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Effect of Laser Welding process parameters on Mechanical Properties of Stainless Steel-316

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Abstract--Laser welding is a high speed welding process, capable of automated production of consistent quality welds. Compared with many other arc welding processes, fewer passes or higher welding speeds can be used, with lower usage of welding consumables. With proper optimization of welding procedures, full advantage can be taken of the low heat input nature of laser welding for a wide variety of materials, producing welds with acceptable hardness and toughness properties. Laser welding input parameters play a very significant role in determining the quality of a weld joint. In this study, the effects of various laser welding parameters on tensile strength and hardness of the weld for Stainless Steel 316 having dimensions 200 mm x 125 mm x 2 mm, welded by laser welding were investigated. The Welding speed, Power and Focal position were chosen as variable parameters. Ultimate tensile strength and Brinell Hardness was measured for each specimen after the welding operations and the effects of the welding parameters on strength and hardness were researched. A plan of experiments based on Taguchi technique has been used to acquire the data. The experiments were conducted based on a Three-factor, Three-level. An Orthogonal array, signal to noise (S/N) ratio are employed to investigate the welding strength and hardness of weld of SS 316 material.

Keywords—Laser welding, SS(Stainless Steel) 316, Taguchi methodology(Design of Experiment),Ultimate Tensile Strength(UTS), HRB (Brinell Hardness)

I. INTRODUCTION

Laser Beam welding is a method of fusing two pieces of metal together by using a high-heat laser. This technique uses one of two types of welding equipment: a solid state welder or a gas laser welder. These machines both create a precise bond by emitting a dense photon beam that can work with both thin and thick pieces of metal. This type of welder is popular in producing airplanes, cars and spacecraft, but has a few disadvantages that prohibit it from working in all industries

Welding with laser beams works because of a dense beam of photons that each type of machine produces. This light ray heats metals up quickly so that the two pieces fuse together into one unit. The light beam is very small and focused, so the metal weld also cools very quickly. Laser beam welding machines can give off a continuous beam to work with thicker metals, or short pulsing bursts to bind thinner materials.

Laser beam welding works well with metals like steel, aluminium, and titanium. Consequently, industries that use these metals typically embrace laser welders. Automotive, aeronautic and aerospace production facilities are well known as the main users of laser welding technique. The laser beam welding industry has utilized lasers for speed, accuracy and power, but there are also a few reasons some do not use this technology. There is a concern with retinal damage when using laser welders, especially solid state machines. To counteract this, operators are encouraged to wear protective eyewear. Another concern is cracking. Metals, like high carbon steels, often crack due to rapid cooling rate of a weld made by laser.

Laser welding operates in two fundamentally different modes: conduction limited welding and keyhole welding. The mode in which the laser beam will interact with the material it is welding will depend on the power density of the focused laser spot on the work piece.

Conduction limited welding occurs when the power density is typically less than 10^5W/cm^2. The laser radiation is absorbed only at the surface of the material and does not penetrate into the material. Therefore, conduction limited welds exhibit a high width to depth ratio.

Laser welding is more usually accomplished using higher power densities, by a keyhole mechanism. When the laser beam is focused to a small enough spot to produce a power density typically > 10^6-10^7 W/cm^2, the work piece surface vaporizes before significant quantities of heat can be removed by conduction. The focused laser beam penetrates the workpiece and forms a cavity called a 'keyhole', which is filled with metal vapour or ionized metal vapour (plasma). This expanding vapour or plasma contributes to the prevention of the collapse of the molten walls of the keyhole in to this cavity. Furthermore, the coupling of the laser beam to the work piece is improved dramatically by the formation of the keyhole. Deep penetration welding is then achieved by traversing the keyhole along the joint to be made (or moving the joint with respect to the laser beam) and results in welds with a high depth to width. Under the action of vapour pressure and surface tension, the molten material at the leading edge of the keyhole flows around the cavity created by the beam to the back, and solidifies to form the weld. This action leaves a top bead with a chevron pattern, which points towards the start of the weld.

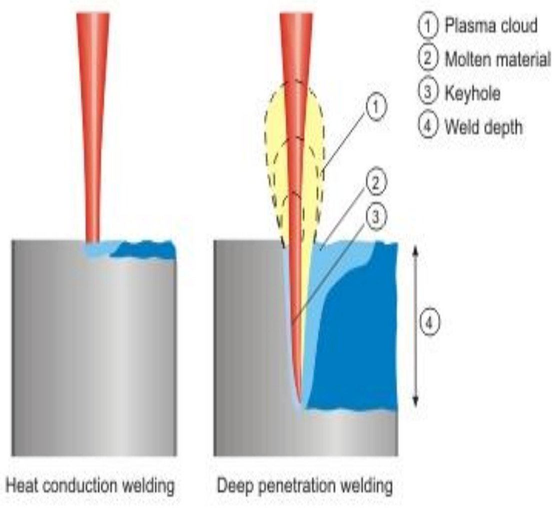

Fig 1 Types of Weld

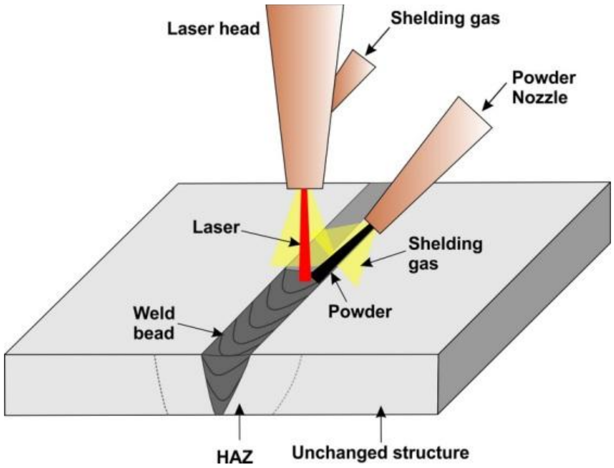

Fig 2 Schematic of Laser welding

II. Literature survey

P. Sathiya, K. Panneerselvam, R. Soundararajan [1] showed that Laser welding input parameters play a very significant role in determining the quality of a weld joint. The joint quality can be defined in terms of properties such as weld bead geometry, mechanical properties and distortion. Therefore, mechanical properties should be controlled to obtain good welded joints. In this study, the weld bead geometry such as depth of penetration (DP), bead width (BW) and tensile strength (TS) of the laser welded butt joints made of AISI 904L super austenitic stainless steel were investigated. Full factorial design was used to carry out the experimental design. Artificial Neural networks (ANN) program was developed in MatLab software to establish the relationships between the laser welding input parameters like beam power, travel speed and focal position and the three responses DP, BW and TS in three different shielding gases (Argon, Helium and Nitrogen). The established models were used for optimizing the process parameters using Genetic Algorithm (GA). The developed ANN model is suitably integrated with optimizing algorithms like GA to optimize the welding parameters. For the optimized welding parameters of GA, the laser welding joints were processed. Joints exhibit better quality. The good agreement between the theoretically predicted (GA) and experimentally obtained tensile strength, depth of penetration and bead width confirms the applicability of these evolutionary computational techniques for optimization of process parameters in the welding process.[1]

G.R. Mirshekari, A.Saatchi, A.Kermanpur , S.K.Sadrnezhaad [2] have shown in their work a comparative study on laser welding of Ni Ti wire to itself and to AISI304 austenitic stainless steel wire. Microstructures, mechanical properties and fracture morphologies of the laser joints were investigated using optical microscopy, scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), X-ray diffraction analysis(XRD), Vickers micro hardness(HV0.2) and tensile testing techniques. The results showed that the NiTi–NiTi laser joint reached about 63% of the ultimate tensile strength of the as-received Ni Ti wire(i.e.835MPa) with rupture strain of about 16%.This joint also enabled the possibility to benefit from the pseudo-elastic properties of the NiTi component. However, tensile strength and ductility decreased significantly after dissimilar laser welding of Ni Ti to stainless steel due to the formation of brittle inter metallic compounds in the weld zone during laser welding. The micro hardness values from the weld zone toward the base metal increased in NiTi–NiTi joint, while it decreased in Ni Ti–SS joint. In addition, Ni Ti – Ni Ti joint was fractured in ductile manner at the weld zone near the fusion line, while brittle failure occurred at the center of the Ni Ti–SS weld zone.[2]

Lifang Mei, Genyu Chen, Xiang zhong Jin,Yi Zhang, Qiang Wu [3] presented some useful results on deep-penetration laser welding of high-strength galvanized steel sheets, which had been carried out by a self-made CO2 laser unit with maximum power output of 1.5kW.The work pieces of high-strength galvanized automobile steels with thickness of 1.5mm were butt-welded with argon as the shielding gas. The effects of such factors as laser power, welding speed, focal position, shielding gas and zinc vaporization on the quality of welds are investigated. With the processing parameters optimized and the proper shielding gas used in both co axial and side-blow direction, most of the defects, such as pores, cracks and softening in HAZ, can be avoided in laser welding joints. The microstructure, the hardness distribution and the elemental distribution in the welding joints can be changed due to laser heating and recrystallization. In order to determine the mechanical properties of the welding joints, the static tensile strength was tested. Experimental results indicated that both the strength and micro hardness of welding joints were higher than those of the base metal. The deep punching performance acquired by adopting Ar as shielding gas is better than that acquired by adopting N2 as shielding gas. Meanwhile, the effect of zinc vaporization on welding joints can be effectively controlled by means of blowing side shielding gas. The experimental results indicate that the promising welding quality can be obtained under the chosen condition of taking Ar as shielding gas, laser power P as 1300W, defocusing amount Df as 0.4mm, welding speed v as 1.0 m/min, coaxial-blown shielding gas-flow rate q as 2.5 m^3/h, side-blown shielding gas-flow rate q as 1.8 m^3/h, and side-blown angle α as 301.[3]

A.G. Olabi, F.O. Alsinani, A.A. Alabdulkarim, A. Ruggiero, L. Tricarico , K.Y. Benyounis [4] investigated dissimilar full-depth laser-butt welding of low carbon steel and austenitic steel AISI316 was investigated using CW 1.5kW CO2 laser. The effect of laser power, welding speed and focal point position on mechanical properties (i.e., ultimate tensile strength, UTS and impact strength, IS) and on the operating cost C was investigated using response surface methodology (RSM). The experimental plan was based on Box–Behnken design; linear and quadratic polynomial equations for predicting the mechanical properties were developed. The results indicate that the proposed models predict the responses adequately within the limits of welding parameters being used. A laser power value of 1.1 kW is suggested as an optimum input process value to obtain excellent welded joints produced from austenitic stainless steel AISI 316 and low carbon steel. The welding speed is the most effective parameter affecting the main weld bead dimensions as the area and the middle width, and it has to be set right on certain values to make all the responses optimized. Being focal point position fixed around -0.41 mm and laser power on 1.17 kW, setting welding speed on 72.66 cm/min, all the weld bead dimensions come out very reduced as area can be minimized by more 9% and middle width by 14%, spending 20% less money than the first criteria solution cost. Anyway, depending on the desired impact strength value for the specific application, if any, and on how much important and critical are mechanical properties on that, fixing welding speed on 57.93 cm/min, focal point position on -0.35 mm and laser power on 1.30kW, can be more efficient and smart, as it ensures a pretty higher value of ultimate tensile strength (360MPa) and impact strength(70.44J).[4]

Shanmugarajan B., Chary J N., Padmanabham G., Arivazhagan B. , Shaju K. Albert , Bhaduri A.K. [5] studied Influence of variables such as laser power, welding speed, shielding gas and laser beam mode on microstructure and mechanical properties. Here autogenous bead-on-plate (BoP) laser welding studies were carried out on 3mm thick 304B4 grade stainless steel using a 3.5kW slab CO2 laser. Dye penetrant testing, macro structural analysis, bead geometry measurements, micro hardness survey, and micro structural analysis in both as-weld and post-weld heat treated conditions were carried out. The macro structural and bead geometry analyses of the welds have shown that the welds were free from cracks in the fusion zone(FZ) and also in the heat affected zone (HAZ) for all the welding parameters studied. The Gaussian mode has given a very narrow weld width compared to donut mode. During welding use of helium and nitrogen has reduced the width of the FZ and HAZ. The as-weld micro hardness was more than double the base metal, and the peak hardness was shifted from the centre to the fusion boundaries with the increase in heat input. The PWHT has reduced the hardness of both the FZ and HAZ[5].

III. Experimental Procedure

In the present work, Stainless Steel 316 specimens used as work piece were prepared with dimensions of 200 mm×125 mm×2mm. Optical emission spectroscopy (OES) has been done to find out the chemical composition of the base metal, i.e. shown in Table 1. Table 2 shows the mechanical properties of the work piece specimen (i.e. SS 316).

Table 1Chemical composition of SS 316

Carbon	Silicon	Manganese	Phosphorus	Sulphur	Chromium	Nickel	Molybdenum
0.029%	0.360%	1.850%	0.025%	0.008%	16.970%	10.120%	2.050%

Table 2 Mechanical properties of SS 316

Grade	Tensile Strength (MPa)	Yield Strength (MPa)	Hardness	
			Rockwell	Brinell
316	515	205	95	217

The effect of the process parameters, viz., Power, Welding speed and Focal position on the weld joint yield strength and hardness of weld has been investigated. Welding was done on automatic laser welding setup available at Sahajanand Laser technology ltd. Taguchi orthogonal L9 array is used for design of experiment in the present study. The factors and the level values are cited in table 3 whereas the experiment reading combinations are cited in doe table i.e table 4.

Table 3 Factors and the level values for laser welding

Factor	**Level 1**	**Level 2**	**Level 3**
Power (W)	1000	1250	1500
Focal Point (mm)	-3	0	+3
Welding speed(mm/min)	600	700	800

Table 4 Doe table

Experiment	Power	Focal Point	Welding Speeed
1	1000	-3	600
2	1000	0	700
3	1000	+3	800
4	1250	-3	700
5	1250	0	800
6	1250	+3	600

7	1500	-3	800
8	1500	0	600
9	1500	+3	700

IV. Design Of Experiment

DOE is a technique of defining and investing all possible combinations in an experiment involving multiple factors and to identify the best combination. In this, different factors and their levels are identified. Design of experiments is also useful to combine the factors at appropriate levels, each with the respective acceptable range, to produce the best results and yet exhibit minimum variation around the optimum results so that better quality products can be produced quickly and at minimum cost.

The marriage of Design of Experiments with optimization of control parameters to find best results is attained in the Taguchi Method. "Orthogonal Arrays" (OA) gives a set of well balanced (minimum) experiments and Dr. Taguchi's Signal-to-Noise ratios (S/N), which are log functions of desired output, serve as objective functions in optimization, help in data analysis and The signal-to-noise (S/N) ratio for each level was based on the S/N ratio analysis. Based on the tensile strength of the weld joint (larger-the-better), a higher S/N ratio produced a better quality value. The standard S/N ratio formula for this type of response is: S/N ratio η is defined as **η= -10 log (M.S.D.)**
Where, M.S.D. is the mean square deviation for output characteristic.

$$n_i = -10 \log \left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Y_{ij}^2}\right]$$

Where 'i' is the number of a trial; 'Yij' is the quality of the i^th trial and j^th experiment; 'n' is the total number of experiments.

Here in the present study our goal is to achieve higher ultimate tensile strength and higher hardness of welded joint, hence larger the better is taken as the criteria to optimize the parameters. Parameters that give us the higher value of both the ultimate tensile strength and hardness of the weld are the optimized parameter and the predicted value obtained from minitab16 software will be cited at last after the analysis.

V. Results and Analysis

Following are the results obtained after performing the experiment using the parameters value as cited in table 4:

Table 5 Result table

Power(A)	Focal Point(B)	Speed(C)	UTS	Weld Hardness(HRB)
1000	-3	600	566.45	83
1000	0	700	561.44	79
1000	3	800	545.94	80
1250	-3	700	554.35	80
1250	0	800	545.25	79
1250	3	600	568.47	81
1500	-3	800	541.26	84
1500	0	600	561.23	80

1500	3	700	553.21	79

5.1 Effect of process parameters on Ultimate Tensile Strength(UTS)

Figure 3 here shows the main effect plot of process parameters of Ultimate Tensile Strength at different parameters like welding speed, power and focal position in Laser welding od SS 316. From the figure, it can be seen that :-

- Effect of Power: As the value of power increases the Ultimate Tensile Strength (UTS) value decreases
- Effect of Focal point: As the value of focal point increases the Ultimate Tensile Strength(UTS) value increases
- Effect of Welding Speed: As the value of Welding Speed increases the Ultimate Tensile Strength (UTS) value decreases.

The regression equation is:

UTS = 606 + 0.0126 A + 5.50 B - 0.0366 C + 0.00305 A*B - 0.000047 A*C - 0.0131 B*C

Where, A= Power
B=Focal Point
C= Welding Speed

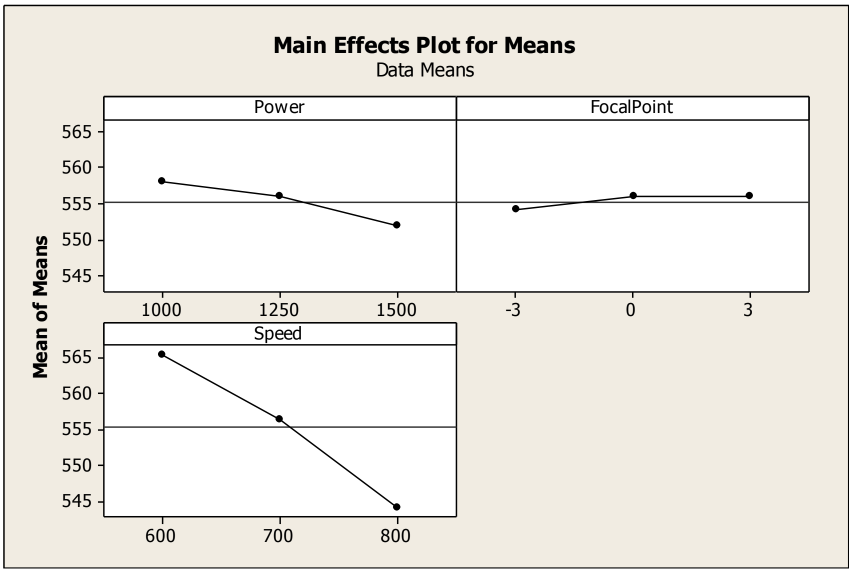

Fig 3 Main Effect plot for UTS

Fig 4 shows the main effect plot for S/N ratio of Ultimate Tensile Strength and table 6 shows the response table for S/N ratio

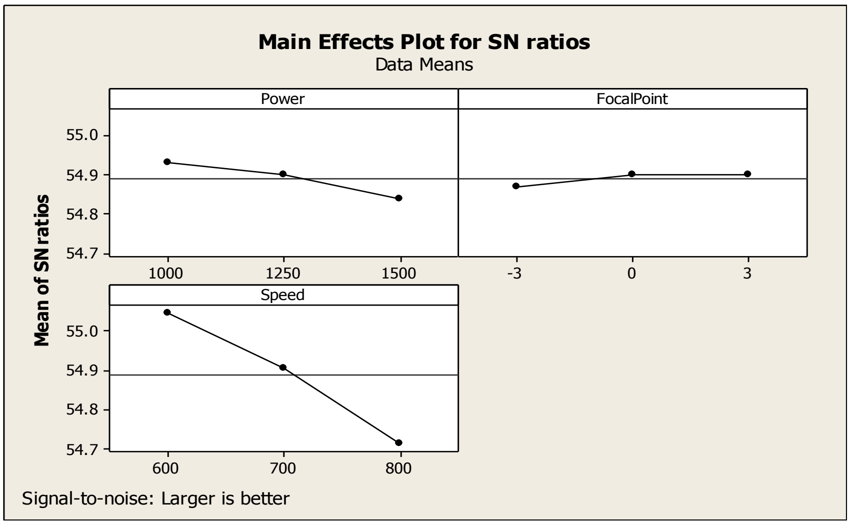

Fig 4 Main effect plot for SN ratio

Table 6 Response table for SN ratio

Level	Power	Focal point	Welding Speed
1	54.93	54.87	55.05
2	54.90	54.90	54.91
3	54.84	54.90	54.71
Delta	0.09	0.03	0.33
Rank	2	3	1

Table 7 Estimated Model Co-efficient for UTS

Predictor	Coef	SE Coef	T	P
Constant	605.87	38.28	15.83	0.004
A	0.01259	0.02849	0.44	0.702
B	5.502	1.825	3.02	0.095
C	-0.03660	0.05710	-0.64	0.587
A*B	0.003048	0.001419	2.15	0.165
A*C	-0.00004651	0.00004258	-1.09	0.389
B*C	-0.013138	0.003548	-3.70	0.066
S = 1.14976		R Sq = 99.7%		R Sq(adj) = 98.6%

5.2 Effect of process parameters on Hardness of Weld (HRB)

Figure 5 here shows the main effect plot of process parameters of Hardness of Weld (HRB) at different parameters like welding speed, power and focal position in Laser welding od SS 316. From the figure, it can be seen that :-

- Effect of Power: As the value of power increases the Hardness of Weld(HRB) decreases upto a value and then it increases.
- Effect of Focal point: As the value of focal point increases the Hardness of Weld(HRB) decreases upto a value and then it increases.
- Effect of Welding Speed: As the value of Welding Speed increases the Hardness of Weld(HRB) decreases up to a value and then it increases.

The regression equation is:

HW = 212 – 0.0950 A + 0.683 B – 0.197 C – 0.00438 A*B + 0.000143 A*C + 0.00714 B*C

Where, A= Power
B=Focal Point
C= Welding Speed

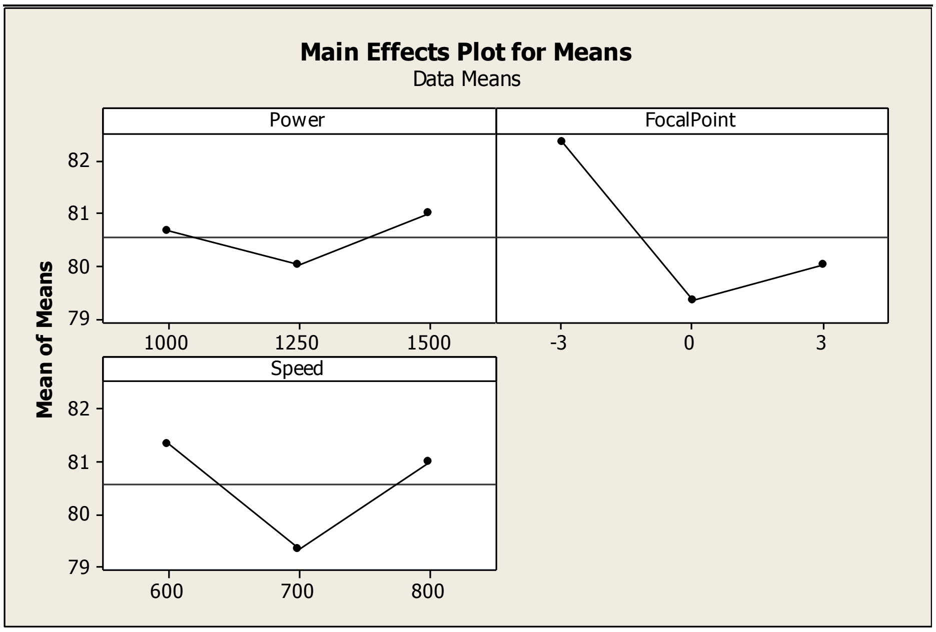

Fig 5 Main Effect plot for Hardness of Weld (HW)

Fig 6 shows the main effect plot for S/N ratio of Hardness of Weld (HRB) and table 8 shows the response table for S/N ratio

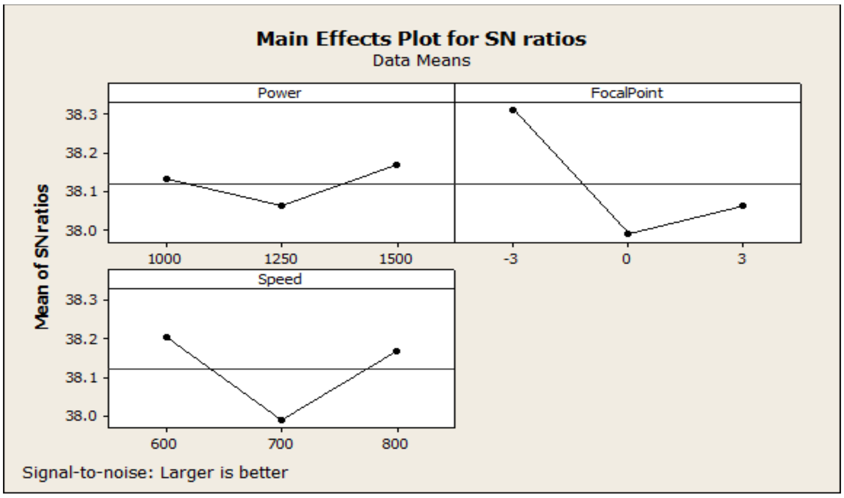

Fig 6 Main Effect plot for SN ratio

Table 8 Response table for SN ratio

Level	Power	Focal point	Welding Speed
1	38.13	38.31	38.20
2	38.06	37.09	37.99
3	38.17	38.06	38.17
Delta	0.11	0.32	0.22
Rank	3	1	2

Table 9 Estimated Model Co-efficient for Hardness of Weld (HRB)

Predictor	Coef	SE Coef	T	P
Constant	212.03	11.10	19.11	0.003
A	-0.095048	0.008260	-11.51	0.007
B	0.6825	0.5290	1.29	0.326
C	-0.19667	0.01656	-11.88	0.007
A*B	-0.0043810	0.0004115	-10.65	0.009
A*C	0.00014286	0.00001234	11.57	0.007
B*C	0.007143	0.001029	6.94	0.020
S = 0.333333	R Sq = 99.2%		R Sq(adj) = 96.6%	

Here in this study we are interested in higher the Tensile Strength (UTS) and higher the hardness of the weld, hence the optimum value for both the output parameters are given in the table 10 and table 11.

Table 10 Optimum value of Ultimate Tensile Strength

Power	Focal Point	Welding speed	Mean UTS(Mpa)	SN ratio(UTS)
1000	3	600	568.622	55.0974

Table 11Optimum value of Hardness of Weld (HRB)

Power	Focal Point	Welding speed	Mean Hardness(HRB)	SN ratio(HRB)
1500	-3	600	83.5556	38.4407

VI. Conclusions

Following conclusions are drawn from the study :

1) Effect of process parameters on Ultimate Tensile Strength(UTS):
- Effect of Power: As the value of power increases the Ultimate Tensile Strength (UTS) value decreases
- Effect of Focal point: As the value of focal point increases the Ultimate Tensile Strength(UTS) value increases
- Effect of Welding Speed: As the value of Welding Speed increases the Ultimate Tensile Strength (UTS) value decreases.

2) Effect of process parameters on Hardness of Weld (HRB):
- Effect of Power: As the value of power increases the Hardness of Weld(HRB) decreases upto a value and then it increases.
- Effect of Focal point: As the value of focal point increases the Hardness of Weld(HRB) decreases up to a value and then it increases.
- Effect of Welding Speed: As the value of Welding Speed increases the Hardness of Weld (HRB) decreases up to a value and then it increases.

3) The optimum value of Ultimate Tensile Strength comes out to be 568.622 Mpa and the optimum value of hardness of weld comes out to be 83.5556 HRB.
4) From the response table of SN ratio of UTS it is concluded that welding speed affects the most the UTS then comes the Power and at last the Focal Point.
5) From the response table of SN ratio of Hardness of Weld it is concluded that focal point affects the most the hardness then comes the Welding speed and at last the Power.

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