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Study of Effect of Metal Arc Welding Parameters on Welding Quality by Taguchis's Orthogonal Array Technique

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Abstract -- Welding is one of the most important operations widely used in fabrication industries for producing fabricated structures of wider range and utilities. Often welded structures process complex geometrical shape with varying capabilities. Stainless steel structures are widely used in chemical industries as well as in making medical and domestic appliances, because of its wide applications and utility, it became inevitable to study depth of penetration, grain microstructure and ultimate tensile strength of weld joint which in turn is influenced by parameters like current, voltage, and Gas flow rate. The life span of the welded structure and its quality is decided by all of the above mentioned parameters. This study proposes to analysis the quality of the weld by parametric optimization through identification of the most significant parameter, which influences depth of penetration, ultimate tensile strength and microstructure of the weld, and also is to determine optimum range for selected controllable parameters mentioned above. The parametric optimization for best response is envisaged by Taguchi's Orthogonal Array which is being one of the most widely used statistical tools used by researchers. The experimental results showed that, current and voltages are most significant factors for depth of penetration (DOP) and ultimate tensile strength (UTS). The experimental values are verified with the confirmation test.

Index Terms: Depth of penetration (DOP), Tensile strength of weld joint, Ultimate tensile strength (UTS), Taguchi's Orthogonal Array, Gas metal arc wielding (GMAW).

I. INTRODUCTION

Welding is a process of permanent joining of two materials (usually metals) through localized coalescence resulting from a suitable combination of temperature, pressure and metallurgical conditions. Depending upon the combination of temperature and pressure from a high temperature with no pressure to a high pressure with low temperature, a wide range of welding processes has been developed. Welding is used as a fabrication process in every industry large or small. It is a principle means of fabricating and repairing metal products. The process is efficient, economical and dependable as a means of joining metals. This is the only process which has been tried in the space. The process finds its applications in air, underwater and in space. Gas Metal Arc Welding is a metal joining process in which the ends of pieces to be joined are heated at their interface by producing coalescence with one or more gas flames (such as oxygen and acetylene), with or without the use of a filler metal. A constant voltage, direct current power source is most commonly used with gas metal arc welding (GMAW), but constant current systems, as well as alternating current, can be used. GMAW originally developed for welding aluminum and other non-ferrous materials in the 1940s; GMAW was soon applied to steels because it allowed for lower welding time compared to other welding processes. The cost of inert gas limited its use in steels until several years later, when the use of semi-inert gases such as carbon dioxide and argon became common. Today, GMAW is the most common industrial welding process, preferred for its versatility, speed and the relative ease of adapting the process to robotic automation. The automobile industry in particular uses GMAW welding almost exclusively. Hence the use of semi-inert gases such as carbon dioxide became common [3]. Two of the most prevalent quality problems in GMAW are dross and porosity. If not controlled, they can lead to weaker, less ductile welds. Dross is an especially common problem in aluminum GMAW welds, normally coming from particles of aluminum oxide or aluminum nitride present in the electrode or base materials. Electrodes and work pieces must be brushed with a wire brush or chemically treated to remove oxides on the surface. Any oxygen in contact with the weld pool, whether from the atmosphere or the shielding gas, causes dross. As a result, sufficient flow of inert shielding gases is necessary, and welding in volatile air should be avoided. Erdal Karadeniz et al. studied the effect of parameters on penetration in gas metal welding by considering welding current, voltage and welding speed as parameters on Erdemir 6842 stainless steel of 2.5 mm thickness. The author conducted 27 experiments considering depth of penetration as response. Authors found that the depth of penetration increased with increase in the welding current and voltage. [1] D.S. Nagesh & G.L. Datta predicted the bead geometry and penetration of the weld meant characteristics in a shielded metal arc welding using artificial neural networking. The authors investigated that the weldment characteristic which includes thermal crack, bead geometry under cutting, penetration and heat affected zone are the profiles and important criteria in determining weldability of metal. The authors have seen arc length, nature of electrode, metal deposition, arc travel rate and polarity arc determine the hardness and load bearing capacity of the joint. [2] P.Sathiya et al. studied the effect of shielding gases on the microstructure & mechanical properties of super austenitic stainless steel by CO2 laser - GMAW hybrid welding. The X –ray diffraction was performed to analyze the phase composition and the microstructure characterization was performed by phase microscopy at the joints. The fracture surface morphology analyzed using SEM. From the study, it has found that the joints by laser- GMAW hybrid had higher tensile and impact strength than the base metal. [3] P.K. Ghosh et al. studied the effect of variation in arc characteristics, stability in shielding of arc environment and behavior of metal transfer with change in pulse parameters using a high speed video photography during pulsed current metal arc (P-GMA) weld deposition using austenitic stainless steel filler wire. The effect of pulsed parameters by considering their hypothetically proposed dimensionless factors mean current, arc voltage and correlation between welding parameters and characteristics have been established. The arc characteristics studied by its root diameter, projection diameter, length and stiffness measured in terms of arc pressure and behavior of metal transfer noted by droplet diameter and velocity of droplet at the time of detachment have been found to vary significantly with the variation in arc characteristics. [4] M.A. Wahab et al. created a new understanding and improved computer understanding to calculate the thermal cycle in the near weld region during gas metal arc welding. The authors have predicted the mathematical model of 2 D & 3 D with finite element models of the weld meant using heat transfer equation. A mechanical weld pool ejection rig developed. This study provided a quick and ready means of defining full 3D weld pool shape. [5] A.K. Laxminarayan et al. studied the effect of welding process such as shield metal arc welding, gas metal arc welding and gas tungsten arc welding on tensile and impact properties of stainless steel conforming to AISI 409 M grade. The authors have found that gas tungsten arc welded joints of ferric stainless steels have superior tensile and impact properties compared with shielded metal arc and gas metal arc welded joints which is found to be mainly due to the presence of finer grains in fusion zone and heat affected zone. [6] Joseph I. Achebo investigated the inadequacies of GMAW process parameters such as welding current, welding time, welding voltage and welding speed using Taguchi‘s Orthogonal array. Here mild steel electrodes were used to make deposits using GMAW machine. Based on Orthogonal array, 18 experiments were conducted, each consisting of five different weld deposits and are subjected to UTS. The use of Taguchi‘s method has improved 2.32 dB of the S/N ratio and 1.1 times UTS of the existing process parameters. [7]

M. Aghakhani et al. studied the effect of GMAW parameters on weld dilution, which affect the quality and productivity of weldment. Using Taguchi‘s method a mathematical model has been developed considering wire feed rate, welding voltage, nozzle to plate distance, welding speed and gas flow rate on weld dilution. Results from the research shown that, wire feed rate, arc voltage have increasing affect while nozzle to plate distance and welding speed have decreasing affect on the dilution, whereas gas flow rate alone has almost no effect on the dilution. Stainless steel structures are widely used in chemical industries as well as in making medical and domestic appliances, because of its wide applications and utility [8], it became inevitable to study depth of penetration, grain microstructure and ultimate tensile strength of weld joint. The life span of the welded structure and its quality is decided by all of the above mentioned parameters, many author have not focus on such characteristic.

Hence, this study proposes to analyze the quality of the weld by parametric optimization through identification of the most significant parameters.

II. EXPERIMENTATION

A. Material Properties

The material selected for the study is austenitic stainless steel of grade 304L. It is a lower carbon variant of grade 304 - the steel can be welded without the resulting issue of carbon precipitation (precipitation of chromium carbide as heat is applied during the welding process which depletes the chromium element of the steel thus reducing its anti-corrosion / oxidation effectiveness). The type 304L stainless steel is sought after material for use in severely corrosive conditions. Weld annealing is only necessary in application where stress loads are excessive. The Mechanical and chemical properties of 304L are shown in table 3.1.1 and 3.1.2.

Table 2.1 Mechanical Properties of SS 304L

UNS No	Grade	Proof Stress 0.2%(MPa)	Tensile Strength (MPa)	Elongation A5 (%)	Hardness	
					HB	HRB
S304	304L	170	485	40	201	92

Table 2.2 Three Factors with Three Levels Parameter Selection Table

UNS No	Grade	C	Si	Mn	P	S	Cr	Mo	Ni	N
S304	304L	0.03	0.75	2.00	0.045	0.03	19.00	-	8.00	0.10

B. PREPARATION OF WORK PIECE

Eighteen austenitic stainless steel (grade 304L) sheets of dimension 150×150mm were cut to the size to perform the welding operation of two sheets. The welded sheets were subjected to CO2 laser cutting to the dongle shape, according to the ASME SEC IX / 2007 Standards to perform tensile test. Laser cutting operation is shown in figure 1

Figure1: CO2 Laser cutting operation

C. Selection Of Welding Parameters And Levels

Based on the literature survey various parameters which influencing weld bead geometry and ultimate tensile strength are found, some of the parameters are controllable and uncontrollable. The GMAW machine we used had, wire feed rate, angle of welding, distance between plate and electrode and shielding gas as uncontrollable parameters. So, we have selected welding current, welding voltage and gas flow rate (CO2) as parameters to study, which were controllable. And the responses considered are depth of penetration (DOP) and ultimate tensile strength of weld joint. The experimentation is designed by considering 3 parameters at 3 levels for each parameter as shown in table 2.3

Table 2.3 Three Factors with Three Levels Parameter Selection Table

Parameters/Factor	Levels		
	1	2	3
Voltage(volt)	5	6	7
Current(amps)	30	35	40
Gas Flow Rate (kg/cm²)	4.5	5.0	5.5

D. Experimental Design By Taguchi's Orthogonal Array

1. The No. of parameters= 3
2. The No. of levels = 3
3. Therefore total degree of freedom (DOF) for parameters = 3*(3-1)=6
4. Therefore from Taguchi's method we have

Minimum number of experiment = TOTAL DOF +1 = 6+1 =7 So, the nearest Orthogonal array is L9. Therefore the L9 Taguchi's Orthogonal Array have been selected for experimentation

The table 2.4 shows assigned tables of L9 OA with three parameters with levels.

Table 2.4: Assigned parameter table

Expt. No	Voltage(volt)	Current(amps)	Gas Flow Rate(kg/cm²)
1	5	30	4.5
2	5	35	5
3	5	40	5.5
4	6	30	5
5	6	35	5.5
6	6	40	4.5
7	7	30	5.5
8	7	35	4.5
9	7	40	5

E. Welding Operation

The prepared samples were welded using MIG-MAG/CO2 Welding machine for different parameter combination according to the experimental layout designed. Two sheets of size 150 x 150 mm were placed adjacent to each other and are welded by changing the different values of current, voltage and gas flow rates according to the DOE layout.

The stainless steel wire of 1.6 mm diameter was fed automatically at the feed rate of 190 mm/min at an angle of 400 by maintaining a distance of 0.2 mm between electrode and plate constant. The MIG-MAG/CO2 Welding Machine is shown in figure 3.5.

Fig. 2 MIG-MAG/CO2 Welding Machine

F. Preparation Of Specimen For Metallographic Inspection 4.6.1 Cutting Of Weld Samples By Edm

Electrical discharge machining (EDM), sometimes colloquially also referred to as spark machining, spark eroding, burning, die sinking or wire erosion is a manufacturing process whereby a desired shape is obtained using electrical discharges. Material is removed from the work piece by a series of rapidly recurring current discharges between two electrodes, separated by a dielectric liquid and subject to an electric voltage. One of the electrodes is called the tool – electrode, or simply the tool or electrode, while the other is called the workpiece-electrode or work piece. When the distance between the two electrodes is reduced, the intensity of electric field in the volume between the electrodes becomes greater than the strength of the dielectric which breaks, allowing current to flow between the two electrodes. The parameters selected for EDM cutting is shown in table 2.6.

Table 2.6 Parameters selected for EDM Cutting

Parameters	Average power	Pulse width	Pulse energy	Processing speed	Focus position
EDM Cutting	19.6W	0.1ms	49mJ	0.5-32 mm/s	At the top of the sheet

G. Tensile Test

The welded specimens were subjected to tensile test under Loyd test machine according to the ASME SEC IX / 2007 standard. The test specimen and its size is shown in figure 3.7. The main objective of the tensile test is to determine the parameters combination at which maximum ultimate tensile strength (UTS) of the weld joint is achieved. The test is performed by placing the specimens under a Loyd test machine. The machine is provided with a threaded attachment to connect the specimens. The machine exert a tensile force on the specimen causing it to extend. The force exerted to create each increment of extension is displayed on the machine along with the total extension. For this test the force exerted for every 0.5mm increment of extension will be recorded.

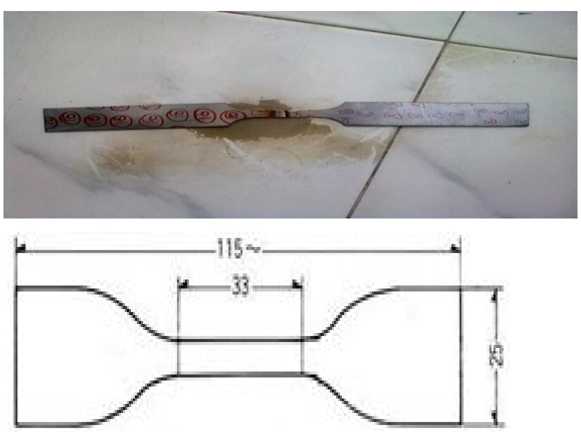

Fig 3 Specimen for Tensile Test According ASME SEC IX / 2007 Standard

H. Procedure To Metallographic Inspection

After the EDM cutting the work pieces are made to gone through Microscopic study and the picture one sample picture is shown in figure 4

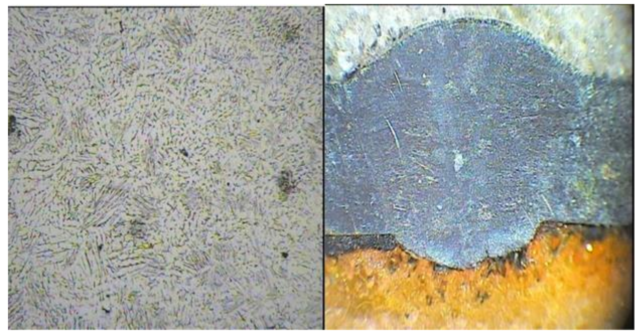

Fig 4. Grain Structure of SS 304l (Etched With Aqua Regia 3:1 Hno3: Hcl) & Weld Picture

III. DATA ANALYSIS

A. Analysis Of Variance (Anova)

The technique for analyzing the effect of categorical factors on a response is to perform Analysis of variance (ANOVA). An ANOVA decomposes the variability in the response variable amongst the different factors. Depending on the type of analysis, it may be important to determine, which factor have significant effect on response and how much of variability in the response variable is attributed to each factor [9-10].

In this study ANOVA is performed to determine the most significant factor on the responses and optimum parameter combination and their level, where we can get the good response. The response measured from the experiments is shown in table 3.1. The ANOVA is performed for both depth of penetration (DOP) and Ultimate tensile strength (UTS).

Table 3.1 Measured responses

Expt. No.	Voltage	Current	Gas Flow Rate	Responses	
	volts	amps	Kg/cm^2	DOP mm	U.T.S N/mm^2
1	5	30	4.5	1.8	465

2	5	35	5.0	2.16	560.4
3	5	40	5.5	2.335	382.943
4	6	30	5.0	1.66	568.737
5	6	35	5.5	2.381	552.863
6	6	40	4.5	2.5	485.423
7	7	30	5.5	2.446	506.193
8	7	35	4.5	2.379	620.713
9	7	40	5.0	2.612	469.197

B. Anova For Depth Of Penetration (Dop)

The table 3.2 shows the response table of ANOVA for depth of penetration. From the table, the current has 51 % of influence on depth of penetration followed by voltage of 30 % and gas flow rate of 11 %. The gas flow rate has minimum effect on the depth of penetration for GMAW. Current and voltage are the most significant factor for the depth of penetration [9]. The suitable gas metal arc welding parameter combination for ANOVA is found from the main effect plot shown in figure 3.2. The parameter combination for GMAW for austenite stainless steel 304 L grade for DOP by considering lower the better is gas flow rate at level 2, current at level 1 and voltage at level 1 is found from main effect plot. i.e. parameter combination gas flow rate (GFR) at 4.5 kg/cm3 , current at 30 amps and voltage at 5 volts. Thus the depth of penetration is higher at GFR 4.5 kg/cm3, current at 30 amps and voltage at 5 volts.

Table 3.2 response of ANOVA for DOP

Factors	D.O.F	Sum of Squares	Mean. Square	F calculated	F tabulated	P%
Voltage	2	0.2408329	0.1204164	4.017085231	5.46	30.042069
Current	2	0.4089562	0.2044781	6.821377296	5.46	51.014174
Gas Flow Rate	2	0.0919109	0.0459554	1.533070819	5.46	11.465183
(ERROR)	3	0.0899282	0.0299761	1		7.4785739
TOTAL	6	0.7417		13.37153335		100

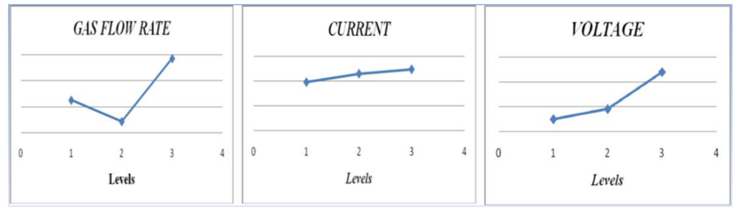

Fig. 4 Main effect plot for ANOVA

An equation (eqn 4.2) is derived for prediction of optimum parameter combination for gas metal arc welding for austenite stainless steel of 304 L grade from text Book Quality Engg Using Robust Design Madhav S Phadke Page. No 59 eqn 3.12[10]

$$R_{a(opt)} = \text{Mean} + (\text{Sum of all square factors}(v) - \text{Mean}) + (\text{Sum of all square factors}(I) - \text{Mean}) + (\text{Sum of all square factors}(G) - \text{Mean})$$

C. Anova For Ultimate Tensile Stress

The table 4.3 shows the response table of ANOVA for ultimate tensile strength. From the table, the current has 65 % of influence on depth of penetration followed by voltage of 20% and gas flow rate of 11 %. The gas flow rate has minimum effect on the Ultimate Tensile Strength for GMAW. Current and voltage are the most significant factor for the Ultimate Tensile Strength. [9-10]

Table 3.3 response of ANOVA for UTS

Factors	D.O.F	Sum of Squares	Mean. Square	F calculated	F tabulated	P%
Voltage	2	8316.311822	4158.156	9.42162556		20.76787
Current	2	26194.39104	13097.2	29.6758647		65.4138
Gas Flow Rate	2	4650.747578	2325.374	5.26887437		11.61405
(ERROR)	3	1324.024995	441.3417	1		2.204276
TOTAL	6	39161.45044		45.3663646		100

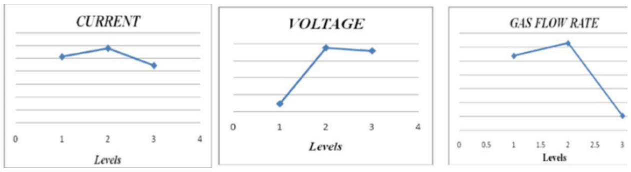

Fig.5 Main effect plot of ANOVA for UTS

The suitable gas metal arc welding parameter combination for ANOVA is found from the main effect plot shown in figure 4.3. The parameter combination for GMAW for austenite stainless steel 304 L grade for UTS by considering higher the better response is gas flow rate at level 2, current at level 1 and voltage at level 1 is found from main effect plot. i.e. parameter combination gas flow rate (GFR) at 4.5 kg/cm3 , current at 30 amps and voltage at 5 volts. Thus the depth of penetration is higher at GFR 4.5 kg/cm3, current at 30 amps and voltage at 5 volts. An equation (eqn 4.3) is derived for prediction of optimum parameter combination for gas metal arc welding for austenite stainless steel of 304 L grade.

$$U.T.S_{(opt)} = \text{Mean} + (\text{Sum of all square factors}(v) - \text{Mean}) + (\text{Sum of all square factors}(I) - \text{Mean}) + (\text{Sum of all square factors}(G) - \text{Mean})$$

IV. CONFIRMATION TEST

From the results of ANOVA we found the optimum combination of parameters for both the responses. With the set of optimum parameters another set of experiments were performed to verify the results. So, the predicted and experimental values both DOP and UTS are shown in table 4.4

Responses	Optimum Conditions of parameters			Predicted values	Experimental values
	Voltage	Current	Gas Flow Rate		
DOP mm	6	30	5	1.778	1.59
UTS N/mm2	6	35	5	481.74	635.145

V. CONCLUSION

The study of effect of gas metal arc welding (GMAW) parameters on austenitic stainless steel of grade 304L was successfully under taken based on Taguchi's orthogonal array. The parameters considered for the study were welding current, welding voltage and gas flow rate and depth of penetration (DOP) and ultimate tensile strength as response parameters. Based on the experimental results the following conclusions are arrived at.

1. The ANOVA showed that current is the most significant parameter on both DOP and UTS followed by voltage.

2. From the ANOVA voltage has 30 % of influence on DOP and 20.76 % on UTS.

3. Gas flow rate has shown very minimal influence on the DOP and UTS.

4. The metallographic and grain structures shown in Appendix reveal that, good fusion between stainless steel filler metal and austenite stainless steel 304 L grade base metal.

5. Finally it is conclude that Lower Current and Voltage value will provide High Ultimate tensile strength.

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