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Parametric Analysis for Fiber Laser Welding of Aluminium Alloy AA7075

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Abstract : Laser beam welding is a fusion welding process with high power density. In comparison with the arc welding process, laser beam welding produces high aspect ratio welds with a relatively low heat input. Laser welding can be performed out of vacuum and the fiber optic delivery of near infra red solid state laser beams provide increased flexibility compared with other joining processes. Laser welding can be used as a principal technique for joining aerospace metallic components. Hybrid MAG laser welding shows a great potential in shipbuilding industry for joining structural steels. Aerospace, shipbuilding and automobile industries are few of the major users of laser beam welding process. Low distortion, high welding speed and easy automation have taken this welding technology to a more advantageous position. Laser welding of glass enables producing joint structure, which is monolithic and possesses excellent mechanical strength, high temperature stability and space selectivity in comparison with prevailing joining processes without heating before or after the process. Most common materials of application of laser beam welding process are aluminium alloys and steel. The width of weld bead and depth of penetration are the major parameters that the laser beam welders wish to control. The processing conditions are selected based on the thickness of material. A common practice is to develop process parameters for a particular application based on an engineering approach using the system parameters such as laser power, travel speed. However in such a case the power is optimized for a particular system only. In this paper experimentations are conducted with associated analysis to find out the key influencing parameters in fiber laser welding of aluminium alloy AA7075, which is used in many applications. The four parameters selected are beam power, welding speed, gas flow rate and beam angle. L_9 (3^4) orthogonal array is used for experimental plan and analysis using Taguchi method.
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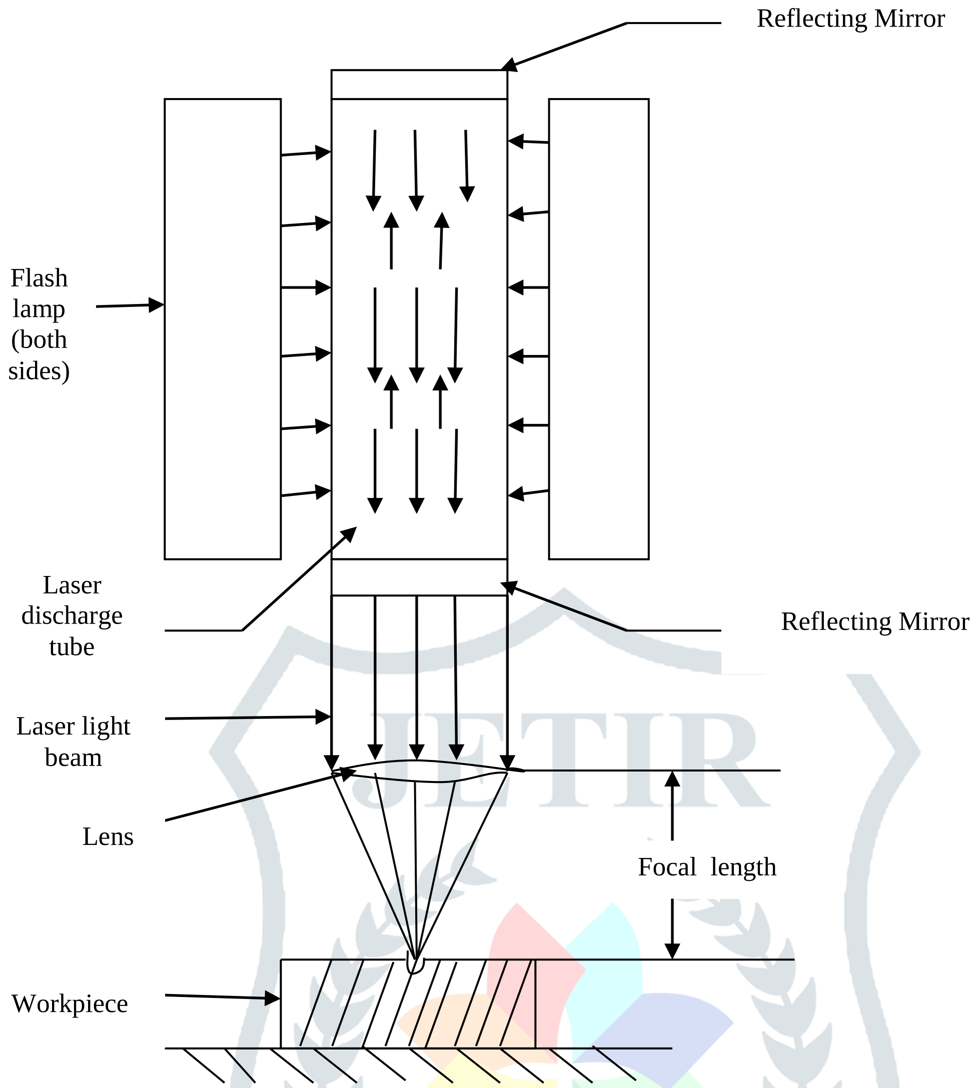
IndexTerms -. **Fiber laser welding, bead width, depth of penetration, parametric analysis, Taguchi Method**

I. INTRODUCTION

Laser Beam Welding (LBW) is a type of welding process in which heat is generated by a laser beam targeted on the workpiece. The laser beam has high energy. This high energy laser beam heats and melts the workpiece forming a welding joint. The concentration of energy of a narrow laser beam is about 10^8- 10^{10} Watt/sq. cm. A weak weld pool is formed very rapidly (for about 10^{-6} second). There is a rapid solidification of the weld pool as soon as the metal is melted. The weld pool is surrounded by a cold metal. The molten metal is in contact with the atmosphere for a very short time and hence there is no gradient (flow, neutral gas) and no contamination. In laser welding, the joint is made either as a continuous weld or as a sequence of overlapped spot welds. The laser beam welding works on the principle that when the electrons of an atom are excited by receiving some energy and after sometimes when they return to the ground state, it emits a photon of light. The concentration of this emitted photon can be increased by the excited emission of radiation and high energy focused laser beam. In a laser beam welding machine, before operation, the machine is set up at the desired location (between the two metal pieces to be joined). After that a high voltage power supply is applied to the laser machine to perform welding (figure-1). A lens is used to focus the laser into the area where welding is required. Computer control is used to control the speed of the laser and the workpiece table during the welding process. The fiber laser welding machine is shown in figure-2.



Schematic diagram of laser beam welding
(Figure-1)

Photo of fiber laser beam welding machine
(Figure-2)

First the flash lamp of the machine is started and it emits light photons is absorbed by crystals (ruby) and the electrons are excited to higher energy levels. When they return to lower energy state they emit a photon of light. This photon again stimulates the atom and produces two photons. This process is continued and we get a focused laser beam that is used for required welding purpose. The main types of laser used in this types of welding are gas laser, solid state laser, many solids are used in synthetic ruby crystals like chromium or aluminium oxide, neodymium in glass and neodymium in yttrium aluminium garnet (Nd-Yag), the most commonly used. In fibre laser optical fibre is the lasing medium. Laser welding can be easily automated and process parameters are also controllable. A very narrow weld can be obtained. The quality of weld structure is also very small. Dissimilar metals can also be welded by this process. Very small delicate workpieces may also be welded. No requirement of vacuum is there and distortion of workpiece is also very little. Laser beam welding is very prominent in automotive industry. It is employed for high precision welds. Laser welding is used for making jewellary and medical industries to hold metal together in a small scale. The controllable process parameters are laser power, gas flow rate, pulse rate, welding speed, focal distance, gap etc. and measurable outputs are width of heat affected zone (HAZ), weld strength, hardness of weld metal etc.

Continous growing of environmental awareness , requirement to improve fuel economy, need to improve efficiency of automobiles and reduction of weight of vehicles, aluminium alloy is widely being used in automobile industries, aeronautics and military applications [1-4]. Friction stir welding and laser beam welding are noteworthy for their present use in commercial aircrafts [5-9]. Laser beam welding has been used to join some parts of fuselage [10]. Hybrid laser arc welding is also a promising technology that has been used to achieve high performance and low welding deformation [11]. Medium strength aluminium alloys are already widely used due to their high strength to weight ratio, good formability, weldability and corrosion resistance. The use of higher series alloys are limited despite higher strength to width ratio because of weldability problems such as hot cracking, porosity and softening the fusion zone [12]. Accuracy of welding depends on the material preparation, the joint fit up and the laser beam to joint alignment. Stainless steel is another material reported to be used as laser beam welding workpiece. It is one of the important materials used for high temperature corrosion resistant components such as aerospace, sensors and rocket engine components which require joining of materials having thickness from 0.1 mm onwards with different joint configurations. The most common austenitic steel is AISI304 [13]

In this paper investigations about major influencing parameters in fiber laser beam welding of aluminium alloy have been carried out in a systematic manner along with required analysis. This is important because laser beam welding is widely used in aerospace, automotive and shipbuilding industries and it is necessary to control the shape of weld bead in laser beam welding. Laser beam welding is a technique with which dissimilar metal can be joined and it can be used along with additive manufacturing. Earlier many efforts were made revealing many corners and facets of laser beam welding but comprehensive analysis using important parameters like beam power, welding speed, gas flow rate and beam angle simultaneously affecting two significant outputs like bead width and depth of penetration and thus finding the vital parameters in a cost effective manner was rarely explored. And that point makes the difference with other research articles on laser beam welding and more particularly on fiber laser welding. It is believed that findings presented in this paper will appeal to the specific scientists, who subscribe this journal. Although very few researches have been conducted on this earlier, the findings of this research will prove to be cost-effective

2. Materials and Methods :---

After study of earlier works done on laser beam welding, and keeping in mind the utility in industrial practice an aluminium alloy is chosen a material for investigation. There are various aluminium alloys of AA series are there. Out of that AA7075 alloy is chosen. The chemical composition of AA7075 aluminium is given in the following table-1.

This alloy has extensive use in producing aluminium sheets, plates, extruded rods, bars and wires, extruded shapes, extruded tubes, cold finished rods, cold finished bars and wires, drawn tubes and forgings. The filler metals used were 4047 aluminium. Samples were cut from a sheet of AA7075 which was prepared by hot rolling at 450°C to a thickness of 250 mm and subsequent cold rolling down to 1.5 mm in cold rolling mill.

TABLE-1
(Properties of AA7075)

Al	Si	Cu	Mn	Mg	Cr	Zn
90.0	---	1.6	---	2.5	0.23	5.6

Before welding, the surface of each sample was cleaned using acetone and dried to remove any oxide layer and contamination present. After the oxide layer has been removed, the surfaces to be welded are electropolished using a mixture of perchloric acid ethyl alcohol electrolyte under 25V and then dried in a furnace at 140°C for 10 minutes.

The welding process is carried out in a fiber laser welding machine of 1080 mm wavelength, power of 1.5 kW, 5-20 kHz frequency, 120 mm output focal length, maximum fiber length of 15m and 4-6 bar air pressure and electricity demand of 220V AC/50/60Hz. An auxiliary gas flow of high purity nitrogen was applied and a shielding gas of helium was used during welding from the top, rear and lateral sides. Metallographic samples of weld seam were prepared using standard mechanical polishing, procedures and etched in a saturated solution of Keller's etchant (95 ml H_2O + 2.5 mL HNO_3 + 1.5 mL HCl + 1.0 mL HF). The microstructure of the weld seam was analyzed with NANOSURF FlexAFM. The parameters chosen for study are beam power, welding speed, gas flow rate and beam angle and the output to be measured are depth of penetration and width of weld bead.

If there are more than one inputs and more than one outputs, then in order to explore the effects of all inputs to all the outputs a lot of experiments are to be performed for which lot of material, cost and time are wasted. So, statistical experimental design plan is required to optimize the number of experiments. Further out of all the inputs, some inputs are more significant and some inputs are less significant. Therefore in a systematic way we shall have to optimize the number of experiments so that more significant and less significant parameters are easily identified. For that a type of unconstrained optimization is required. In Taguchi method, which was developed by Genichi Taguchi of Nippon Telegraph and Telephone company, Japan an orthogonal array is used to design the experimental plan, gives much reduced variance for the experiment with optimum setting of control parameters. Generally in static problems a process to be optimized has several control factors which directly decide the target or desired value of the output. The optimization then involves determining the best control factor levels so that the output is at the target value. Noise is present in the process but the experimental plan is such that noise has no effect on the output. The primary aim of the Taguchi method is to minimize the variations in output even though noise is present. But if the process to be optimized has a signal input that directly decides the output, the optimization involves determination of best level of control factors, so that the (input signal/output) ratio is closest to the desired relationship. Such a problem is called dynamic problem. To minimize the variations in output, even though noise is present, is achieved by getting improved linearity in the input/output relationship. There are generally 3 different types of signal to noise ratio for optimization of static problem. Smaller the better S/N ratio is given by ----

$$\eta = -10 \log_{10} \text{(mean of sum of squares of the reciprocals of the measured data)} \qquad \text{---------- (1)}$$

It is used for all undesirable characteristics for which ideal value is zero and also when an ideal value is finite and its maximum and minimum value is defined. Larger the better S/N ratio is given by ----

$$\eta = -10 \log_{10} \text{ (mean of sum of squares of reciprocals of the measured data)} \quad \text{---------- (2)}$$

This case can be converted to smaller the better by taking the reciprocals of the measured data and then using the S/N ratio as in the smaller the better case. This is used when as large system response as possible is used. The nominal the best S/N ratio is as given below ---

$$\eta = 10 \log_{10} \text{ (square of mean/variance)} \quad \text{--------- (3)}$$

This case arises when a specified value is most desired meaning that neither a smaller nor a larger value is desirable. As here in this case of laser beam welding four control factors are chosen for convenience and hence $L_9\,(3)^4$ orthogonal array is chosen for experimental design. Table-2 represents the levels of the four parameters selected. 3 measurements are taken for each reading and the averages are taken. Then according to $L_9\,(3)^4$ the values of control factors for each experiment are given in table-3.

The outputs chosen are width of weld bead and depth of penetration. The measuring units of both are in millimeters. As less width of weld bead is desirable, so smaller the better S/N ratio is chosen. As laser beam welding requires restricted heat affected zone (HAZ), hence less depth of penetration is suitable. Hence smaller the better S/N ratio is used in case of depth of penetration also. The results of experiments in terms of S/N ratio are presented in table-4.The analysis of results was done with MINITAB.

TABLE-2
(Control Factors and their levels)

Control Factors	Level 1	Level 2	Level 3
Beam power (Watt)	750	1000	1250
Welding Speed (mm/min)	700	900	1100
Gas flow rate (L/min)	5	8	10
Beam angle (Degree)	80	85	90

TABLE-3
(Experimental Plan)

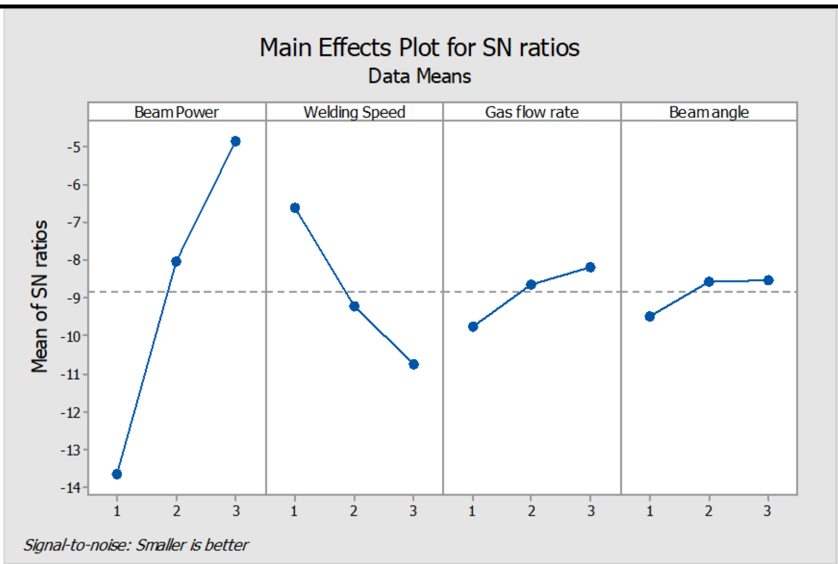
Expt No.	Beam power (Watts)	Welding Speed (mm/min)	Gas Flow Rate (L/min)	Beam Angle (Degrees)
1	750	700	5	80
2	750	900	8	85
3	750	1100	10	90
4	1000	700	8	90
5	1000	900	10	80
6	1000	1100	5	85
7	1250	700	10	85
8	1250	900	5	90
9	1250	1100	8	80

TABLE-4
Experimental Results

Expt No.	Levels of Control Factors				S/N Ratio for Bead Width	S/N Ratio for Depth of Penetration
	Beam Power	Welding Speed	Gas Flow Rate	Beam Angle		
1	1	1	1	1	4.44	7.33
2	1	2	2	2	4.73	8.18
3	1	3	3	3	5.35	8.87
4	2	1	2	3	1.83	3.48
5	2	2	3	1	2.62	4.15
6	2	3	1	2	3.35	4.58
7	3	1	3	2	1.21	1.51
8	3	2	1	3	1.94	2.38
9	3	3	2	1	2.27	2.97

4. Analysis of Results:--

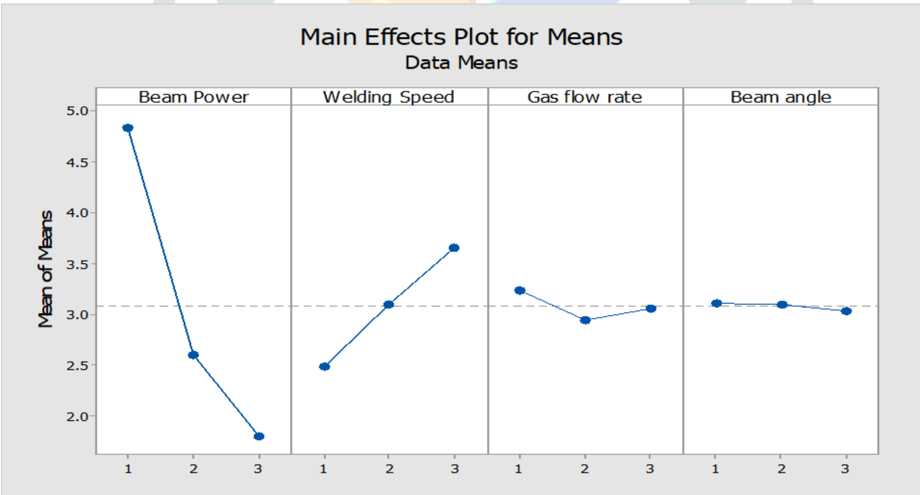
In analysis the responses bead width and depth of penetration are considered separately. The main effect plots for S/N ratio of bead width are presented in figure-3. The response table for Taguchi analysis for bead width against beam power, welding speed, gas flow rate and beam angle in terms of signal to noise ratio (smaller the better) is presented in table-5. The main effect plots for means of bead width is presented in figure-4. From the main effect plots for S/N ratio it is observed that the change in S/N ratio is maximum in case of beam power and next major variation is observed in case of welding speed. Hence these two parameters are vital for controlling the laser beam welding. The effect of gas flow rate and beam angle are less. Further the effects of gas flow rate and beam angle on bead width are more or less similar. Thus in case of effect on bead width, gas flow rate and beam angle are less important parameters



Main effect plot (S/N ratio) for bead width
(Figure-3)

TABLE -5
Response table for S/N ratio of bead width

Level	Beam Power	Welding Speed	Gas Flow Rate	Beam Angle
1	-13.671	-6.617	-9.735	-9.478
2	-8.039	-9.206	-8.622	-8.55
3	-4.844	-10.729	-8.196	-8.524
Delta	8.827	4.112	1.539	0.954
Rank	1	2	3	4



Main effect plot (means) for bead width
(Figure-4)

It is further observed that effect of beam power and welding speed are contradictory to each other in case of bead width. It is observed that lowest value of bead width can be observed for level 1 in case of beam power, level 3 in case of welding speed, level 1 in case of gas flow rate and level 1 in case of beam angle.

An effort was made to develop a linear model for bead width in terms of means. If bead width is denoted as BW, beam power is denoted as BP, welding speed is denoted WS, gas flow rate is denoted as GFR and beam angle is denoted as BA, then in terms of means the linear model becomes ---

W = 1.75778 x (BP) – 0.58889 x (WS) + 0.16111 x (GFR) + 0.02778 x (BA) + 3. 08222 ------------ (4)

The corresponding analysis of variance for means is given in table – 6. Similarly an effort was made to develop a linear model for bead width in terms of S/N ratio. The corresponding linear model becomes ----

BW = - 4.81952 x (BP) + 2.23367 x (WS) – 0.88373 x (GFR) – 0.62694 x (BA) – 8.85113 ----------- (5)

The corresponding analysis of variance for S/N ratio are given in table-7. Further, the effect of individual parameters on bead width was analyzed with one way analysis of variance. In all cases the null hypothesis was taken as all means are equal and alternative hypothesis was taken as atleast one mean is different. The significance level is taken as α = 0.05. Equal variances were assumed for the analysis.

TABLE-6

Analysis of variance (means) for bead width

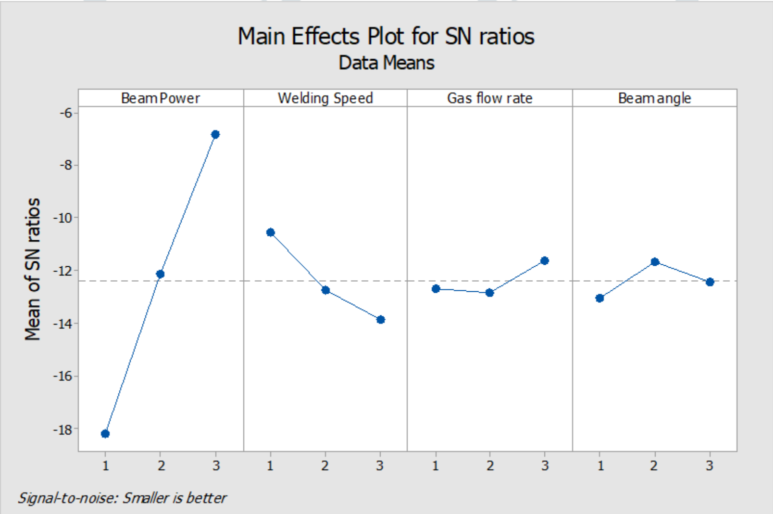
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Beam power	2	14.8481	14.8481	7.42404	---	---
Welding speed	2	2.0310	2.0310	1.01548	---	---
Gas flow rate	2	0.1372	0.1372	0.06861	---	---
Beam angle	2	0.0083	0.0083	0.00414	---	---
Residual error	0	---	---	---		
Total	8	17.0246				

TABLE – 7

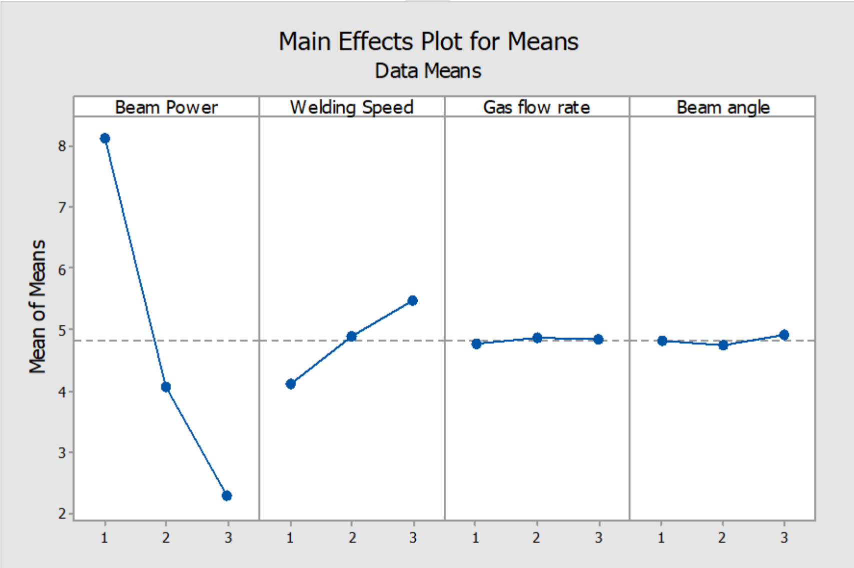
Analysis of variance (S/N Ratio) for bead width

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Beam power	2	119.833	119.833	59.9165	---	---
Welding speed	2	25.931	25.931	12.9656	---	---
Gas flow rate	2	3.787	3.787	1.8933	---	---
Beam angle	2	1.770	1.770	0.8849	---	---
Residual error	0	---	---	---		
Total	8	151.321				

The main effect plot for S/N ratio for depth of penetration is presented in figure-5.The main effect plot for means for depth of penetration is shown in figure-6. The response table for Taguchi analysis for depth of penetration against beam power, welding speed, gas flow rate and beam angle in terms of signal to noise ratio (smaller the better) is presented in table -8



Main effect plot (S/N ratio) for depth of penetration
(Figure-5)



Main effect plot (means) for depth of penetration
(Figure-6)

TABLE -8
Response table for S/N ratio for depth of penetration

Level	Beam power	Welding speed	Gas flow rate	Beam angle
1	-18.172	-10.571	-12.684	-13.039
2	-12.137	-12.716	-12.847	-11.684
3	-6.855	-13.877	-11.633	-12.441
Delta	11.316	3.306	1.214	1.355
Rank	1	2	4	3

From the main effect plot for S/N ratio in case of depth of penetration it is observed that the change in signal to noise ratio is maximum in case of beam power and next major variation is observed in case of welding speed. Hence, these two parameters are vital for controlling the laser beam welding. The effect of beam angle on depth of penetration in terms of signal to noise ratio is more prominent than in case of gas flow rate. Therefore from the point of view of effect on depth of penetration, beam angle is more significant parameter than gas flow rate. It is further observed that like in case of bead width, effects of beam power and welding speed are contradictory to each other. It is observed that the lowest value of depth of penetration is observed for level 1 in case of beam power, level 3 in case of welding speed, level 2 in case of gas flow rate and level 1 in case of beam angle.

An effort was made to derive a linear model for depth of penetration in terms of means and S/N ratio. If depth of penetration is denoted by DOP, beam power is denoted by BP, welding speed is denoted by WS, gas flow rate is denoted by GFR and beam angle is denoted by BA, then in terms of means the linear equation is ---

DOP = 3.29889 x (BP) – 0.72111 x (WS) – 0. 06444 x (GFR) – 0.01111 x (BA) – 12.3880 -------------- (6)

In terms of S/N ratio the linear equation is ----

DOP = - 5.7839 x (BP) + 1.8169 x (WS) – 0.2957 x (GFR) – 0.6514 x (BA) -12.3880 -------------- (7)

The corresponding analysis of variance for means and S/N ratio are presented in table -9 and table -10 respectively.

TABLE -9
Analysis of variance (means) for depth of penetration

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Beam power	2	53.7424	53.7424	26.8712	---	---
Welding speed	2	2.8274	2.8274	1.4137	---	---
Gas flow rate	2	0.0204	0.0204	0.0102	---	---
Beam angle	2	0.0358	0.0358	0.0179	---	---
Residual Error	0	---	---	---		
Total	8	56.6260				

TABLE – 10
Analysis of variance (S/N ratio) for depth of penetration

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Beam power	2	192.378	192.378	96.1890	---	---
Welding speed	2	16.877	16.877	8.4386	---	---
Gas flow rate	2	2.605	2.605	1.3025	---	---
Beam angle	2	2.768	2.768	1.3841	---	---
Residual error	0	---	---	---		
Total	8	214.629				

The effects of individual parameters on depth of penetration was analyzed with one way analysis of variance. In all cases, the null hypothesis was taken as all means are equal and alternative hypothesis was taken as atleast one mean is different. The significance level is taken as $\alpha = 0.05$. Equal variances were assumed for the analysis.

In order to verify the validity of the model a confirmation experiment was done at the optimum level of the control factors for both bead width and depth of penetration. The results of the confirmation experiment are presented in table-11. The sample SEM photos for the welding are presented in figure-7.

TABLE - 11
Results of Confirmation Experiment

Signal or Output	Optimum values of Control Factors				Predicted Value	Observed Value
	Beam Power (Watt)	Welding Speed (mm/min)	Gas Flow Rate (L/min)	Beam Angle (Degrees)		
Bead Width (mm)	750	1100	5	80	0.51	0.53
Depth of Penetration (mm)	750	1100	8	80	0.38	0.36

SEM micrograph for sample of laser beam welding
(Figure-7)

5. Conclusions :--

Parameters controlling the profile of the weld in fibre laser welding of aluminium alloy were investigated. It is observed that in case of the weld bead width controlling the effect of beam power and welding speed are most prominent. The effect of gas flow rate and beam angle are less significant. It is further observed that effect of beam power and welding speed on bead width are contradictory and opposite. It is observed that at level 1 lowest value of bead width was observed in case of beam power. At level 3 lowest value of bead width was observed in case of welding speed. Lowest values of bead width were observed in level 1 in case of both gas flow rate and beam angle. In case of depth of penetration it was observed that effect of beam power and welding speed are more prominent but in case of depth of penetration it was found that beam angle is more significant parameter than gas flow rate. Like bead width in case of depth of penetration also the effect of beam power and welding speed are opposite. The lowest value of depth of penetration was observed in level 1 for beam power, level 3 for welding speed, level 2 for gas flow rate and level 1 for beam angle. A linear equation has been tried to develop between the each output viz bead width and depth of penetration and four control factors viz. beam power, welding speed, gas flow rate and beam angle duly supported by corresponding analysis of variance for both S/N ratio and means. Also individual one way analysis of variance was carried out for both outputs against all the control factors. Finally a confirmation experiment was carried out in an experimental setting with optimal levels for all the parameters in case of both the outputs viz bead width and depth of penetration. The results obtained were observed to be within permissible variation from the predicted value. A sample SEM photograph of weld bead is presented which is the result of the above experimentation. The results of this experimental study will be useful for further analysis and of practical use for laser beam welding of aluminium alloy.

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