ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 2, Issue 4, July 2013

Optimization of Laser Welding Process by Fuzzy Logic Technique

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Abstract: Laser welding process can be used for welding of dissimilar metals to meet industrial demand for low cost, light weight and excellent weld strength. In this work, Laser welding of two dissimilar metals namely Inconel and stainless steel plates has been carried out to attain optimum tensile strength of the weld joint. The welding experiment was performed according to Taguchi method based on four factor three levels design. The optimization of the process parameters is carried out by using fuzzy logic technique and the results are compared by regression analysis and Anova. It was found that values of parameters namely depth of penetration and ultimate tensile strength obtained from fuzzy logic and regression was in close agreement with each other. Laser welding is increasingly used in automobile, aerospace, defence, electronics industries.

Keywords: **Dissimilar metals, Fuzzy Logic, Laser Butt welding, Optimization, Taguchi method.**

I. INTRODUCTION

According to the Legenberg R. [1], the prime requirement of automotive industry is to improve durability, reduce weight and protect product from the environment. The welding of stainless steel and Inconel sheets has a great importance in the industry for manufacturing of industrial products. There is an ever increasing demand for reliable and good quality welds of dissimilar metals and these joints are susceptible to deformation and cracking due to their high co-efficient of thermal expansion. The high energy laser beam welding process is expanded into modern industries and new applications because of its many advantages over other welding techniques in terms of weld penetration and minimizing heat input. Laser welding became one of the much reliable processes. This process performs key role in manufacturing and maintenance sectors of the industry. Laser can be operating in continuous or pulsed mode depending on whether power output is continuous over time or output takes form of pulses of light. Tadamalle et. al[2]investigated the effect of speed and laser power on weld bead geometry, bead diameter from pulse to pulse, duty cycle and effective pulse energy.

K.R.Balasubramanian et. al. [3] analyzed that laser beam power and welding speed were major parameters influencing on depth of penetration and bead width. The gas flow rate does not influence significantly on the process. Tadamalle et al [4] determined that the optimal process parameters can predict tensile strength of the weld joint using Taguchi and response surface methodology and the results obtained from both methods are compared. K.Y.Benyounis et.al.[5] reported that controlled mechanical properties can leads to good welded joints. The optimal welding conditions were identified in order to increase productivity and minimize total operating cost. K.R.Balasubramanian et. al. [6] carried out research to comprehend and prediction of laser welding parameters for butt joints using neural network. K. K. Kanaujia et.al[7] stated that Nd:YAG laser welding process was successfully used for joining of dissimilar metals. The experimental results pointed out that laser welded joints strength is improved successfully by optimizing the input process parameters using Taguchi method. Vidyut Dey et. al[8] reported that genetic algorithm was able to determine optimal weld bead geometry and recommend necessary process parameters for obtaining full depth of penetration and weld strength.

A Ruggiero et. al[9] reported weld bead profile and cost optimization of CO_2 laser welding was carried out using Regression analysis. The results indicate that the proposed models predict the responses adequately within the limits of welding parameters being considered for the study. A.G. Olabi et. al [10] focuses on the knowledge of methods and their ability to integrate their functions. Two methods to design of experiment have been employed, back prapogation artificial neural network and Taguchi approach. The optimal solutions were valid in the ranges of welding parameters that were used for training the neural network. The literature survey reveals that the laser power, laser energy, laser current, beam travel speed strongly influences the mechanical properties of laser weld joints. The investigation was carried out to study mechanical and micro structural properties of the welding of dissimilar welds.

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II. DESIGN OF EXPERIMENT

The experiments have been conducted using on solid state laser Neodymium-doped yttrium aluminium garnet (Nd: YAG) for welding of dissimilar metals that is stainless steel 304L and Inconel 625. The experiments have been performed according to Taguchi L9 array based on four factor three level design. Four parameters considered were laser power (P), laser energy (E), laser current (C) and beam travel speed (T). The values of process parameters selected based on the capability of the instrument and available ranges. The other process parameters such as gas flow rate, pulse duration, pulse frequency, focal distance, and incident laser beam angle were kept constant. The depths of penetration (DOP), ultimate tensile strength (UTS) were considered as responses. The major steps involved in the experimentation are material selection, study of chemical, physical and mechanical properties, specimen preparation, experimental work and testing.

The austenitic steel 304L (SS) and Inconel 625 material is selected for the experimentation because 304L is low carbon variant steel can be welded without resulting issue of carbon precipitation. Inconel 625 is often encountered in extreme environments. It is common in gas turbine blades, combustors, turbocharger rotors and seals, electric submersible well pump motor shafts, chemical processing and pressure vessel, steam generators in nuclear pressurized water reactors, automotive exhaust systems. It has good acid resistivity and weld ability. Inconel alloys are oxidation and corrosion resistant and have high strength over a wide range of temperatures. Austenitic stain less steel 304L and Inconel 625 sheets were cut to 300 x 60 x 0.7 mm size using laser cutting machine, electric discharge machine and finished by deburing and polishing as shown in fig.1. The surfaces were polished to meet absolute surface to surface contact for a good quality of weld.

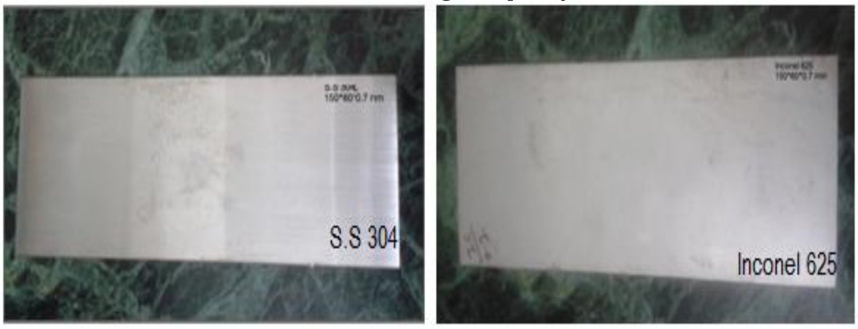

Fig 1: Sample specimens cut out of sheets

Experimental Procedure

The experimental set up for Solid state laser welding is shown in fig 2, it consists of argon gas cylinder for regulating gas flow rate. The specimen was mounted on table of *Hans laser machine PB 300* with help of clamps.

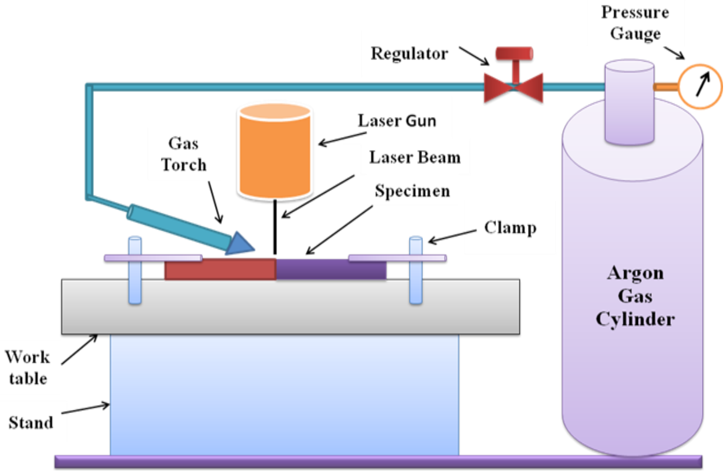

Fig 2. Experimental set up for laser welding.

The commercial argon gas was used as the shielding gas to prevent the specimen from oxidation and heat dissipation and avoid distortion. Laser gun was positioned exactly above the specimen joint. Most affecting parameters as laser power, laser energy, laser current and beam travel speed were defined and other process parameters are mentioned in table I.

Table I: Process variables and experimental design levels

Variables	Notation	Units	Limits		
			-1	0	+1
Laser Power	P	Watt	1200	1300	1400
Laser Energy	E	Joule/mm^2	170	185	200
Laser Current	C	Ampere	155	165	175
Travel Speed	T	mm/sec	1.0	1.5	2.0
Sheet Thickness	t	mm	0.7		
Gas Flow Rate	R	N/mm^2	07		
Pulse Duration	λ	ms	1.0		
Working Frequency	f	Hz	07		
Atm. Temperature	T_0	^{0}C	28		
Focal Distance	D	mm	180		

According to Taguchi design nine experiments were expected to be carried out. The experimental layout for orthogonal array is presented in table II along with process parameters and their levels. First set of experiment was carried out for joining Inconel 625 and SS specimens and second set of experiment was carried out on SS and SS specimens. Its orthogonal array matrix along with process variables is shown in table II.

Table II. Orthogonal array matrix with process variables

Sample No.		Levels				Current (A)	Present Simple energy(J)	Power (W)	Travel Speed (mm/sec)
Inconel+ SS SS	SS+S S								
1	A	-1	-1	-1	1	155	170	1200	2.0
2	B	-1	0	-1	1	155	185	1200	2.0
3	C	-1	1	0	1	155	200	1300	2.0
4	D	0	-1	1	0	165	170	1400	1.5
5	E	0	0	0	0	165	185	1300	1.5
6	F	0	1	1	0	165	200	1400	1.5
7	G	1	1	0	-1	175	200	1300	1.0
8	H	1	1	1	-1	175	200	1400	1.0
9	I	-1	0	1	0	155	185	1400	1.5

Micro structural Analysis

The welded specimens were cut into transverse directions and cross section surface was prepared for metallographic inspection according to ASTM E112 standards. The weld joints are polished using different grade polishing papers and the specimens are etched using $FeCl_3$+HCL+CH_3OH and picric acid and HCL; time of etching was 30 sec. A 10 % oxalic acid used for SS +SS specimen, time of etching was 20 sec to observe weld bead geometry and microstructure. The sample figure of microstructure and weld bead geometry used for metallographic inspection is as shown in fig.3.

The measurement of weld bead geometry was carried out using optical microscope make-Carl Zeiss, Germany, magnification-25x. The micro structural analysis has been carried out by magnifying the images to 200x times. The measurements are given in table III. Weld microstructure of SS+SS specimen shows curved lines as merging zone, fine dendrites with delta ferrite and fine chromium type carbide precipitation and chromium nitride precipitation. Also a Widmannan Stannan structure within austenite grains and fine particles at austenite grain boundaries and lamellar form extending outwards from grain boundaries. Weld microstructure of Inconel 625+SS specimen shows some macro fissure lamellar chromium carbides at coarse austenite grain boundaries, light acicular form of sigma .The cast dendritic structure of filler metal; fibrous weld fusion zone with some twinning and precipitate TiC cast fine dendrites.

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Table III: DOP and UTS values of welded specimens

Sample No.	A	B	C	D	E	F	G	H	I
DOP (micron)	223.60	289.37	168.19	194.47	303.6	246.87	193.16	228.57	210.5
UTS (MPa)	170	186	257	376	379	388	453	485	232
Sample No.	1	2	3	4	5	6	7	8	9
DOP (micron)	398.61	375.41	430.98	380.69	436.4	435.53	434.26	311.72	401.8
UTS (MPa)	356	218	340	517	450	697	711	674	287

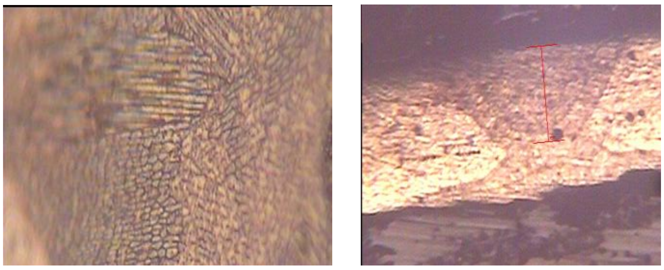

Fig 3: "(Weld zone microstructure)" and "(weld bead geometry dimensions)"

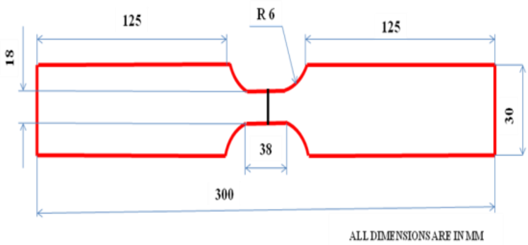

Fig 4. Specimen for tensile test

Tensile test

All welded specimens were cut to a required shape according to the ASTM standards as shown in Fig.4. Tensile test have been conducted at room temperature using universal testing machine (AMT- 40) make- ASI sales private limited, New Delhi. Maximum operating capacity of 400 KN. The results obtained are shown in table III.

III. OPTIMIZATION OF DOP AND UTS USING FUZZY LOGIC

The fuzzy logic controllers are special expert system that can be used to optimize desired values from the set of input and output variables. The set of values that is determined from experimental results. Fuzzy controllers are capable of utilizing knowledge elicited from human operators. A general fuzzy controller consists of four modules, fuzzification, fuzzy rule base, fuzzy inference engine and defuzzification. A fuzzy controller operates by repeating a cycle of above four steps. In fuzzification, the measurements of all variables is taken, these measurements are converted into appropriate fuzzy sets. These fuzzy sets are fuzzy numbers which represent linguistic labels such as approximately zero (AZ), positive small (PS), negative small (NS), positive medium (PM) , negative medium (NM), positive large (PL), negative large (NL). Two conditions are monitored by the controller, an error (e) defined as the difference between the actual value of controlled variable and its desired value and the derivative of error (e'), which expresses rate of change of error. Using values of e and e', fuzzy controller produces values of controlling variable (v). The linguistic states are represented by a triangular shaped fuzzy numbers, we get fuzzy quantization for variables e, e' and v as shown in fig. 5 as in [11].

Table IV. Standard fuzzy inference rules

		e'						
	V	NL'	NM	NS'	AZ'	PS'	PM	PL'
e	NL	PL				PM	AZ	
	NM							
	NS	PM		PM	PS	AZ	NM	
	AZ			PS	AZ	NS		
	PS			AZ	NS	NM		
	PM	AZ		NM	NL			
	PL							

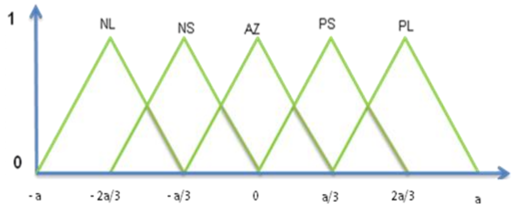

Fig 5.Fuzzy quantization by a triangular shaped fuzzy numbers.

The knowledge pertaining to the given control problem is formulated in terms of fuzzy inference rules. Standard fuzzy inference rules are tabulated in table IV. A set of input output data is determined by $\{(X_{K,} Y_{K,} Z_K / _{K \in} K\}$, where $X_{K,} Y_K$ are values of input variables e and e' respectively. Z_K is desirable value of output variable v, K is an index set. A (X_K), B (Y_K) and C (Z_K) denotes largest membership grades in fuzzy sets representing the linguistic state of variables e, e' and v respectively. Then degree of relevance can be defined by formula, i_1 [i_2 (A (X_K), B

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(Y_K), C (Z_K)] where i_1 and i_2 are t-norms. The degree of relevance can be calculated for all rules activated for input and output data. Activated data allow us to avoid conflicting rules in fuzzy rule sets among the rules that conflict with one another. The largest degree of relevance has been considered for the further calculations. The fuzzy inference rules can be converted into simple fuzzy conditional proposition to the desired form using fuzzy inference engine.

If (e, e') is (A x B) then v is C. [A × B] takes on (x, y) for minimum of [A(x), B(y)], for all X Є [-a, a] and all Y Є [-b, b]. Fuzzy inference rules takes following form,

Rule 1: If (e, e') is (A_1 x B_1), then v is C_1

Rule 2: If (e, e') is (A_2 x B_2), then v is C_2

.....

Rule n: If (e, e') is (A_n x B_n), then V is C_n

The symbols A_j, B_j, C_j (j = 1, 2...n) denotes fuzzy sets that represent the linguistic states of variables e, e' and v respectively.

The defuzzification of the process is done using centre of area method the value $d_{CA}(C)$ for discrete case. The parameter C is defined as an finite universal set {$z_1, z_2, z_3 \ldots z_n$ }.The formula referred is presented in equation (1) below as in [8].

$$d_{CA}(C) = \frac{\sum_{k=1}^{n} C(Z_k) Z_k}{\sum_{k=1}^{n} C(Z_k)} \quad (1)$$

Regression Analysis

From regression method mathematical model is developed to predict the optimum response value for each response which is used as expert system for optimum parameter prediction. Regression analysis is used to determine most influencing parameter on UTS and DOP. The regression coefficients were calculated using Minitab 16 software. The response was modeled as linear function of the independent variables laser current, laser energy, laser power and beam travel speed. The following equations are generated to estimate the value of UTS and DOP for different combination of materials. The equation (2) - (3) is written for the welding of Inconel 625 and SS specimens and whereas equation (4) - (5) is written for the welding of SS and SS combinations.

$$U.T.S. = -1960 + 10.2C + 0.661E + 0.449P \quad \ldots (2\text{-}3)$$
$$D.O.P. = 448.139 + 0.6467C - 0.3630E - 0.1884P - 4.6T$$

$$U.T.S. = 1167 - 0.69C - 0.39E + 0.168P - 384T \quad \ldots (4\text{-}5)$$
$$D.O.P. = 450.112 - 1.06956C + 0.9076E - 0.0459P + 9.3T$$

IV. RESULT DISCUSSIONS

The optimized values of process parameters for specimen obtained after eight iterations are tabulated in table V.

Table V. Optimized values of process parameters

Material	Method	Optimized Parameters			DOP (Micron)	UTS (N/mm^2)
		Laser Power (Watt)	Travel Speed (mm/s)	Laser Energy (Joule)		
Inconel 625 and SS 304L	Fuzzy Logic	1300	1.5	185	299.84	476.83
	Regression	--	--	--	255.87	428.98
Error					14%	10%
SS 304L and SS 304L	Fuzzy Logic	1300	1.5	185	432.92	698.55
	Regression	--	--	--	395.82	623.40
Error					07%	10%

Fig. 6 shows graphs of optimized values of UTS verses process parameters for Inconel 625 and SS specimens and SS and SS specimens. The process parameters used during experimentation are laser energy, laser power and welding speed. The UTS values are nearly equal for laser energy and laser power.

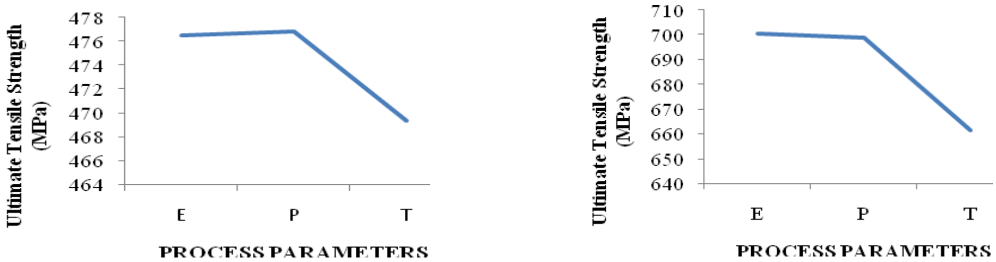

Fig 6 "(Inconel 625 and SS specimens) and "(SS and SS specimens)"

Fig.7 shows graphs of optimized values of D.O.P verses process parameters. The D.O.P values decreases from laser energy to laser power to beam travel speed.

Fig 7 "(Inconel 625 and SS specimens)" and "(SS and SS specimens)"

Increase or decrease in strength of weld joint depends upon grain size pattern. Coarse grain size exhibits more strength whereas fine grain size exhibits less strength. The process parameters selected for study significantly effects on strength.

V. CONCLUSION

Based on result of optimization analysis and micro structural analyses following conclusions were made. It was found from Regression analysis that current and power are the most significantly affecting parameters. Estimated UTS values are within difference of 6 N/mm^2 and 38 N/mm^2 for process parameters E, P, T for Inconel 625+SS and SS+SS specimens respectively. Estimated DOP values are within difference of 4 microns for process parameters E, P, T for Inconel 625+ SS and SS +SS specimens. UTS and DOP values estimated by fuzzy logic and regression are found to be in close agreement with each other. Fine dendrites with delta ferrite, fine chromium type carbide precipitation, chromium nitride precipitation, Widmannan Stannan structure, light acicular form of sigma are significantly affecting features of microstructure. The experimentation can be performed by considering sheet thickness as 0.8 mm, 1.0 mm, 1.2 mm and 1.5 mm. Material selection could be combination of mild steel, austenitic steel and aluminum.

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