Experimental Investigation of Welded Joint Prepared Using Powder Plasma Arc Welding Process on 304 Austenitic Stainless Steel

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Abstract: Plasma Arc Welding has advantages of less welding defect and excellent directional control and has been used in sheet metal Industry, space shuttles, airplanes, rockets, etc therefore the study of improve welding quality is a great technological interest. The main purpose of the study is investigation carried out on plasma arc welding by using powder as filler metal at weld joint and ensure feasibility of welding with good quality by optimizing process parameter and study mechanical and metallurgical properties of welds. To study the influence of each parameter to the response value, Analysis of Variance (ANOVA) technique has been used and optimized process parameter to achieved best possible weld quality. Experiments are performed with SS 304L as workpiece material and SS316L as powder consumable. Central Composite Design (CCD) experimental design used to perform experiment. process parameters such as plasma arc current, welding speed and gas flow are considered as input parameter were Radiography test, tensile strength, hardness and microstructure are considered as response valve to study the weld quality. Analysis of variance indicates the above process parameter has most Signiant affecting on strength and hardness. Combine effect of gas flow rate and plasma arc current is observed in strength. At weld zone dendritic fine grain microstructure is observed. Optimized parameter gives Sound joining of 10mm thick SS304L could be accomplished by plasma arc welding with SS316L powder as filler meta by eliminating welding defects such spatter, distortion, crack and gas holes or porosity.

Index Terms: **Powder plasma arc welding, joint design, Tensile strength, hardness, microstructure, optimization.**

I. INTRODUCTION

The Plasma Arc Welding (PAW) process is essentially an extension of Gas Tungsten Arc Welding (GTAW). The energy density and gas velocity and momentum in the plasma arc are high.[1] In PAW the electric arc generated between a non-consumable tungsten electrode and the working piece is constrained using a copper nozzle with a small opening at the tip. Arc is generated between electrode and workpiece (transfer PAW) or water cool nozzle (non-transfer PAW) [2]. By forcing the plasma gas and arc through a constricted orifice, the torch delivers a high concentration of energy to a small area, giving higher welding speeds and producing welds with high penetration/width ratios, thus limiting the HAZ dimensions. For this reason PAW is very useful techniques for welding of austenitic steels, structural steels etc [3-4]

Plasma Arc Welding Further classify based on range of winding current, following three mode of Plasma Arc Welding used in industry based on application to be weld. [5]

1) Micro plasma (0.1-1 5 A)
2) Medium plasma welding (15-100 A)
3) Keyhole plasma welding (>100 A).

In Micro PAW The concentrated arc enables it to remain stable down to a current of about 0.1 A, which means that the process can be used for welding metal thicknesses down to about 0.1 mm. This makes the process attractive to, for example, the space industry. In medium plasma welding (15-100 A). In this range, the method competes more directly with TIG welding. It is suitable for manual or mechanised welding and is used in applications such as the automotive industry for welding thin sheet materials without introducing distortion or unacceptable welded joints, as are produced by MIG welding, or for the welding of pipes in breweries or dairies. In key hole mode the third type of plasma welding is referred to as keyhole plasma welding, taking its name from the 'keyhole' that is produced when the joint edges in a butt weld are melted as the plasma jet cuts through them. As the jet is moved forward, the molten metal is pressed backwards, filling up the joint behind the jet.[5-6]

PAW has a number of critical advantages over TIG welding process. The high-power arc that is produced and eliminates the need for time consuming weld preparation work such as: V-type or U-type joint preparation and square cut joint preparation. This preserves around 30% of the filler metal. In turn, increases the welding speed by around 20% in soft-plasma welding. PAW also saves time and costs at the same time as ensuring deeper penetration. The tungsten electrode has a much longer service life because it is enveloped in the protective plasma gas.[6-7]. Form the literature survey powder consumable used for coating and wire from of consumable used for welding [8]. Main aim of the research is used powder consumable for welding purpose and study mechanical and metallurgical property at weld joint to study weld quality.

II. EXPERIMENTAL PROCEDURE

1) Selection of work piece material

Stainless steels are known for their corrosion resistant. Among the different types of stainless steels, austenitic stainless possess very good weldability. Due to its good weldability, it is widely used in structural applications, shipping industries, pressure vessels, etc. [9] In this work, stainless steel of grade SS304L is used for experimentations. The dimensions of each plate which were welded together is 150mm × 150mm × 10mm. SS 316L powder consumable used and it mainly consists of iron (Fe) and other materials are added to modify its properties. A spectrographic test was performed to know the chemical composition of base metal considered for the present study. Composition of 316 grade steel is shown in Table 1.

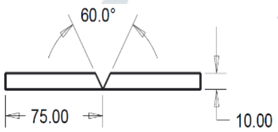
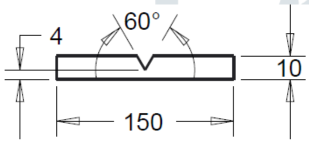
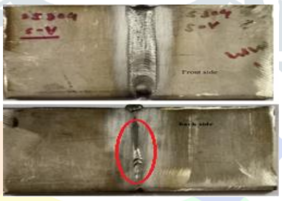
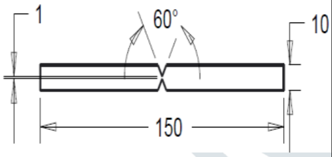
Table 1 Composition of SS304 & SS316

Grade	C	Mn	Si	P	S	Mo	Cr	Ni
SS304L	0.012	1.64	0.39	0.012	0.025	-	18.59	8.205
SS316L	0.03	2.0	0.75	0.045	0.030	2.0	18	14

2) Joint design

Joint configuration is critical phase in powder plasma arc welding. To identify joint configuration and also to check the feasibility of powder plasma arc welding first pilot run is carried out. There are three pilot runs carried out based on following joint configuration and study the weld quality. Pilot run with observation show in below table 2

Table 2 Observation on pilot run

Pilot Run	Joint Congregation	After Welding	Observation
1			Poor Performance Diffusion of powder due to improper joint design Corner edge of V groove is burn during welding process.
2			Poor Performance Poor penetration in root face is observed but diffusion of powder and burning of edge is eliminated.
3			Sound weld quality eliminate above all defect. Experimental run Performed based this joint design.

3) Conclusion From pilot tests

From the results of the pilot test, we identify that double v groove give batter result for 10mm thickness specimen to be welded by powder plasma arc welding process. And also identify process parameter by which we can weld specimen by using powder consumable. From the literature survey identify that main process parameter such as welding current, welding speed and plasma gas flow rate are primary factor to influence weld bead quality. Further experimental work is preform based on design of experiment and to perform DOE main variable process parameter is selected based on third pilot run and study influence of each parameter to the response value. In short pilot run gives the idea about joint design and process

4) Selection of Experimental design

Design of Experiments (DOE) is aimed to identify the significant active factors and investigate their effects on the output responses. [9] Center composite design is used for conducting experimental runs. Here we have total 3 factors. All three are continuous variables with three levels. According to the center composite design total 16 experimental runs should be carried out. Table 3 shows a three variable Center composite design.

Table 3 Domain of Experiment

Factors (Notation)	Unit	-1	0	+1
Plasma arc current (I)	A	140	160	180
Welding Speed (V)	mm/min	140	160	180
Plasma gas flow rate (F)	kg/hr	2.5	4.0	5.5

Table 4 Values of the variables of the matrix of experiments.

Std order	Run order	Coded Variable			Real Variable		
		Plasma arc current 'A'	Welding Speed 'B'	Plasma gas flow rate 'C'	Plasma arc current (I)	Welding Speed (V)	Plasma gas flow rate (F)
11	1	0	-1	0	160	140	4.0
13	2	0	0	-1	160	160	2.5
1	3	-1	-1	-1	140	140	2.5
3	4	-1	+1	-1	140	180	2.5
6	5	+1	-1	+1	180	140	5.5
7	6	-1	+1	+1	140	180	5.5
10	7	+1	0	0	180	160	4.0
12	8	0	+1	0	160	180	4.0
16	9	0	0	0	160	160	4.0
14	10	0	0	+1	160	160	5.5
9	11	-1	0	0	140	160	4.0
4	12	+1	+1	-1	180	180	2.5
15	13	0	0	0	160	160	4.0
5	14	-1	-1	+1	140	140	5.5
2	15	+1	-1	-1	180	140	2.5
8	16	+1	+1	+1	180	180	5.5

5) Experimentation

Robotized or automate system of plasma arc welding consist power supply unit, plasma torch, powder hopper, plasma gas shielding gas and carrier gas unit, six axis robot, coolant etc shown in below Figure 3 3. In experiment variable parameter is taken from above table 4, were all other parameter is fixed which is shown in below table 5.

Figure 1Automating robotized plasma arc welding setup

Table 5 Fixed Parameter

Sr No	Fixed Parameter	Value	Sr No	Fixed Parameter	value
1	Powder flow rate (kg/hr)	1.8	6	Powder	SS316L
2	Torch stand-of distance (mm)	4.0	7	Size of the work piece	150×75 ×10
3	Plasma gas, Shielding gas, Carrier gas	Ar	8	Work piece / torch alignment	SS304/ Horizontal
4	Electrode diameter (mm)	4.0	9	Number of pass	2
5	Plasma nozzle	2.80	10	Oscillation wave mode	Trapezoidal

As generated from DOE matrix, all 16 experiments were performed as per DOE table. Plates that were utilized in the experiments were having the dimensions 150mm × 75mm × 10mm. Figure 3 shows the welded samples after performing all 16 experiments as specified by DOE.

III.Measurement of Experimental Responses:

After Welding experiments, to study the influence of each variable parameter to response value various Non-distractive and distractive testing is carried out at weld joint. tests are performed in following sequence.

a) Visual inspection,

b) NDT Test (Radiography test),

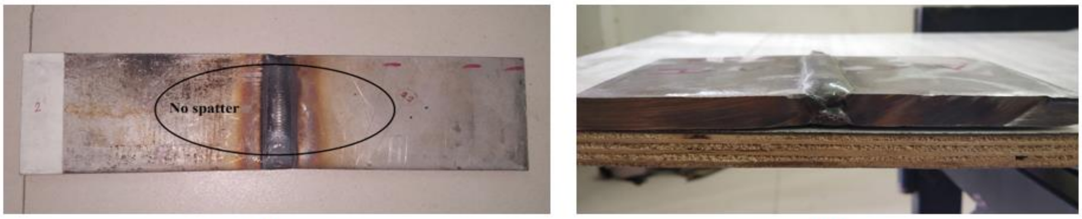
c) Tensile test,

d) Micro Hardness,

e) Microstructure

a) Visual inspection

Powder plasma arc welding give sound weld bead quality with good appearances and external defect such as spatters, cracks and distortion is not observed in all sixteen experiment as shown below figure 2. but reinforcement is observed due to variation of welding speed.



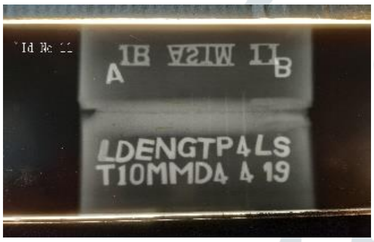
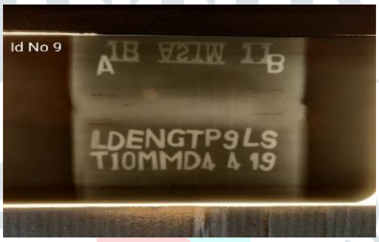
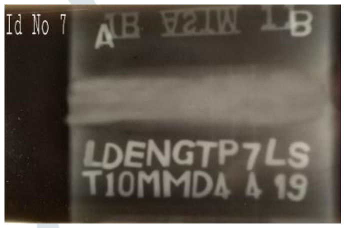
(A) (B)

Figure 2 (A) Free from spatter, (B) Free from distortion

b) Radiography test

The quality of the powder plasma arc welded specimens is assessed using radiography test. From the test results, lack of fusion is observed in parameter which contain lower level welding current and higher welding speed e.g. Id No 4,6,11 and 3 due to insufficient heat input, batter fusion with less defect observed in Id 2,8,12,16. Where good fusion with no internal porosity, slag inclusion etc completely eliminated in higher current with lower welding speed. Rt film for increasing current show in below table 6.

Table 6 RT Film Observation

Id No 11	Id No 9	Id No 7
		
I=140A, V=160mm/min, f=4 l/min	I=160A, V=160mm/min, f=4 l/min	I=180A, V=160mm/min, f=4 l/min

c) Tensile strength Testing

As per ASME section IX, specimens for tensile tests were prepared as shown in below fig. According to the standard, the full thickness specimen where be used for thickness less than 25mm. As per ASME section IX [10] test specimen should be free from reinforcement caused due to welding. So, the reinforcement from both top and bottom sides were removed using grinder before preparing the specimen. Below figure shows the prepared samples for tensile testing.

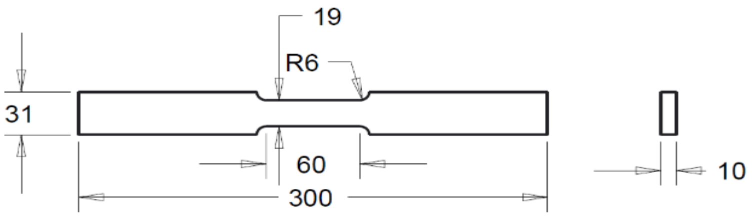


Figure 2 Dimension of tensile specimen as per ASME Section IX

Figure 3 Prepared specimen

d) Hardness

To measure the Vickers micro hardness, test surface usually must be highly polished because for smaller force higher the metallographic finish required observed value show in table. HV on fusion zone find higher than base metal.

IV. RESULTS AND DISCUSSION

Using Design expert software (Version 10.0), the experimental data points were analyzed through Analysis of variance (ANOVA) and Lack of fit test. Mathematical modelling was carried out to find the relation between response variables and input parameters. Table 6 presents the input parameters and output responses for all experiments. Using Design expert software relationship between input parameters and output responses were obtained.

Table 6 Experimental results of Ultimate Tensile strength, and microhardness

Std order	Run order	Input parameters			Output Responses	
		Plasma arc current (I)	Welding Speed (V)	Plasma gas flow rate (F)	UTS (MPa)	Hardness (Hv)
11	1	160	140	4.0	489.868	248.67
13	2	160	160	2.5	454.550	257.33
1	3	140	140	2.5	463.109	217.67
3	4	140	180	2.5	421.484	229.33
6	5	180	140	5.5	572.379	256.67
7	6	140	180	5.5	425.718	242.33
10	7	180	160	4.0	534.133	277.33
12	8	160	180	4.0	435.844	266.6
16	9	160	160	4.0	459.507	273.33
14	10	160	160	5.5	473.652	261.34
9	11	140	160	4.0	433.689	251.33
4	12	180	180	2.5	504.271	273.33
15	13	160	160	4.0	463.885	271
5	14	140	140	5.5	473.506	224.67
2	15	180	140	2.5	541.110	246.8
8	16	180	180	5.5	522.546	264.67

A. Effects of welding parameters on the UTS:

The effect of welding speed, plasma arc current and gas flowrate on UTS is shown in Figure 3. (a), (b), and (c) respectively. Where Figure (d) show combine effect of welding current and gas flow rate on UTS.

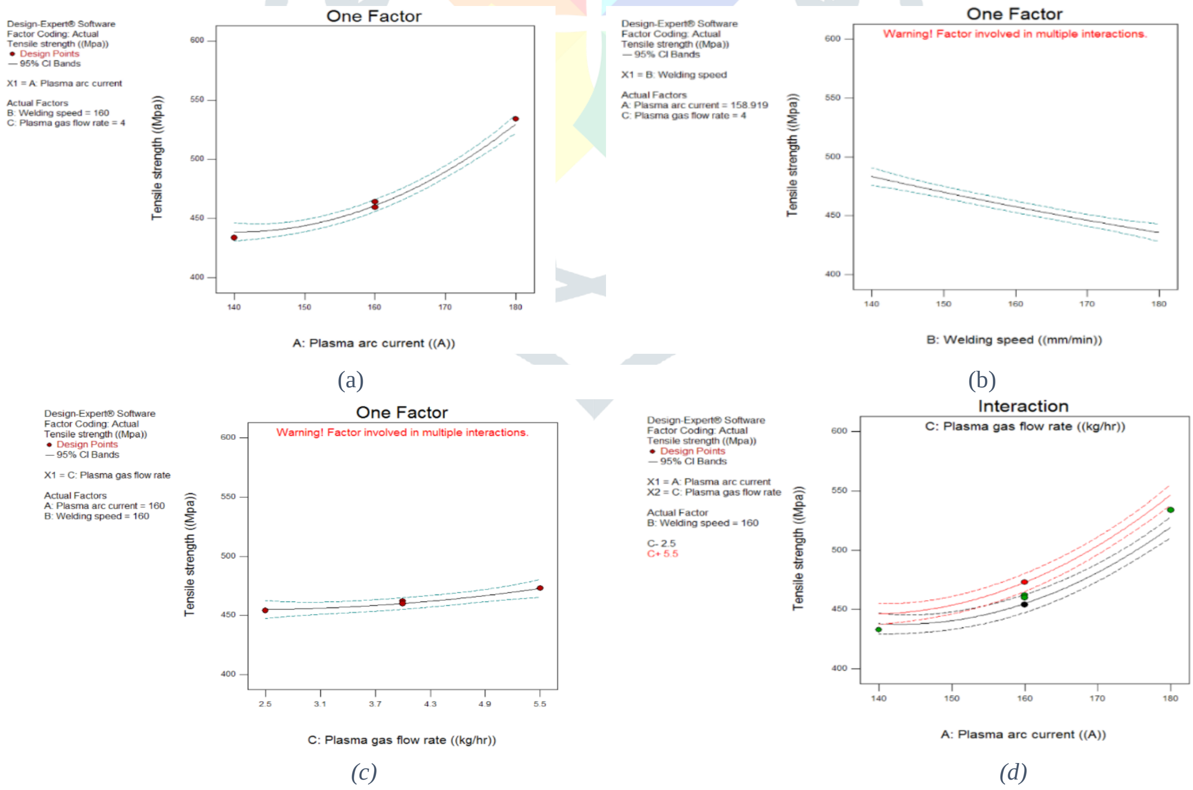
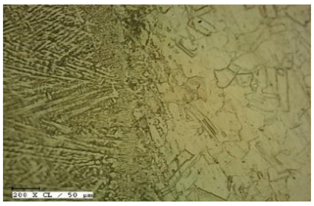
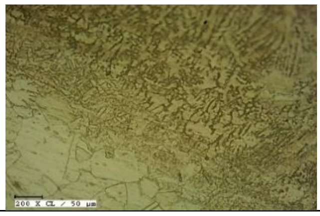
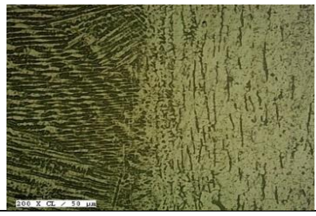


Figure 4 (a) Welding current Vs UTS, (b)Welding speed Vs UTS, (c) Gas flow rate Vs UTS, (d) Combine Effect of welding current and flow rate

Constant welding speed (V=160), plasma gas flow rate (F=4 L/min) with variable plasma current vs tensile strength graph show in Figure 3(a), as increase in plasma current, form lower level to higher level, tensile strength at weld zone is observed continues increase as shown in figure. The reason is interaction of heat input, as we know that heat input is directly proportional to welding current, lower the plasma current, lower the heat input and which is not sufficient to melt the root of double v groove as we observed on radiography film. Where good fusion with better weld quality is observed in higher current, and observed higher strength.

And also, metallurgical changes observed at fusion zone as change of heat input. Based on microstructure observation dendritic structed observed at fusion zone, as current is increase from 140A to 180A, dendritic structure become more finer as shown below table 7 which gain result in increased strength.

Table 7 Microstructure observation with change in current

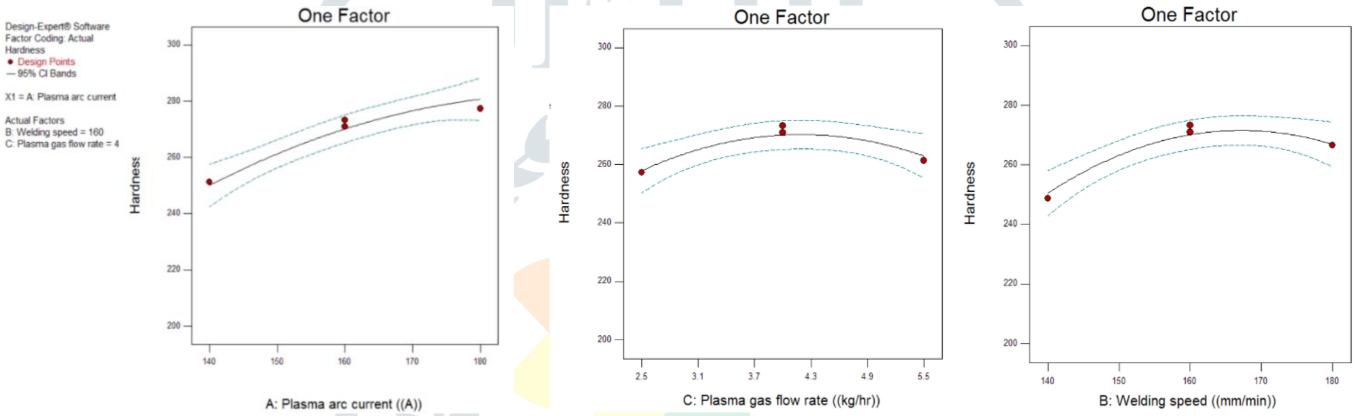
Id No 11	Id No 9	Id No 7
		
I=140A, V=160mm/min, f=4 l/min	I=160A, V=160mm/min, f=4 l/min	I=180A, V=160mm/min, f=4 l/min

Above figure 3 (b) and (c) indicate that as welding speed increase strength at weld zone is continually reduce and slight interaction of plasma gas flowrate is observed with strength

Above figure 3(d) indicate that at low plasma current e.g. 140A, interpretation of gas flow rate from low level to high level is observed negligible and it increase slightly with current and at higher welding current e.g. 180A, Interpretation of gas flow rate from low level to higher level is observed grater. Which indicate at higher current interpretation of gas flow rate is higher in welding.

B) Effects of welding parameters on Hardness:

The effect of welding speed, plasma arc current and gas flowrate on Hardness is shown in Figure 4 (a), (b), and (c) respectively. Where Figure (d) show combine effect of welding current and gas flow rate on UTS.



(a) *(b)* *(c)*

Figure 5 (a) Welding current Vs Hardness, (b)Welding speed Vs Hardness, (c) Gas flow rate Vs Hardness

Constant welding speed (V=160), plasma gas flow rate (F=4 L/min) with variable plasma current vs micro hardness graph show in figure 4 (a) as increase in plasma current, form lower level to higher level, hardness value at weld zone is observed continues increase as shown in figure. The reason is metallurgical changes observed at fusion zone as change of heat input. Based on microstructure observation dendritic structed observed at fusion zone, as current is increase dendritic structure become more finer which gain result in increased hardness at fusion zone.

Constant plasma current (V=160), plasma gas flow rate (F=4 L/min) with variable welding speed vs hardness graph show in Figure 4 (b), Graph indicate that as welding speed increase hardness value at weld zone is increase first and then slightly reduce. reason is as welding speed increase from 140 mm/min to 160 mm/min dendritic structure become more finer result observed higher hardness values and from 160 mm/min to 180mm/min slight reduction of hardness is observed due changes of microstructure. It is observed that slight interaction of plasma gas flowrate is observed with hardness. Frist slight increase and then start reducing due to metallurgical changes at fusion zone.

V. OPTIMISATION

Here our goal in optimization is to achieve best values of responses which gives us the satisfactory result according to the ultimate tensile strength and hardness. Our aim of optimization is to, UTS is gather than base metal and Hardness is minimize. Goals apply to the factors and responses are shown in table 8.

Table 8 constraints values for the optimization.

Name	Goal	Lower Limit	Upper Limit
Plasma arc current	is in range	140	180
Welding Speed	is in range	140	180
Gas flow rate	is in range	2.5	5.5
Hardness	Minimize	217.67	277.33
Tensile Strength	is target = 540	421.484	572.379

we have found total 80 solutions for our constraints table. Below table 9 represents the result having highest desirability. Based on above parameter get ultimate tensile strength which is higher than base metal with lower hardness.

Table 9 Optimisation solutions

Plasma arc current (A)	Welding speed (mm/min)	Gas flow rate (l/min)	UTS (MPa)	Hardness (HV)	desirability
179.152	140	2.5	539.99	248.626	0.694

VI. Conclusions

The present study develops a procedure for powder plasma arc welding on SS304L plate by using SS316L powder consumable and ensure feasibility of welding with good quality by optimising process parameter and study mechanical and metallurgical properties of welds. In this procedure Filler consumable used in powder form instead of wire and get the required result using double v groove joint in two passes. In the present study develops optimization using response surface method. It is found that three input parameters and some of their interactions have a significant effect on responses considered in the present study. Finally, an attempt has been made to assess the optimum welding parameter to produce the best possible weld quality within the experimental constraints.

• Sound joining of 10mm thick SS304L could be accomplished by plasma arc welding with SS316L powder as filler metal. Due to particular powder plasma arc welding process, welding defects such spatter, distortion, crack, gas holes or porosity completely eliminated.
• Radiography test show that at lower level current with higher level welding speed lack of fusion is observed, where at higher level current and lower level welding speed sound weld quality without any inter defect is observed.
• The quadratic model developed using RSM were reasonably perfect and can be used for prediction within the limit of factors investigated. Where Plasma arc current (A), Welding speed (B) and plasma gas flow rate (C) is input parameter and Tensile strength and hardness is consider as response value.
• The ANOVA revealed that the A, B, C, AC, A^2 are the most significant factors influencing the tensile strength examined. It has been found that as plasma arc current increase tensile strength is increased while another parameter is kept constant.
• As welding speed is increase tensile strength is reduced while other parameter is kept constant due to insufficient heat input. Were as slight influence is observed while increasing plasma gas flow rate from 2.5l/min to 5.5l/min and other parameters keep constant.
• The ANOVA relive that combine effect of plasma arc current and gas flowrate (AC) has significant effect on strength. At low plasma current e.g. 140A, interpretation of gas flow rate from low level to high level is observed negligible and it increase slightly with current and at higher welding current e.g. 180A, Interpretation of gas flow rate from low level to higher level is observed grater. Which indicate at higher current interpretation of gas flow rate is higher in tensile strength.
• Maximum tensile strength of 572.39MPa is obtain at plasma current 180A, welding speed 140 mm/min and gas flow rate 5.5 l/min. which is higher than base metal strength
• The ANOVA revealed that the case A, B, B2, C2 are the most significant factors influencing the hardness values examined. As plasma arc current increased form lower level to higher level, hardness value at weld zone is observed continues increase. The reason is metallurgical changes observed at fusion zone as change of heat input. In microstructure examination dendritic structed observed at fusion zone, as current is increase dendritic structure become more finer which gain result in increased hardness at fusion zone.
• As welding speed increase hardness value at weld zone is increase first and then slightly reduce while other parameters kept constant. Where slight interaction is observed in plasma gas flow rate.
• The optimal condition of input variables is at 179 Amp of welding current, 140 mm/min of welding speed and 2.5 l/min of gas flow rate to get the required value of each response.
• In the present study, plasma arc current, welding speed and plasma gas flow rate are taken into account as input parameters. The other input parameter such as torch stand-off distance, changes of plasma gas, heat input can be investigated on same as well as other metal.

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