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MODELING AND OPTIMIZATION OF ELECTRON BEAM WELDING PROCESS USING ANOVA

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ABSTRACT

Electron Beam welding (EBW) has emerged a mature manufacturing technology especially for welding of titanium alloys and other difficult to weld metals. It has found several applications, especially in development of critical aerospace hardware, to meet stringent quality requirements. EBW is a complex and non-linear process and is controlled by several parameters. Modeling of EBW is an important task so that engineers can predict the performance of Electron beam welding process. This paper presents the stages of development of the model, design of experiments and optimization of parameters using Analysis of Variance(ANOVA). Experiments have been conducted using Taguchi L9(3^4) orthogonal array considering four input parameters- welding speed, accelerating voltage, beam current, distance between gun to work. The performance of EBW was measured in terms of weld strength and weld penetration levels. Two sets of nine experiments were conducted to predict the performance of the model. Test specimens were machined to the required accuracy levels using CNC Wire-cut Electro Discharge Machine. The weld penetration was measured using NDT methods. The paper analyses the influence of the weld parameters on weld strength and weld penetration. This paper also compares the results of the regression model with the experimental results.
Keywords: Electron Beam Welding(EBW);Analysis of Variance(ANOVA);Optimization; Modeling; Design of Experiments(DOE);

1. INTRODUCTION

Welding is one of the important processes of aerospace manufacturing. Manufacturing of critical air-bottles, servo valves, turbine components, engine components require precision welding of high strength materials like AISI 304, 15CdV6 and Marazing steels and especially Titanium alloys. Welding processes such gas tungsten arc welding, plasma welding and electron beam welding are adopted for fabricating titanium alloy components. The extreme power density associated with the Electron Beam (EB) and the ability to work in a vacuum environment make it possible to use the process for joining metals which not only have high melting points but also those which are extremely reactive when hot or molten. Titanium and many of its alloys can be welded readily using the EB process without the danger of oxidation and subsequent undetectable degradation of ductility. For this reason, the process is used widely in the aero engine industry for welding safety-critical titanium alloy parts.

Modeling of Electron Beam Welding EBW is a complex and stochastic process where this process is controlled by several parameters like beam current, voltage etc.,[1]. Two basic defects that are associated with EBW are porosity and incomplete fusion. Various authors have studied these factors in detail for many titanium alloys [2-5]. some efforts were made to reduce pore size to 0.01mm by controlling travel speed to 200cm/mi with single pass for a 10mm thick Ti-alloy[6].

A process model which allows for the prediction of the process output parameters, complete with supporting experimental data, is essential in determining the factors which influence the strength and quality of welding. Some researchers have used AI techniques to model the welding process [7]. Literature shows that several researchers have made valuable contributions in developing prediction models for different manufacturing processes. Most of the models were developed using orthogonal arrays, multiple regression analysis and Analysis of Variance (ANOVA) was used to determine the main influencing factors and the optimal parametric settings of the process [8,9]. In this context, an effort has been made to develop regression model for Electron Beam Welding process and optimize the parameters using ANOVA. In the rest of this paper, the specific features of Electron Beam Welding, the input and output variables of Electron Beam Welding are discussed first. The details of Design of experiments and development of mathematical models for Electron Beam Welding process, are then described. Finally, this paper provides the optimized parameters for electron beam welding of Titanium alloys using ANOVA.

2. ELECTRON BEAM WELDING (EBW)

The schematic of the EBW process is shown in Fig.1. A stream of electrons (1) is generated by heating a tungsten filament (2) and accelerated by a high voltage between the filament or cathode and the anode (3). By careful shaping of the anode and cathode, the electrons pass through a hole in the anode and start to diverge. A magnetic focusing coil, or lens (4), fed with a DC current, brings the electrons to a point focus on the surface of the part to be welded (5). Precision alignment of the beam onto the joint can be achieved by viewing a low power tracer beam with the magnifying optics (or closed circuit television camera and monitor) via a prism (7). The beam may be moved accurately in X and Y axes by adjusting the current flowing through two pairs of deflection coils (8).

The whole of the gun and work-chamber are maintained under vacuum to prevent:

- dispersion of the beam by collision with air molecules
- high voltage discharges between anode and cathode
- oxidation of the weld zone and the surface of the work-piece

The most critical of these is prevention of gun discharges, which cause serious weld defects. To overcome this problem the electron gun is kept continuously pumped to a higher vacuum than the work chamber by the diffusion pump (alternatively a turbo molecular pump) (9), via valve (10). The chamber can operate in the high vacuum: $10^{-4}/10^{-5}$ mbar range, or low vacuum, $10^{-1}/10^{-2}$ mbar range dependent upon the type of materials to be welded. The high power density of the beam impinging on the work surface forms a molten pool of metal that is rapidly heated above its boiling point. The pressure of escaping metal vapour maintained by the beam then allows the molten surface to tunnel through the material until the beam fully penetrates. The result is a metal vapour filled column termed a 'keyhole' surrounded by molten metal. Welding is then achieved by relative motion between the component and the beam so that the keyhole passes along the joint. It is necessary to slope out the beam power gradually to ensure a defect-free weld. Normally on circular welds there is a small overlap to ensure complete 360 degree fusion. To control the beam power the current is regulated by altering the potential difference between the cathode (2) and the bias cup (12). It enables smooth control of the beam power from a few watts to many kilowatts for setting the slope and the power level required to achieve weld penetration.

3. DESIGN OF EXPERIMENTS

The Design of Experiments (DOE) is a guide for formulating and conducting experiments efficiently. The aim of implementing it to any experimental test is to improve the performance characteristics of the product or process. This approach uses the Taguchi Orthogonal Arrays for conducting the Fractional Factorial Experiments (FFE). DOE techniques try to maximize the information per run by choosing a reduced number of input sample points

The Design of Experiments process is divided into three phases. The first is the Planning phase where the factors and levels are selected which are thought to impact the concerned characteristics of product or process. Depending on the number of factors and their levels an appropriate Orthogonal Array (OA) is selected and factors are assigned to the columns. The second phase is the conducting phase, where the tests are performed according to the factor level combination and the test results are collected. Lastly, it is the Analysis phase, where the impact of the factor levels on the concerned product / process feature are analysed and conclusions drawn.

3.1 TAGUCHI ORTHOGONAL ARRAYS: An orthogonal array (OA) is a matrix of numbers arranged in columns and rows. Each column represents a specific factor that can be changed from experiment to experiment. Each row represents the state of the factors in a given experiment. The array is called orthogonal because the levels of the various factors are balanced and can be separated from the effects of the other factors within the experiment. It is a balanced matrix of factors and levels, such that the effect of any factor or level is not confounded with the effect of any other factor or level [10]. Taguchi method has been applied for optimisation of cutting parameters [11].

3.2 ANALYSIS OF VARIANCE (ANOVA): ANOVA is used to evaluate the response magnitude (%) of each parameter in the experiments, for identifying and quantifying the sources of different trial results from different conditions [12]. The results from different runs are different due to variations produced by unknown parameters or random interferences (noise factors) and the changes of machining parameters (control factors). The percent contribution of each parameter is evaluated to make a decision on how significant the effect of each parameter (known or unknown) on the penetration and number of defects.

4. EXPERIMENTS

This experimental was conducted to optimize the welding parameters for obtaining better high quality welds by EBW. The experiment are conducted using L9(3^4)Taguchi Orthogonal Arrays. The experiments are conducted on Low kV EBW machine (Techmata of France make) of DRDL, Hyderabad, India as shown in Fig 2. The operating conditions of the machine are 8Kw , 60 kV and 133mA. The material selected is Titanium alloy (Ti 6 Al4V). It is widely used in aerospace industry due to its high strength to weight ratio. The welding operation has been conducted in auto mode on 5.5 mm thick plate of Ti alloy. The following are the selected levels for the factors under which the first set of experiments are conducted:

S.No	Weld Parameter	LEVEL1	LEVEL2	LEVEL3
1	Accelerating Voltage in kV	40	50	60
2	Beam Current in mA	30	60	90
3	Welding Speed in m/min	1	2	3
4	Distance between Gun to work in mm	200	300	400

Another set of experiments were conducted from the inferred values to obtain better results. The experimental results were given in Table 1 and Table 2. After completion of the experiments, the tensile strength and weld quality was measured. The tensile test specimens were machined using wire-cut electro-discharge machine and the tensile strength was measured using tensile testing machine. The penetration levels of the weld samples were checked by radiography tests.

5. WELD DEFECTS AND MEASUREMENT: Usual defects of welding include lack of fusion, solidification cracking, porosity and contamination. The color of the titanium weld is an obvious indication of contamination. A good weld has a bright silvery appearance although a light straw-colored weld is often acceptable as well. Physical defects present in the weld may be detected by various non-destructive testing methods, such as radiography, the dye penetrant method and ultrasonic testing. Of these, radiography testing is the best weld inspection for detecting pores and cracks and the same has been used to test the specimens.

5.1 WELD STRENGTH (TENSILE TESTING): Testing Welded joints depend on the specimen size (width, overlap, thickness and length) and the weld quality, size and location. The importance of testing specimen size has been recognized by several researchers. Measured tensile-shear strength usually increases with sheet thickness, usually with increased weld diameter made with the increase in thickness. The Heat Affected Zone (HAZ) size (h) was also found to be very important in the determination of the critical width. Failure modes observed during tensile shear testing provide a direct indication on the adequacy of specimen sizes. The width is the most important factor in influencing testing measurement. It is sufficient if the overlap is the same as the width. A length of 150 mm was determined to be enough for all possible widths.

6. DATA ANALYSIS: The experimental results of Titanium alloys have been used for discussion. Initially, first set of experiments is conducted using L9 Orthogonal arrays. The results of the first set shown in Table 1, were used for selection of final range of control parameters to conduct another set of experiments using Taguchi Orthogonal arrays. As the welding speed and distance between gun to work is increasing weld strength and its penetration levels are decreasing. With an aim for even better results another set of experiments were conducted using the inferred level values and are depicted in response graphs. Finally nine experiments were conducted using Taguchi Orthogonal arrays and the results of experiments have been used for discussion.

Once the practical experiments were conducted using design of experiments the effect of each factor on the weld strength and weld penetration are studied using the Level average response analysis and also ANOVA (Analysis of Variance) a regression model has been developed using Statistica 6.0, a statistical analysis software module.

6.1 Level Average Response Analysis using Average Value: To separate the effect caused by each parameter, the other parameters are set to a middle value in the allowable working spaces when one of the welding parameters is varied and analyzed. The level average analysis is based on combining and averaging the response associated with each level for each factor. Fig 3 and Fig 4 show the results of the final experiments. From the average data of each of the experiments wherein one level of each factor occurs, the optimum value of factors is determined.

6.2 Analysis of Variance (ANOVA): The total variation of the experimental results (for the total number of trial runs, n=9) caused by both the controlled parameter and uncontrolled parameters is represented as the sum of the squares(SS) deviation of all the resulting data from the trial runs. The results of ANOVA graphs are shown in Fig 5.a and Fig 5.b respectively.

6.3 Development of Regression Model: Statistica 6.0, a statistical analysis software module was used to compute the regression constants using the experimental data. The best fitted equation with a regression coefficient of 0.95 for weld strength is given below:

$Y1=112.3767+3.055x_1+5.5867x_2+3.755x_3+4.0183x_4–4.8217x_1^2–6.2767x_2^2–6.2767x_3^2–6.2767x_4^2$.

Similarly the best fitted equation with a regression coefficient of 0.95 for weld penetration level is:

$Y2=107.54+2.9267x_1+5.35x_2+3.5933x_3+3.8417x_4–4.6133x_1^2–6x_2^2–5.3933x_3^2–8.7583x_4^2$.

6.3 RESULTS AND DISCUSSIONS

For the analysis of weld quality generated by electron beam welding process, penetration and tensile strength of the weld were considered. From the level average response analysis using the average values of each trial run, the optimum conditions for each of the factors Accelerating Voltage (V), Beam Current (I), Weld Speed (S), Distance between Gun to Work (D) can be determined. Fig 3 and Fig 4 show the average effect of each parameter level on the weld quality. The optimum conditions are those that give the best welds quality. It can be seen from Fig 3 and Fig 4 that V_3 (Accelerating Voltage at 50 kV), I_3 (Beam Current at 60 mA) and S_2 (Weld Speed at 1 m/min) and D_2, (Distance between Gun to Work at 200 mm) are the optimum conditions. So V_3 I_3 S_2 D_2 can produce best results in terms of weld strength and weld penetration levels Therefore the optimum conditions are Accelerating Voltage of 50kV, Beam Current of 60mA, Weld Speed of 1m/min and Distance between Gun to Work of 200mm.

Fig 5.a and Fig 5.b show the results of the ANOVA for weld strength and weld penetration respectively under different trial runs. It can be seen from these figures that for both responses i.e., weld strength and weld penetration, the influence of both beam current (34.06%) and distance between gun to work (33.8%) is more significant than weld speed (18.9%) and all three of them are more significant than accelerating voltage(13%).

The experiments of set-II produced better results as seen from Table 2 compared to set-I. The tensile test specimens of electron beam welded components are shown in Fig 6 The welded tensile test specimens after tensile testing are shown in Fig 7. It has been observed from Fig 7, that most of the welded specimens were broken at the parent metal. No breakage has taken place at the weld joint, which shows that the selected weld parameters have resulted in optimum joint strength. The effect of each control parameters on the weld quality is given as follows.

- Accelerating Voltage: The selection of Accelerating Voltage for different materials is less significant. For Design of experiments, a set of voltages ranging from 40-60kV are selected and voltage in range of 50-55kV has shown good results.
- Beam Current: The impact of Beam current is more significant on the weld quality out of all the other factors considered. From the results, it has been observed that moderate currents are good for producing quality welds. For experiments, a set of currents ranging from 30-90mA is selected and current in range of 60-70mA has shown good results.
- Weld Speed: The impact of weld speed on weld quality is average from the factors considered. Increasing the weld speed decreases the penetration levels. For experimental trials, speed ranging from 0.55-3m/min was selected and better results were obtained in the range of 1to 1.25m/min.
- Distance between gun to work: The impact of welding distance has very high influence on the weld quality. As the welding distance is increased the weld strength also reduced considerably. For experiments welding distance ranging from 150-400mm was selected and better results were obtained in the range of 200-250mm.

7. CONCLUSIONS

In this paper, Electron beam welding process for Ti alloy (Ti6Al4V) of 5.50 mm thick plate has been modeled using multiple regression approach. These approaches are used in an attempt to determine the optimal combinations of control parameters like accelerating voltage, beam current, weld speed and distance between gun to work of electron beam welding. Based on the results, the following conclusions can be drawn from this project

- With statistical analysis, the generated regression model is concluded as a valid model, which can be used for obtaining the output values within reasonable limits.
- The accuracy of predicted results of regression models for weld penetration levels and weld strength is 97% and 99% respectively as shown in Table 3.

The control parameters have been optimized using ANOVA. To achieve a better quality weld, moderate accelerating voltage and low weld speed and distance between gun to work is suggested. Therefore the optimum conditions were : accelerating voltage of 50kV, beam current of 60mA, and weld speed of 1m/min and distance between gun to work of 200mm. Further research is planned to estimate the effect of focusing current on weld strength and to also measure the depth of penetration of the welds. Finally this work is very much helpful for wide applications especially in aerospace industries with minimum efforts.

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FIGURES

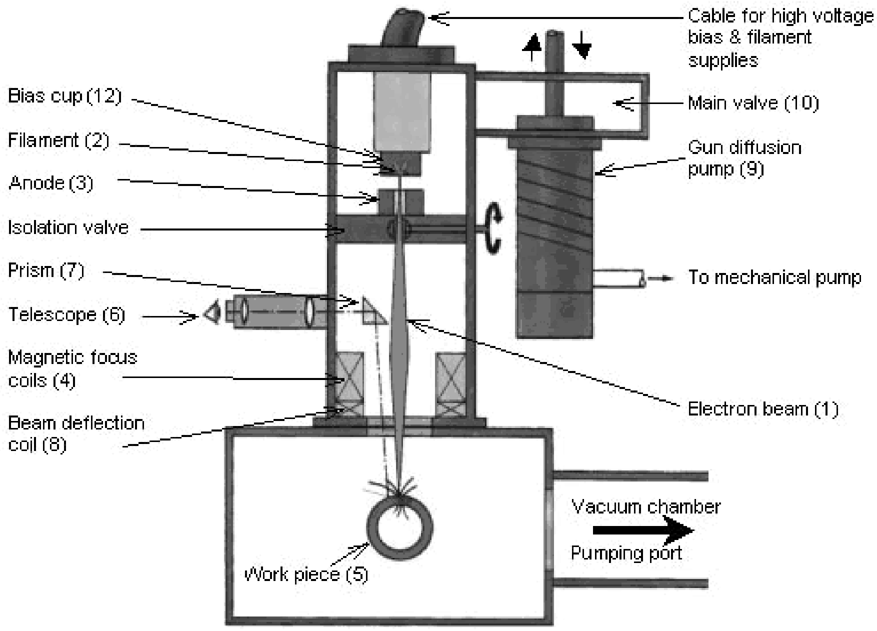

Fig 1 Schematic diagram of EBW Process

Fig 2. Low kV EBW machine (Techmata of France make)

Figure 3 Effect of Accelerating Voltage, Beam Current, Welding Speed and distance between Gun to Work

Accelerating Voltage kV	Tensile Strength Kgf/mm^2	Penetration level %
40	71.54	69.2
45	90.46	86.56
50	98.34	94.1
55	96.57	92.42
60	79.66	77.04

3. a)Accelerating Voltage

Beam Current mA	Tensile Strength Kgf/mm^2	Penetration level %
30	52.8	50.79
50	87.44	83.68
60	99.31	95.03
70	98.62	94.38
90	86.24	83.4

3.b. Beam Current

Welding Speed m/min	Tensile Strength Kgf/mm^2	Penetration level %
0.75	89.49	85.64
1	98.88	94.62
1.25	97	92.82
2	80.93	77.99
3	67.48	65.27

3.c.)Welding Speed

Distanc e B/W Gun to Work mm	Tensile Strength Kgf/mm^2	Penetration level %
150	88.05	84.27
200	101.22	96.87
250	96.09	91.95
300	84.18	81.41
400	63.33	60.97

3.d.Distance between Gun to Work

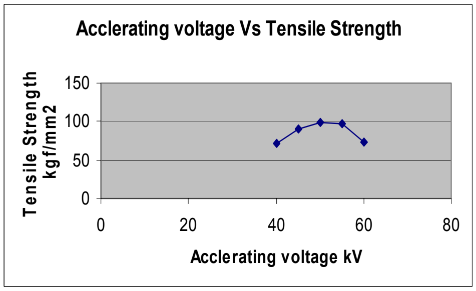

Fig 3.a

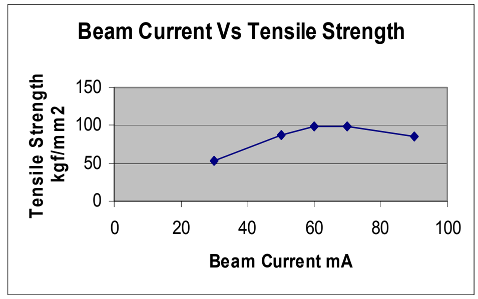

Fig 3.b

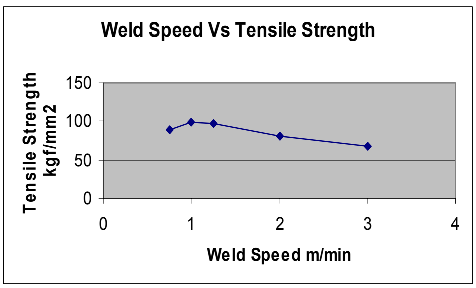

Fig 3.c

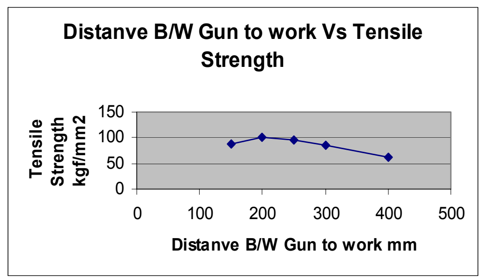

Fig 3.d

Fig 3. Effect of Accelerating Voltage, Beam Current, Weld Speed and Distance Between Gun to Work on Tensile Strength

	ANOVA; Var.:Var5; R-sqr=1. 4 3-level factors, 1 Blocks, 9 F DV: Var5				
Factor	SS	df	MS	F	p
(1)Var1 L+Q	102.4951	2	51.2475		
(2)Var2 L+Q	266.0582	2	133.0291		
(3)Var3 L+Q	148.0315	2	74.0157		
(4)Var4 L+Q	264.3880	2	132.1940		
Error	0.0000	0			
Total SS	780.9728	8			

Fig 5.a Results of ANOVA for Weld Strength

	ANOVA; Var.:Var6; R-sqr=1. 4 3-level factors, 1 Blocks, 9 F DV: Var6				
Factor	SS	df	MS	F	p
(1)Var1 L+Q	93.9580	2	46.9790		
(2)Var2 L+Q	243.8150	2	121.9075		
(3)Var3 L+Q	135.6484	2	67.8242		
(4)Var4 L+Q	241.9672	2	120.9836		
Error	0.0000	0			
Total SS	715.3886	8			

Fig 5.b Results of ANOVA for Weld Penetration

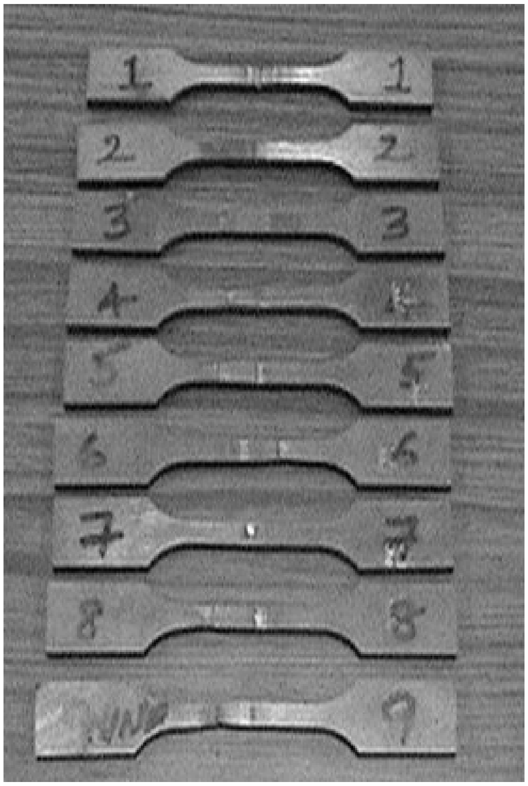

Fig 6. Tensile test specimens of set-II

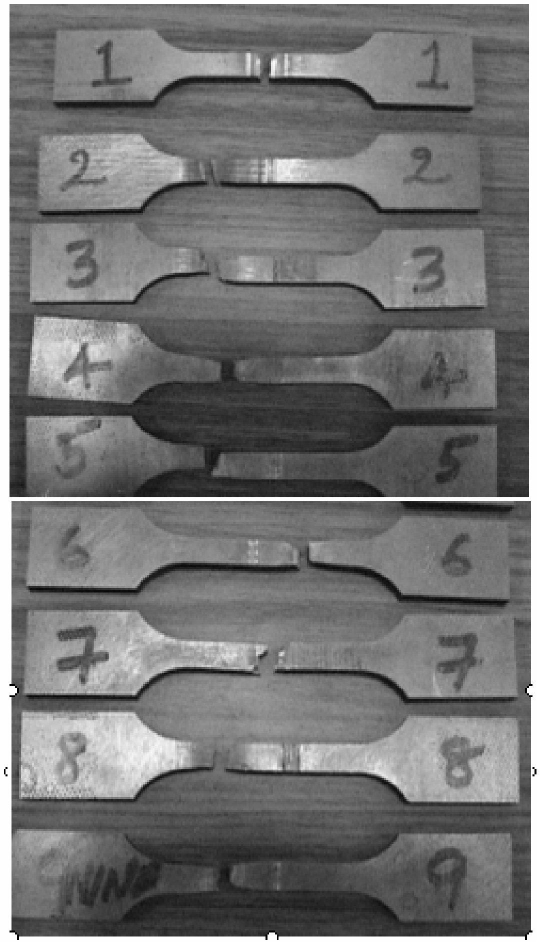

Fig 7. Tensile test specimens after Testing

Table 1. Experiments Results of set

S.No	Accelerating Voltage in kV	Beam Current mA	Welding Speed m/min	Distance GUN to work mm	Weld Strength UTS Kgf/mm^2	Weld Defects from Radiography Tests	Relative Penetration %
1	40	30	1	200	61.01	Cracks, ,pores	59.00
2	40	60	2	300	97.60	Weld Ok	94.40
3	40	90	3	400	56.00	Lack of penetration	54.16
4	50	30	2	400	45.86	Lack of penetration	43.52
5	50	60	3	200	94.90	Weld Ok	91.80
6	50	90	1	300	103.40	Weld Ok	100.00
7	60	30	3	300	51.53	Lack of penetration	49.84
8	60	60	1	400	88.13	Weld Ok	85.23
9	60	90	2	200	99.33	Weld Ok	96.06

Table2. Experimental Results of set-II

S.No	Accelerating Voltage Kv	Beam Current mA	Welding Speed m/min	Distance B/w gun to Work Mm	Weld Strength UTS Kgf/mm^2	Weld Defects	Relative Penetration %
1	45	50	0.75	150	70.08	Cracks, Pores	67.06
2	45	60	1.00	200	104.50	Weld Ok	100
3	45	70	1.25	250	96.80	Weld Ok	92.63
4	50	50	1.00	250	95.38	Weld Ok	91.27
5	50	60	1.25	150	97.33	Weld Ok	93.14
6	50	70	0.75	200	102.30	Weld Ok	97.90
7	55	50	1.25	200	96.87	Weld Ok	92.70
8	55	60	0.75	250	96.09	Weld Ok	91.95
9	55	70	1.00	150	96.75	Weld Ok	92.60

Table 3. Comparison of Results of Experimental and Regression Model

S.No	Experimental Results		Calculated Results from Regression model generated	
	Weld Strength Kgf/mm^2	Weld Penetration Level %	Weld Strength Kgf/mm^2	Weld Penetration Level %
1	70.08	67.06	70.0799	67.0634
2	104.50	100	104.5	94.00
3	96.8	92.63	96.7999	92.6334
4	95.38	91.27	95.3799	97.2734
5	97.33	93.14	97.33	93.14
6	102.30	97.90	102.30	103.9034
7	96.87	92.70	96.86995	92.7034
8	96.09	91.95	96.08995	85.9502
9	96.75	92.60	96.75	92.6034