19	664.61	23
7	1600	1.4	90	0.1	20	684.61	12
8	1600	1.6	91	0.2	16	681.54	18
9	1600	1.8	92	-0.2	17	593.85	27
10	1600	2.0	88	-0.1	18	569.23	26
11	1800	1.2	90	0.2	17	585.38	28
12	1800	1.4	91	-0.2	18	688.46	21
13	1800	1.6	92	-0.1	19	616.15	24
14	1800	1.8	88	0.0	20	730.77	26
15	1800	2	89	0.1	16	685.00	28
16	2000	1.2	91	-0.1	20	167.69	26
17	2000	1.4	92	0.0	16	688.46	27
18	2000	1.6	88	0.1	17	731.54	28
19	2000	1.8	89	0.2	18	246.15	15
20	2000	2.0	90	-0.2	19	603.07	26
21	2200	1.2	92	0.1	18	533.07	28
22	2200	1.4	88	0.2	19	572.31	26
23	2200	1.6	89	-0.2	20	510.00	28
24	2200	1.8	90	-0.1	16	369.23	26
25	2200	2.0	91	0.0	17	513.84	24

Table. 2. ANOVA for Means of UTS

Source	DF	SS^2	Adj SS	Adj MS	% C
A	4	201576	201576	50394	31.33
B	4	102646	102646	25661	15.96
C	4	93493	93493	23373	14.53
D	4	66765	66765	16691	10.38
E	4	71882	71882	17971	11.17
Error	4	106980	106980	26745	16.63
Total	24	643343	-	-	100.0
S = 163.5 R^2 = 83.4% R-Sq(adj) = 0.2%					

Table. 3. ANOVA for Means of IS

Source	DF	SS^2	Adj SS	Adj MS	%C
A	4	145.04	145.04	36.26	18.22
B	4	125.04	125.04	31.26	15.70
C	4	168.64	168.64	42.16	21.18
D	4	77.84	77.84	19.46	9.78
E	4	157.04	157.04	39.26	19.72
Error	4	122.64	122.64	30.66	15.40
Total	24	796.24	-	-	100.0
S = 5.537 R^2 = 84.6% R-Sq(adj) = 7.6%					

Table. 4. FA optimal Results

A (W)	B (m/min)	C (Degrees)	D (mm)	E (mm)	Optimal value
1568.1	1.9	88.6	0.1	16.3	UTS=588.2452 & IS=22.1112