Integration Of Robust Design And Simulation to Predict Optimum Parameters for Laser Beam Welding

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ABSTRACT

In this paper, an attempt is made to achieve a robust weld quality that is insensitive to uncontrollable factors. The best process parameters are identified by integrating the Robust Design Concept and simulation. The influence of process parameters on Laser Beam Weldrng are studied The controllable parameters considered are heat flux, welding speed, focus diameter and plate thickness. The ambient temperature is taken as uncontrollable factor. Sirnulation of Experiments is performed for different combinations of parameter using ANSYS software based on Taguchi's Robust technique. Three dimensional non-linear transient thermal analysis is performed and the temperature distribution along the laser welded plate is obtained in the form of contour plots. Bead width and penetration depth are determined from these plots. To find the effect of control factors on the responses, ANOVA table is formed. Also, the best parameters for different responses are identified using S/N curves.

Keywords : *Laser Beam Welding. Simulation, FEA, Design ot Experiments, Robust Design.*

INTRODUCTION

Mild steel is a common material which is used in many of the Engineering Industries and they are fabricated in many forms and serves as Engineering product. In fabrication, welding plays a major role and conventional welding has always been on a broad welded path or heat affected zone. Both electron and laser beam welding technique have been proven to meet the crucial criteria for modern welding. In electron beam wel.ding, it is required to maintain a vacuum system, which has held back its further applications, whereas laser beam welding has become popular in industry.

Laser beam has a reputation for rapid, precise and easy operation in weldtng (I). But, the use of the technique in inappropriate settings can reduce its effectiveness in welding applications. The optimum setting of the laser parameters becomes very crucial. Specifically, excess heat, inappropriate welding speed, laser spot diameter etc., may cause improper bead profile which may not be suitable for specific application which is intended. The combination of these parameters creates a complicated reaction during welding process. It is costlier to perform laser beam welding and also the number of laser systems are very few, an attempt is made to simulate the laser welding system and the results based on simulations are discussed here. By simulating the weld system, valuable insight into the system and into the relative importance of the different variables are gained. Simutation allows for the compression of real time. Predicting the behavior of a system consumes much time but it takes only a few hours using computer simulation. Simulations are performed using Taguchi's Robust Design Concept. Nine combinatian of three parameters in welding are set according to Taguchi and to obtain the optimal setting for laser beam welding on mild steel.

The main parameters of the Laser Beam Welding process shown in Fig.1 are considered and the simulation is performed using the Finite Element Analysis package ANSYS 9.0.

DESIGN OF EXPERIMENTS

A series of structured trials are designed for simulation af laser welding, in which planned changes are made to the input process parameters. The effects of these changes on the output are then analyzed.

Traditionalty, the effect of parameters on the response is studied by trial and error method. In the trial and error method, the number of experiments required for complete study is quite high. Taguchi's method of 'Design of Experiments' (DOE) based an Robust Design Concept overcomes the above inconvenience. The Taguchi's approach more engineering oriented, than science oriented. Robustness is the state where product or process performance is minimally sensitive to factors causing variability either in manufacturing or users environment. There are two main types of quality in a product which are customer quality and engineered quaiity. Robust Engineering is associated with engineered quality, It ensures that the product wili have acceptable performance throughout the intended life span of the product. Customer quality is described as the quality at the time of purchase [2].

The Aspects of Robust Design are to:

- Find a set of conditions for design variables which are robust to noise.
- Minimize the No. of experiments using orthogonal arrays.
- Achieve the smallest variation in a Product function about a desired target value.

An attempt is made to introduce the concept af robustness in laser beam welding process and to produce quality weld products.

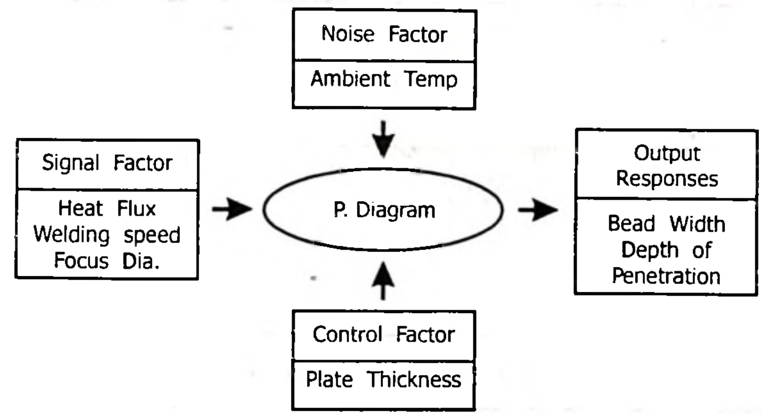


Fig.1 Parameter Diagram for the Laser Beam welded structure

METHODOLOGY :

It consists of the following steps:

i. Selection of independent or cantrol variables

ii. Selection of number of level settings for each independent variable

iil. Selection orthogonal array based on the above two step.

iv. Simulating the experiments

v. Model Validation

vi. Analyzing the data

vii. Inferences based on the abave analysis.

IDENTIFICATION OF PARAMETERS

The Parameter diagram shown in Fig.1 is used to classify the variables associated with the product into noise, control, signal (input), and response (output) factors. The weld bead geometry is shown in 2.

Parameter diagram is a must for every developmental project. It is a way of succinctly defining the development scope. The signal factors are identified as Heat flux, Welding Speed and Focus diameter. For robust design of welding the bead width and depth of penetration which constitute the bead geometry are considered as output response. The parameter that is beyond cntrol is considered to be the ambient temperature, which is the noise factor. Here, the plate thickness is considered as the control factor which is varied by three levels.

DECIDING THE NUMBER OF LEVELS

After deciding the independent variables, the number of levels for each variable is decided. The selection of nuntber of levels depends on trend in which, the parameter influences the output responses.

All parameters except noise parameter are varied at three levels for better prediction of results. Noise parameter is varied by two levels. Variation of input signal, control parameters and noise parameter are given in Table 1.

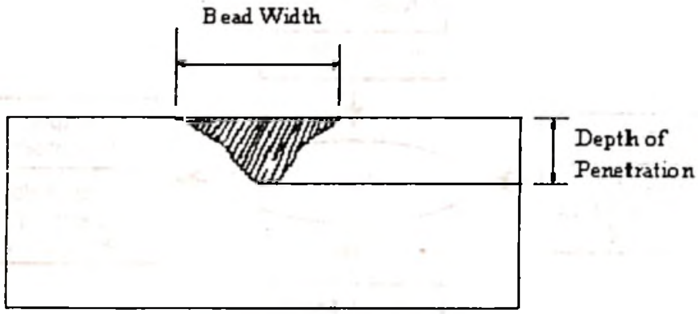


Fig.2 Weld Bead Geometry

Parameters		Level		
		1	2	3
Input Signal	Heat Flux (q) x 10^8, W/m^2	1	1.1	1.2
	Welding Speed (WS), m/sec	8	10	12
	Focus diameter (FD), mm	0.6	0.8	1
Control Factor	Plate thickness (PT), mm	1	2	3
Noise Factor	Room temperature, ^{0}C	25	35	--

Table I : Level of LBW Parameters

SELECTION OF ORTHOGONAL ARRAY

The design af experiments using the orthogonal array is in, most cases efficient when compared to many other statistical designs like one factor at a time experimentation. Each column in orthogonal array shown in Table 2 represents a specific factor that can be changed from experiment to experiment. Each row represents the state of the factors in a given experiment. It is called so, because the effects af the various factors are balanced and can be separated from the effects of the other factors within the experiment. Minimum number of experiments to be conducted:

The number of experiments that are required can be calculated based on the degrees of freedom approach.

$$N_{taguchi} = 1+\sum_{1-1}^{NV} (L1-1) \;.....(1)$$

Where, NV is number af independent parameters and L_i is the number of levels far each input parameter respectively.

In this investigation, the minimum number of experiments is Calculated as follows:

Number of variables (NV) = Number of input signals + Number af control parameters = 4

These 4 variables are varied ta 3 levels; L_i= 3

$$N_{taguchi} = 1+\sum_{i-1}^{4} (3-1)$$

$$=9 \text{ experiments}$$

orthogonal array is given in table 2. Once the orthogonal array is selected, the experiments are simulated as per the treatments. Nine experiments for two noise level settings are carried out and the response af each experiment is investigated. Afler simulating the 18 experiments, the results are analyzed through ANOVA table. From the result of ANOVA, it is easier to predict both the most predominant and the least predominant factors. These results are also useful for design parameter selection.

SIMULATION OF EXPERIMENTS

Simulation af Experiments are carried out using commercial ANSYS Finite Element Analysis software V.9.

Geometric Model

The 3D model of the plate to be welded is created using the solid modeling technique. Solid modeling is comparatively less time consuming than direct generation method. In solid modeling, the models are created using geometric primitives which are fully developed lines, areas and volumes. The material. af the model is Mild steel. The model consists of two weld plates of size 30 x 20 mm with thickness of 1, 2 and 3 mm.

DISCRETIZATION

The modeled plate discretized wrth 20 noded brick element (solid 90). consisting of I343 nodes and 628 elements. They have single degree of freedom, temperature at each node, applicable to 3D steady state or transient thermal analysis. Heat flux is input as surface loads. It becomes very important to discretize the plate with finer elements where the heat input is applied on to the plate [3, 4], since the temperature gradient in that location is higher comparatively than at farther away locations. Meshed model of the plate is shown in Fig.3

Solution

A non-linear transient thermal analysis is conducted to obtain the temperature distribution. The temperature dependent properties of Conductivity, Enthalpy and Convection film coefficient are given as input material properties as stated by Pathak and Datta [5]. It is assumed to have Natural convection on all surfaces of the plates. Based on the laser beam power, Heat fluxes are obtained and are given as thermal load. From the welding speed, time is given as input to different load steps. The load steps are solved and the contour plots of temperature distribution are obtained from the post processor. From the temperature plots, depth of penetration (P) and weld bead width (W) are measured. Contour plot of temperature distribution at the third and last load step for third experiment shown in Fig.4(a)& 4(b).

The sectioned model of the weld plate at four cross sections at room temperature of 25°C are shown in Fig.5 and at room temperature of 35°C are shown in Fig.6.

The Heat flux, Welding speed, Focus diameter and Plate thickness are varied to three levels and the effect of each parameter on the weldment is studied for two different ambient temperatures (noise parameter).

Expl. No.	Heat Flux W/m²	Welding speed m/sec	Focus diameter mm	Plate Thickness mm
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table II : Layout of L9 Orthogonal array

Traditional method requires 81 experiments for the above study. But by using Taguchi's technique of design of experiments, it is reduced to nine experiments. Each experiments are analyzed for two, different ambient temperature thus in total 18 cases are analyzed. In this investigation, effect of weld parameters on bead width and penetration depth is studied for the eighteen cases. The estimated response values for bead width and penetration depth are given in Table.3

Model Validation

To validate the resuits, five AISI type 304 stainless steel sheets of 2.5 mm thickness were laser Welded using the process variables given in Table 4 in Welding Research Institute, Trichy. The finite element simulations are also performed for the same process parameters. The results of Experiments and FEA simulations are compared and given in Table 4. The contour plot of the FEA simulations are given in Figs 7 - 9. Errors are observed to be within 10%. This is due to the assumptions in FEA model. The experimental values and the resuits of FEA simulations are compared in Fig.10 (a) and (b).

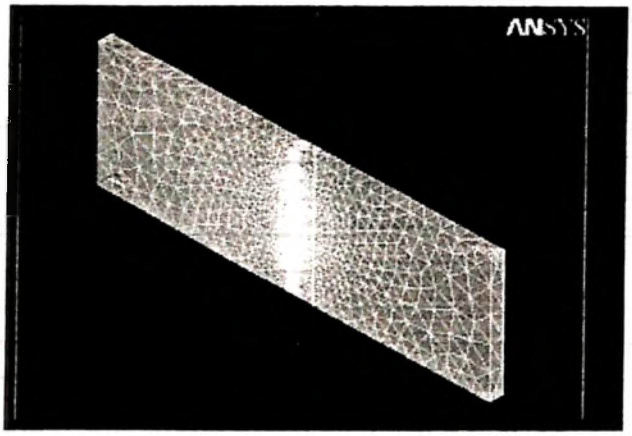
ANALYSIS OF DATA

The ultimate aim of the present investigation is to reduce the variation and making the weld bead geometry insensitive to the noise factor. So S/N ratio is calculated for the 18 cases.

The S/N ratio selection is based on the objective of the preset investigation. In this investigation, responses considered are bead width and penetratian depth. Based on the objectiive of each response S/N ratio varies and is shown in Table 5.

Effect of Process parameters on Bead Width

ANOVA technique is used to detect the percentage effect of each parameter on the bead width. The ANOVA table for the Bead Width is given in Table 6. By comparing the calculated and tabulated $F_{0.05,2,9}$ = 4.26) F-ratio all the signal and contcol factors are identified as significant. The percentage effect of Heat flux, welding speed and focus diameter are found to be 35.23%, 32. 51% and 21 . 88% respectively. It is clearly evident that the



Element used: Solid90, No. of Nodes: 1343, No. of Elements: 628

Fig.3 Meshed model of the welded plates

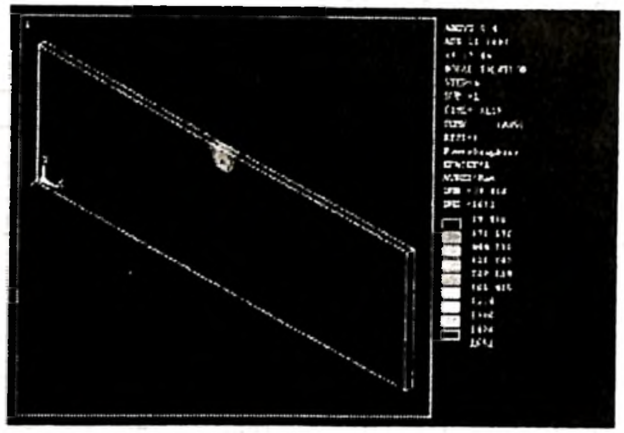


Fig.4(a) Temperature distribution at the third load step

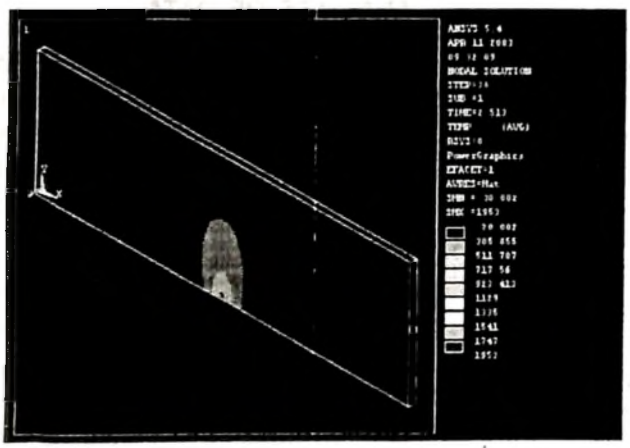


Fig.4(b) Temperature distribution at the last load step

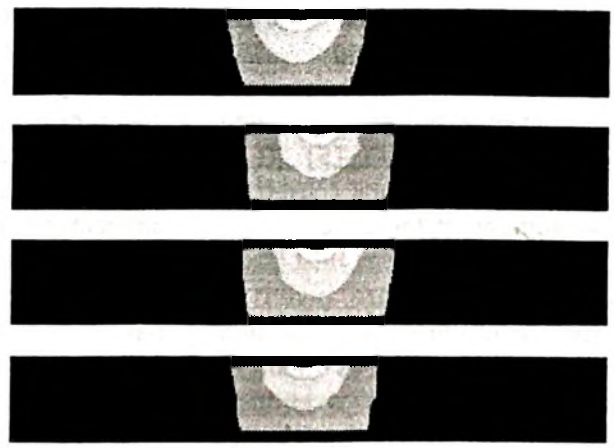


Fig.5 Temperature distribution at four cross sections for 3rd experiment -noise level 1

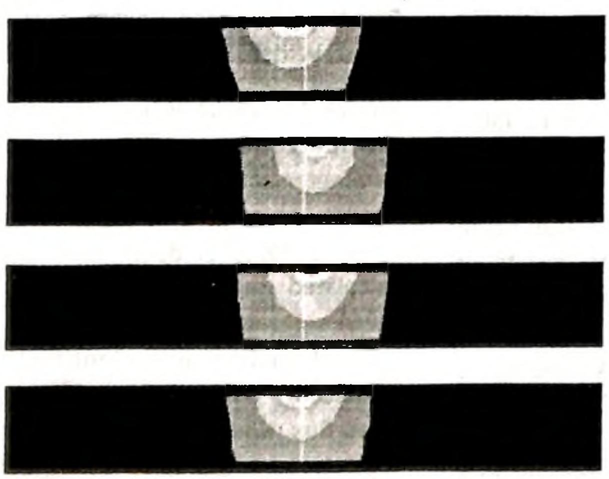


Fig.6 Temperature distribution at four cross sections for 3rd experiment -noise level 2

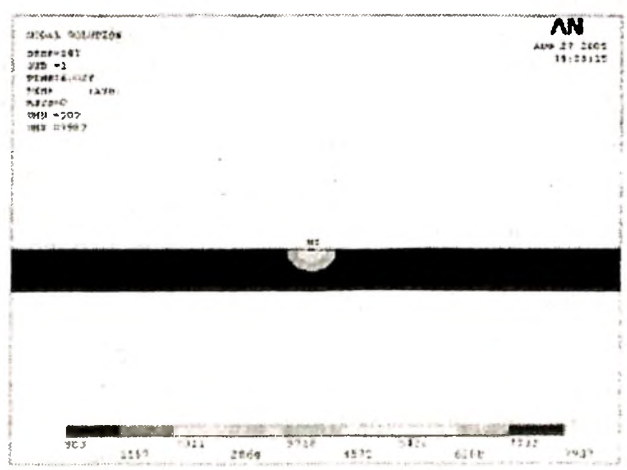


Fig.7 Contour Plot of Temperature Profile: Beam Power :750 Watts, Welding Speed:1250 mm/min

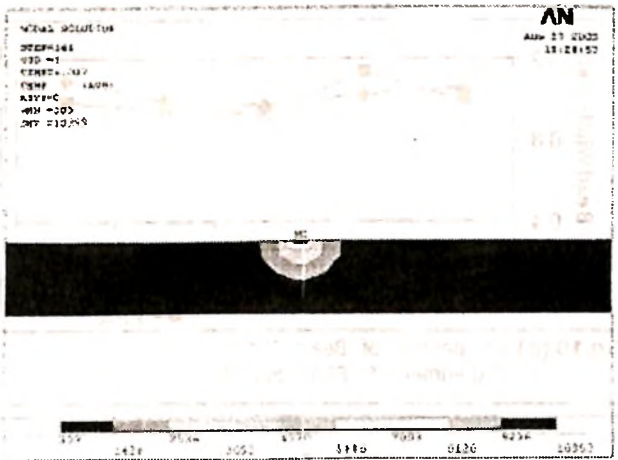


Fig. 8 Contour Plot of Temperature Profile: Beam Power :1420 Watts, Welding Speed: 1000 mm/min

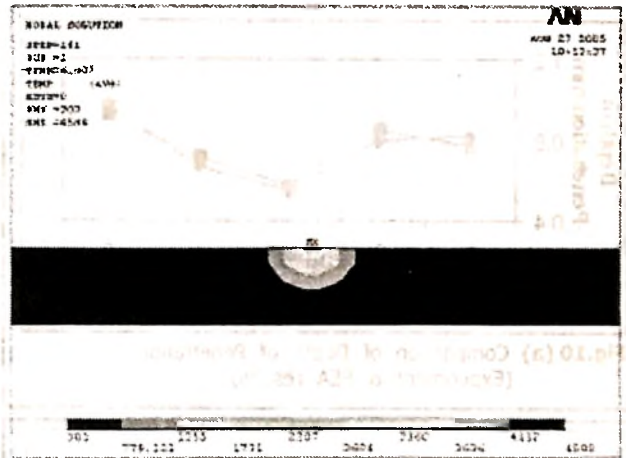


Fig.9 Contour Plot of Temperature Profile: Beam Power :580 Watts, Welding Speed: 1000 mm/mln

Expt. No.	Bead Width mm		Penetration Depth, mm	
	Levels		Levels	
	1	2	3	4
1	1.1	1.09	0.548	0.546
2	1.22	1.19	1.128	1.024
3	0.99	0.96	1.506	1.505
4	1.29	1.26	1.599	1.5895
5	1.42	1.41	0.575	0.573
6	1.04	1.02	1.051	1.149
7	1.43	1.41	1.654	1.051
8	1.22	1.21	1.626	1.622
9	1.28	1.26	0.596	0.587

Table III : Bead Width and Penetration for noise Level 1 and 2

Sl. No.	BP, Watts	WS, mm/min	BA, deg	Bead Width, mm			Depth Penetration, mm		
				Experiment	FEA	% Error	Experiment	FEA	% Error
1	750	1250	85	1.05	0.999	5.11	0.82	0.769	5.63
2	1250	1250	85	1.02	1.134	-10.05	0.8	0.856	-6.54
3	580	1000	90	0.97	0.924	4.98	0.55	0.568	-3.17
4	1000	1420	90	0.99	0.955	3.66	0.67	0.718	-6.69
5	1000	1000	90	1.09	0.983	10.89	0.98	0.925	5.95

error % = (actual value - predicted value / predicted value)* 100

Table IV : Comparison of actual and predicted values of bead parameters

predominant parameters that affect the weld bead width are Heat flux, welding speed and focus diameter.

Contribution of Remaining parameters is less when compared to these factors. The percentage effect of each parameter on the bead width is pictured as a Pie chart and shown in Fig.11.

Signal to Noise ratio (S/N Ratio):

This raiio is used in evaluating the quaiity of the product. The S/N ratio measures the level of performance and the effect of noise factors on performance and is an evaluation of the stability of performance of an output characteristic. Higher performance as measured by a higher S/N ratio implies a smaller loss as measured by the corresponding quality loss function (6). The S/N ratio is an objective measure of quality that takes both the mean and the variance into account. The calculated average S/N ratio for process parameters considered is given in Table 7.

Obtaining optimum Process Parameters For Bead Width

Objective of the robust design is to select the control factors, in such a way that the product is too robust to the uncontrollable factors. The best process parameters for the weldment are selected, to improve the quality. S/N ratio is generally used as a measure of robustness. Higher the S/N ratio means the process parameter more sensitive to weld bead quaiity and the effect of noise is significant. The optimum level is selected such that the S/N ratio is the maximum. S/N curve for heat flux, Welding speed, focus diameter and plate thickness for various levels are shown in Figs.12 to 15.

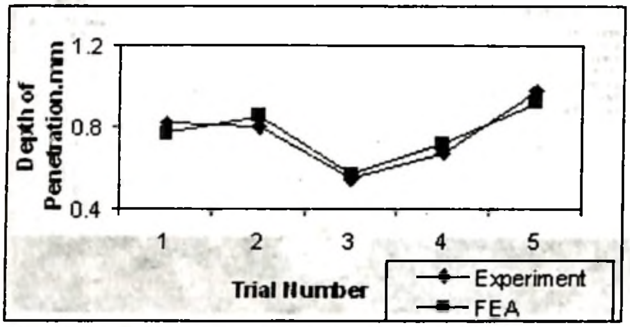


Fig.10 (a) Comparison of Depth of Penetration (Experiment & FEA results)

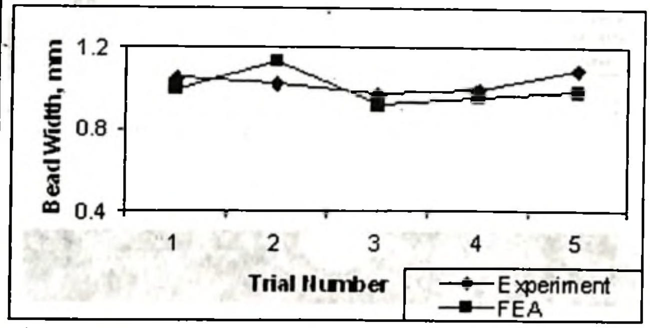


Fig.10 (b) Comparison of Bead Width (Experiment & FEA results)

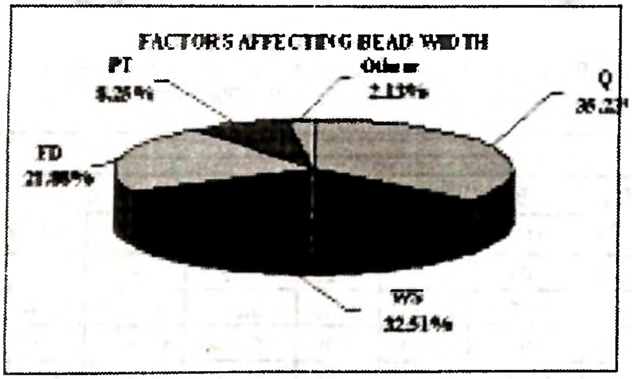


Fig.11 Effect of Various Parameters on Bead Width

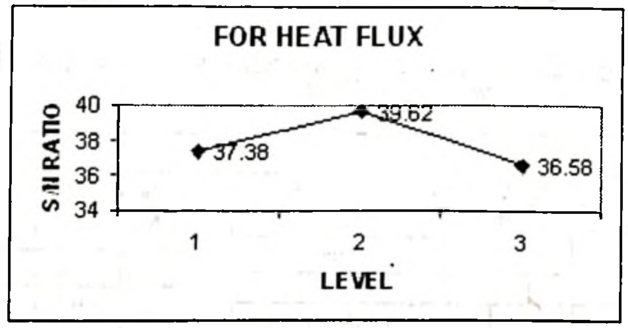


Fig.12 S/N curve for heat flux

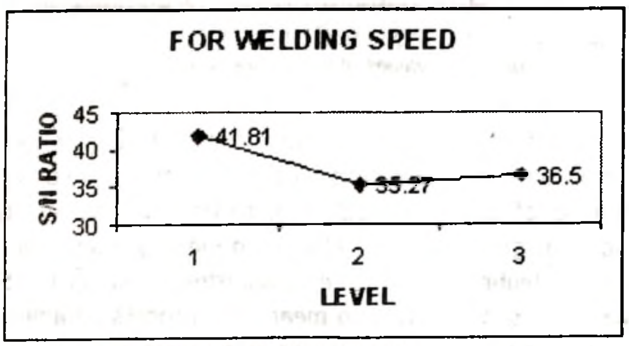


Fig.13 S/N Curve for Welding Speed

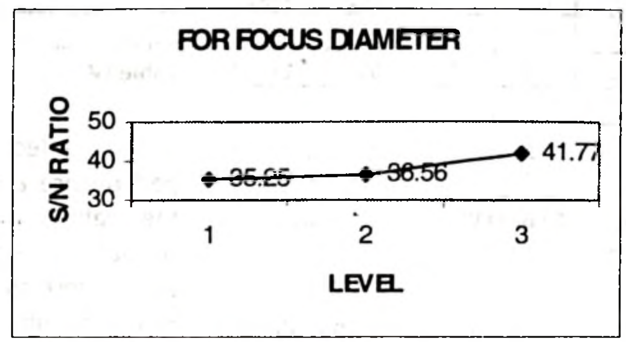


Fig.14 S/N curve for focus diameter

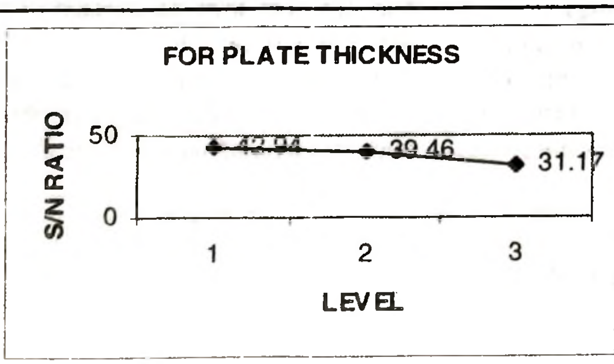


Fig.15 S/N curve for Plate Thickness

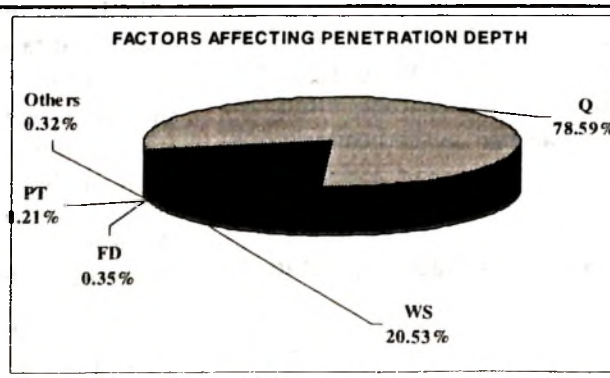


Fig.16 Effect of Various Parameters on Penetration Depth

Sl. No	Response	Objective	S/N ratio equation
1	Bead Width	Nominal is best	10 log (Mean response/ standard deviation)^2
2	Depth of penetration	Larger the better	-10 log [1/n Σ 1/ response^2)]

Table V : S/N ratio equation for responses

Factors	Dof (f)	Sum of squares (S)	Mean sum of squares (V)	F ratio	Pure sum of s (S)	% Contribution
Heat flux W/m²K	2	0.1398	0.0699	142.945	0.1388	35.23
Welding speed, mm/sec	2	0.1291	0.0646	132.106	0.1281	32.51
Focus diameter mm	2	0.0872	0.0436	89.16	.0862	21.88
Error	9	0.0044	0.000489	1	.0084	2.13

Table VI : ANOVA table for bead width

Level	Heat Flux	Weldings peed	Focus dia.	Plate Thickness
1	37.8	41.81	35.25	42.94
2	39.62	36.27	36.56	39.46
3	36.58	36.5	41.77	31.17

Table VII : Average S/N for Parameters

Effect of process parameters on Penetration Depth

Similar to bead width, the percentage effect of each parameter on the penetration depth are obtained and is given in Table 8. From the table $F_{0,05,2,9}$ = 4.26) the heat flux and welding speed are identified as significant. The percentage effect of Heat flux and welding speed are 78.59 and 20.53 respectively. The percentage effect of each parameter on the penetration depth is pictured as a Pie chart and shown in Fig.16.

Obtaining Optimum process parameters for Penetration Depth

Penetrationdepth is to be maximized for better root fusion. So larger is the best equation is used as quality characteristic. for setting of best parameter S/N curves are used. The

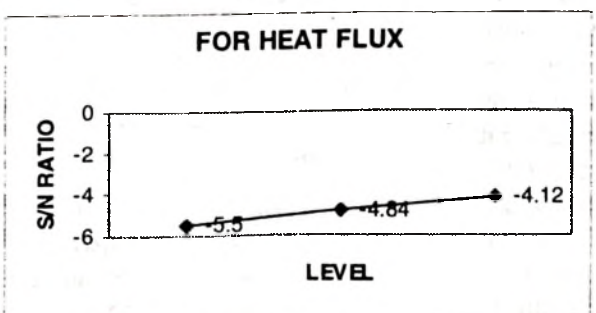


Fig.17 S/N curve for heat flux

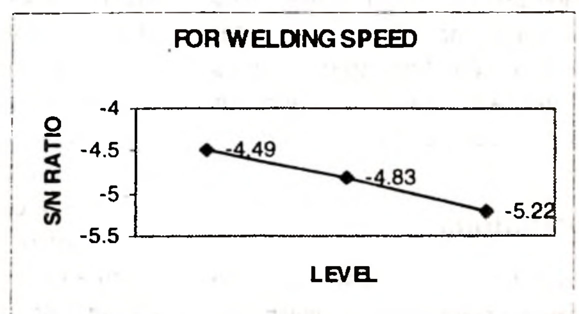


Fig.18 S/N curve for welding speed

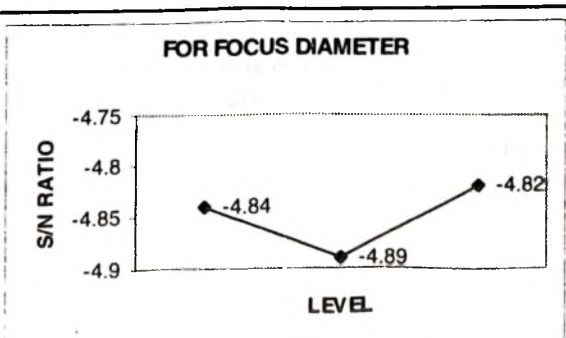


Fig.19 S/N curve for focus diameter

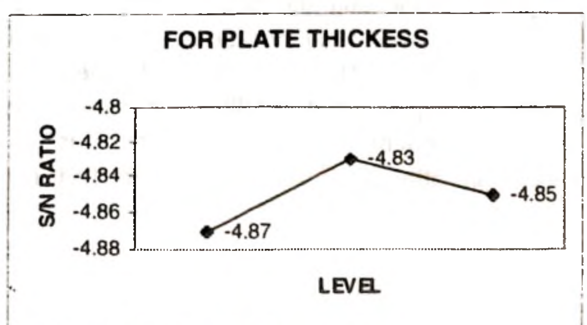


Fig.20 S/N curve for plate thickness

Factors	Dof (f)	sum of squares (S)	Mean sum of squares (V)	F-Ratio	Pure sum of Squares (S')	% Contribution
Heat flux, W/m²K	2	0.0279	0.01395	127.98	0.0277	78.59
Welding Speed mm/sec	2	0.0072	0.0036	33.03	6.98E-3	20.53
Focus diameter, mm	2	0.00013	6.5E-5	0.596	8.8E-5	0.35
Plate thickness mm	2	9E-5	4.5E-5	0.413	1.28E-4	0.21
Error	9	9.8E-4	1.09E-4	1	1.902E-3	0.32

Table VIII : ANOVA for penetration Depth

Level	Average S/N ratio			
	Heat Flux	Welding speed	Focus diameter	Plate Thickness
1	-5.5	-4.49	-4.84	-4.87
2	-4.84	-4.83	-4.89	-4.83
3	-4.12	-5.22	-4.82	-4.85

Table IX : Average S/N for Parameters

Factor	Bead Width		Penetration Depth	
	LEVEL	VALUE	LEVEL	VALUE
Heat flux, W/m²K	2	1.1E8	3	1.2E8
Weld speed	1	8	1	8
Focus dia mm	3	1	3	1
Plate thickness mm	1	1	2	2

Table X : Optimum settings for the control parameters

average S/N ratio for the parameters are given in table 9. S/N curve for heat flux, Welding speed, focus diameter and plate thickness for various levels are shown in Fig. 17 to 20.

CONCLUSIONS

Manufacturing Industries and Research Establishments which use welding as their main fabrication process are implementing the DOE concept and are producing quality engineered product. The current investigation is implemented in LBW based on Taguchi's concept. Simulations are attempted using the ANSYS package as per the number of experiments proposed by Taguchi. The best parameter combination is selected from the resulting analysis of bead geometry, using S/N ratio. ANOVA table is used to find the percentage contribution of the signal and control factors on the bead width and penetration depth. For the output response of bead width, heat flux is the predominant factor, which affects 35.23% out of the total contribution. For the output response of penetration depth, heat flux plays a major role and its percentage effect is 78.59. The parameters selected for the best response improves the quality of the weldment, which are insensitive to the noise factor. The optimum combination of parameters is obtained from the S/N ratio calculations.

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