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Parametric Optimization of Submerged Arc Welding using Taguchi Method on P91 Steel

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Abstract: **Welding is one of the fabrication processes use to join metals permanently. Submerged arc welding (SAW) is one of the fusion welding process in which continuously fed consumable wire electrode is used for welding purpose. Selection of welding parameter plays an important role on weld quality. The main aim of our work in this paper is to investigate the influence of welding parameters like feed rate of wire electrode, welding speed and stick out distance on the weld bead of modified 9Cr-1Mo steels (P91). In this study parameters are optimized by Taguchi L9 orthogonal array (OA) experimental design and other statistical tool Analysis of Variance (ANOVA) techniques. Percentage contributions of individual parameter are validated by using ANOVA technique. The experimental results were analyzed by using statistical software Minitab 17. Further variation in hardness in weld zone and microstructure of welds are investigated.**

Index Terms: **SAW, ANOVA, S/N ratio, P91, Optimization**

I. Introduction

American Welding Society (AWS) defines welding as a permanent joining of metals or non-metals produced by heating the materials to a suitable temperature with or without the application of pressure along with or without the use of filler material. Welding is more economical joining methods as compared to casting and riveting. Welding is used for the fabrication of sheet metal, joining of ferrous and non-ferrous metal, automobile and aircraft industries. It has been preferred owing to its capability to produce joints at low unit production, extremely reliable and works under severe conditions [1]. The characteristic of the weld zone is mainly affected by some important control process parameters such as welding speed, welding current, voltage, stick out distance, electrode wire feed rate. Welding quality like weld bead size or geometry, penetration, and hardness of different zone play an important role in the fabrication industry. Estimation of perfect parameters for sound weld joints is a very complex process. Some researchers have made several attempts to estimate the optimum process parameters for smooth and quality weld. Commonly used are welding are as follow:

Arc welding is a type of welding process which uses an electric arc to generate heat for the joining purpose. It creates an arc between electrode and work metal that electrode may be consumable or non-consumable. Contamination of air particles and elements like oxygen, helium, and nitrogen is considered as the biggest problem in arc welding. Many times this contamination results in poor weld surfaces.

Friction welding involves mechanical deformation of specimens in order to achieve a strong joint. As the process does not require melting, melting-solidification and other heat related defects are eliminated. However, this process is preferred for low melting points metals.

Friction stir welding (FSW) is also called the solid-state welding. It joins the workpiece through mechanical deformation. The process used to join previously reported non-weldable aluminum grades. It can produce joints with approximate 30% to 50% stronger than simple arc welding. However, the process is found much slower than others, limiting its application.

Flash welding (FW) this process is used to produce butt joints through the application of arc welding along with pressure. This is capable to produce weld joint which are equal in strength of base metal. However, this process wastes comparatively much material during the flushing process. Further, it is used for zinc and its alloy, cast iron and lead.

In addition of above described welding commonly used welding process are Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW), Plasma Arc Welding (PAW), Laser Beam Welding (LBW), Electron Beam Welding (EBW), Diffusion Welding (DFW), this study is focused on submerged arc welding.

Submerged arc welding (SAW) is one of the most commonly used welding methods in these decades. SAW is a semiautomatic welding process firstly used in the 1930s to make good quality welds. The SAW process turned out as the best welding process, especially because of high rate of deposition, high depth of penetration and neat quality of weld [2]. Thus, it is applied in pipe making, ship building, structures (beams, girders etc.), pressure vessels, nuclear and power plants etc [2].

Weld quality has been considered an important parameter in its applications. According to experts welding quality including strength, appearance, durability and reliability are strongly characterized by process parameters [3]. Vinodh & Bharathi [4], pointed out that various welding process parameters like amperage setting, arc voltage, feed rate of consumable wire electrode, speed of welding, weld angle and the electrode standoff distance affect weld quality to a great extent. Process parameters play an important role in determining the mechanical properties of the welded specimen [6]. So, the selection of proper parameters is an

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important task for sound and qualitative weld joint. Therefore, the selection of the optimal welding process parameters combination is very essential for obtaining desired qualities in weldments [4]. Many experts have emphasized that by the use of control systems the guesswork can be eliminated in the selection of welding parameters. In order to optimize process parameters the statistical Taguchi design method has been widely used by many researchers [5,6]. For instance, multiple regression methods or techniques are employed to obtain the empirical model for different arc welding processes by Murugan et al. [7]; Ravindra & Pramar [8]. A mathematical programming optimization technique was implemented for optimization of the welding flux composition and it was found accountable for weld metal characteristics as a function of welding flux level [10]. In their study, Hsiao et al. [11] analyzed the optimal process parameters of plasma arc welding by the Taguchi method with Grey relational analysis with input parameters as Torch stand-off, welding current, welding speed, and plasma gas flow rate (Argon). Similarly, Hakan et al. [12], used the Taguchi based Grey relational analysis for parametric optimization of Friction stir welding [12]. Usually, welding parameters for a given welding process are preferred based on experimental outcomes, welder's experience, welding standards and empirical laws [9].

In present study selected parameters are as follows:

a) Input
   i. Wire feed rate;
   ii. Welding speed; and
   iii. Stick out distance based on previous research on SAW;

b) Output
   i. Penetration depth;
   ii. Weld bead width;
   iii. Weld zone hardness.

II. Experimentation

Modified 9Cr-1Mo steels (P91) steel is selected over other materials because of its distinct properties and its application. It is widely used in thermal power plant applications in view of its excellent creep strength, corrosion and oxygen resistance, toughness and reasonable cost. This steel is especially used in steam boilers, pressure vessel, steam popes and so many engineering application. The chemical composition of the specimen used in this study is presented in Table I. This steel pertains to be in the category of ferritic/martensitic steel. It's critical characteristics are its stability at high temperature and creep resistance.

Bead on plate type techniquees of size 100x50x8 mm dimension were prepared for welding by submerged arc welding set up at constant current and voltage. Bead on plate not a butt welding of two different plates, in this welding has been done on the surface of plate without any joint preparation. Many research articles are using this technique because there is no chance of distortion in the welded plate for study purposes. Welding process parameters and their range are selected based on the number of trial runs experiment on 8 mm thickness of P91 steel as given in Table II.

Table I.
Chemical Composition of P91 Steel

Components	Cr	Mo	C	Mn	Si	V	Nb	Fe
Weight %	8.91	0.98	0.09	0.42	0.31	0.21	0.07	rest

Table II.
Process parameters and their levels

Process Parameter	Level 1	Level 2	Level 3
Wire feed rate (mm/min)	150	200	250
Welding speed (mm/min)	60	75	90
Stick out (mm)	20	22	24

The experiments were outlined by L9 orthogonal array, experimental plan for the welding process characteristics with L9 orthogonal array and experimental outcomes for the weld bead geometry using L9 orthogonal array which can be observed in Table III. The experiments were conducted by taking a bead on 100 X 50 X 8 mm P91 steel plates.

After removal of slag the job was allowed to cool, then specimens were cut, polished and etching was done in the direction of the cross section of the weld to weld zone, heat affected zone and base metal regions. After that, the polished samples were etched by a chemical solution containing 1 gm Picric acid with 5 ml HCl and 100 mL Ethanol. To measure the responses, average values of the penetration, reinforcement width and heights were taken using a digital vernier caliper of least count 0.02mm.

Table III.
L9 Orthogonal array design and response output

S.no.	Wire feed rate	Welding speed	Stick out	Penetration(mm)	Bead width(mm)	HAZ(mm)	HV
1	150	60	20	3.6	14.25	1.2	265
2	150	75	22	3.25	14.12	1.1	271
3	150	90	24	3.2	13.52	1.08	255
4	200	60	22	4.9	14.55	1.29	260
5	200	75	24	4.4	14.30	1.21	268
6	200	90	20	4.3	14.13	1.15	252
7	250	60	24	6.5	14.65	1.35	270
8	250	75	20	6.0	14.35	1.22	264
9	250	90	22	6.1	14.20	1.18	265

III. Analysis

In this section analysis of responses are presented, it makes the understanding of relationship between process parameters electrode feed rate, welding speed and electrode stick out distance and output response penetration, weld bead width, hardness of weld zone of submerged arc welding. In order to evaluate optimal process parameters the Taguchi method has been used as a statistical measure. Taguchi provides the minimum set of experiment and signal to noise ratios which are logarithmic functions of desired response that serve as objective functions during optimization of process parameters. The S/N ratio developed by Dr. Taguchi is a benchmark to choose control levels that best suit with noise. The S/N ratio considers mean as well as variability. It is the ratio of the mean (signal) to the standard deviation (noise). The standard S/N ratios usually taken are, nominal-is-best (NB), lower-the-better (LB) and higher-the-better (HB)[13]. In present investigation, the output

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responses are bead width, depth of penetration, heat affected Zone and hardness of weld zone. In this study for penetration, bead width and hardness HB is selected whereas LB is selected for heat affected zone.

Further, a statistical analysis of variance (ANOVA) has been applied to inspect the statistical process parameters. The optimal combination of the characteristics has been determined by ANOVA and S-N analysis.

A. Analysis of Variance (ANOVA)

ANOVA is used to identify the SAW parameters that significantly affect the multiple performance characteristics. ANOVA Table IV (A-D) consists of degrees of freedom, sums of squares, the F-ratios corresponding to the ratios of two mean squares, and the contribution proportions from each of the control factors.

TABLE IV (A).
ANOVA FOR PENETRATION

Welding Parameter	DOF	Sum of square	Mean square	F- ratio	Contributed %
Wire feed rate	2	12.4172	6.20861	1719.31	97.16
Welding speed	2	0.3372	.016861	46.69	2.63
Stick out	2	0.0172	0.00861	2.38	0.13
Error	2	0.0072	0.00361	R-Sq(adj)=99.98%	
Total	8	12.7789	R-Sq= 100 %		

TABLE IV (B).
ANOVA FOR BEAD WIDTH

Welding Parameter	DOF	Sum of square	Mean square	F- ratio	Contributed %
Wire feed rate	2	0.32807	0.16403	8.16	39.73
Welding speed	2	0.42987	0.21493	10.69	52.06
Stick out	2	0.02747	0.01373	0.68	3.32
Error	2	0.04020	0.2010	R-Sq(adj)=80.52%	
Total	8	0.82560	R-Sq=95.13%		

TABLE IV (C).
ANOVA FOR HAZ

Welding Parameter	DOF	Sum of square	Mean square	F- ratio	Contributed %
Wire feed rate	2	0.024422	0.012211	1099.00	41.85
Welding speed	2	0.032822	0.016411	1477.00	56.24
Stick out	2	0.001089	0.000544	49.00	1.86
Error	2	0.000022	0.000011	R-Sq(adj)=99.85%	
Total	8	0.058356	R-Sq=99.96 %		

TABLE IV (D).
ANOVA FOR HARDNESS

Welding Parameter	DOF	Sum of square	Mean square	F- ratio	Contributed %
Wire feed rate	2	104.22	52.11	4.55	27.50
Welding speed	2	118.22	59.11	5.17	31.19
Stick out	2	133.56	66.78	5.83	35.25
Error	2	22.89	11.44	R-Sq(adj)=82.71%	
Total	8	378.89	R-Sq=89.98%		

B. Mathematical Modeling

Multiple linear regression models were developed for penetration, bead width, HAZ (heat affected zone), Vickers hardness (HV) by using Minitab17 software. The responsible variables are penetration, bead width, HAZ and hardness whereas the predictors are wire feed rate, welding speed and stick out distance. The equations of the best suited model for tensile and bending strengths are given below:

- Penetration= -0.21+ 0.02850 Wire feed rate- 0.01556 Welding speed+ 0.0167 Stick out (1)
- Bead width= 15.167+ 0.00437 Wire feed rate- 0.01778 Welding speed- 0.0217 Stick out (2)
- HAZ= 1.181+ 0.001233 Wire feed rate- 0.004778 Welding speed+ 0.00583 Stick out (3)
- HV= 255.2+ 0.0267 Wire feed rate- 0.256 Welding speed+ 1.00 Stick out (4)

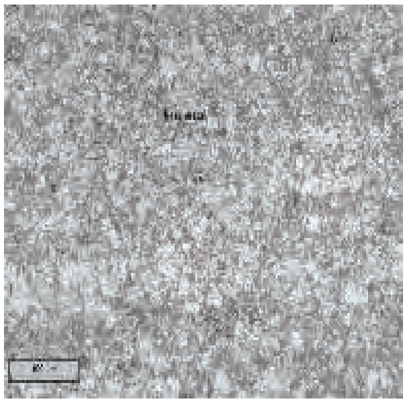
Figure 1(a). Base metal

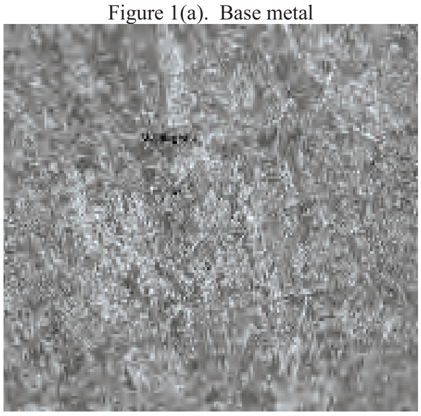
Figure 1 (b). Welding zone

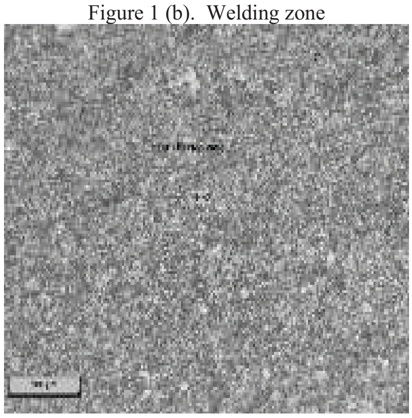
Figure 1(c). HAZ

C. Study of microstructure

The study gives a view of the material characteristics in the grain growth at the weld region, HAZ and in the base metal portion. Observation of microstructure shows a little inclusion near the HAZ region and also differences in grain sizes which are developed during the process of welding.

Figure 1(a) to Figure 1 (c) presents the structure of base metal, weld zone and HAZ.

IV. RESULTS AND DISCUSSION

The analysis is performed by MINITAB 17. The main effect plots for S/N ratio can be seen in Fig. 2 and Fig. 3. Figures indicate the alteration of discrete response with the three criterions i.e. wire feed rate, welding speed and stick out individually. In the plots, the x-axis represents the value of each process criteria at three levels and y-axis the response value. Horizontal line represents the mean value of the response. The main effects plots are applied to obtain the optimal design situations to find out the optimum response surface.

Effect of process parameters on penetration shows that penetration is mainly affected by wire feed rate and it has a contribution of 97.17% from ANOVA analysis presented in table IV(A). It decreases with increase in welding speed and slightly increases with stick out distance.

Contribution of process parameters on bead width, it is mainly affected by welding speed and it has a contribution of 52.07% from ANOVA analysis as shown in table IV(B). Wire feed rate has also a significant effect on bead width.

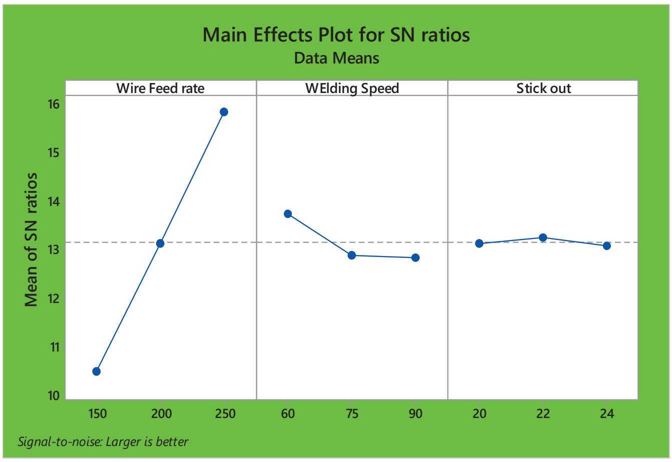

Figure 2. Main effect plot for penetration

Effect of process parameters on HAZ. Both wire feed rate and welding speed have significant effect with a contribution of 41.85% and 56.24% respectively. Stick out distance has a negligible contribution with 1.86% as presented in table IV(C). Effect of process parameters on hardness of weld zone, shows that wire feed rate, welding speed and stick out has significant effect as shown in table IV(D).

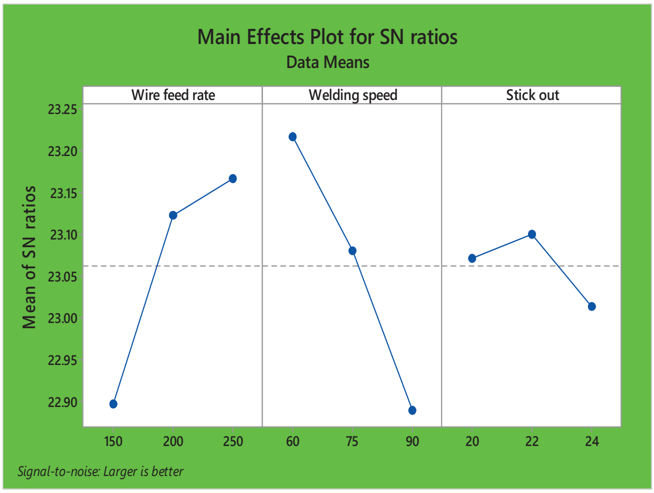

Figure 3. Main effect plot for bead width

Fig. 2 shows the main effect plot for penetration. The plot reveals that penetration increases with wire feed rate. It also shows decrease in penetration with increase in welding speed and stick out distance is non-significant in penetration. Fig. 3 shows the main effect plot for bead width with parameters involved. It shows that response value increases with wire feed rate and decreases with welding speed and slightly increases and then decreases with electrode stick out distance.

Fig. 4 shows the main effect plot for the heat affected zone. From this plot it is clear that HAZ decreases with electrode wire feed rate, increases with welding speed and decreases with stick out distance. Fig. 5 shows that the response first decreases and then increases with wire feed rate, there is an increment and decrement with welding speed. With stick out distance it shows an increment and slightly decreases the hardness of weld zone.

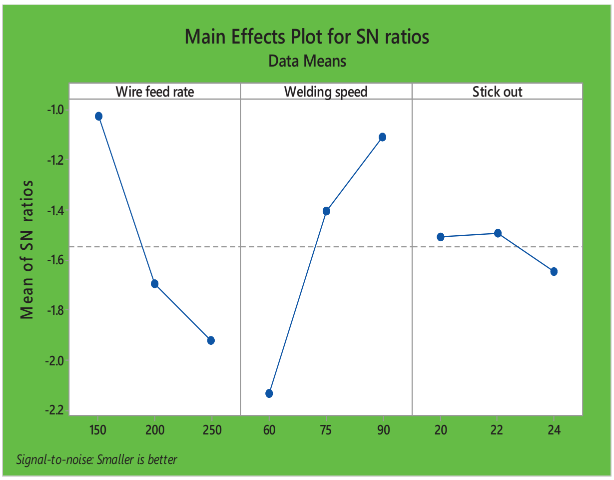

Figure 4. Main effect plot for HAZ

Welding parameters (feed rate, speed, and stick out distance) need to be in perfect combination to obtain sound weld bead. With increase in wire feed rate the deposition should be high, whereas welding speed controls the volume of molten metal (deposition per unit volume). It influences the bead width and penetration significantly and stick out distance maintains the burn-off rate. For perfect output there should be an optimum combination of welding speed and stick out distance.

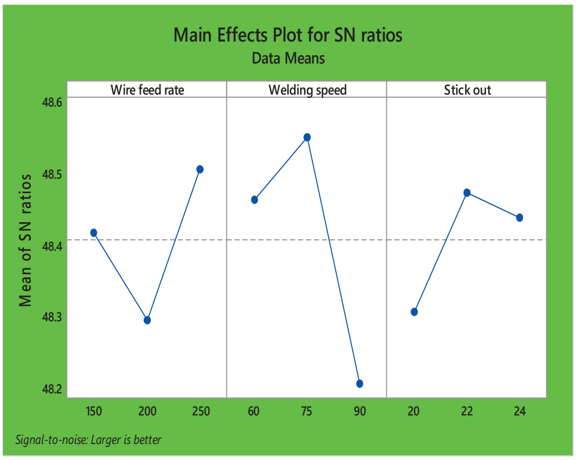

Figure 5. Main effect plot for Hardness

V. Conclusions

Optimal parametric conditions and main effect plot have been obtained for each response separately by Taguchi method. Using, Analysis of variance (ANOVA) it is found that wire feed rate (96.16% contribution) and welding speed (56.24%) have the highest impact on penetration and heat affected zone, respectively. Further the influence of stick out on penetration, bead width and HAZ has been obtained. It is found that stick out has greater influence on hardness (35.25% contribution) on hardness of weld zone

1. Penetration is greatly influenced by wire feed rate and optimal parameters for maximum penetration according to main effect plot are wire feed rate (250 mm/min), welding speed (60 mm/min) and stick out (22 mm).
2. As shown in the main effect plot optimum condition for maximum bead width is wire feed rate (250 mm/min), welding speed (60 mm/min) and stick out (22 mm). Bead width is greatly affected by welding speed.
3. Heat affected zone is a function of wire feed rate and welding speed and optimal condition for LB, parameters are wire feed rate(250 mm/min), welding speed (60 mm/min) and stick out (25 mm).
4. Hardness is a function of wire feed rate, welding speed and stick out distance.
5. Regression equations were developed based on the experimental values of penetration, bead width, HAZ and hardness of weld zone of submerged arc welded joints of P91 steel. The developed models can be used to predict the responses at 95% confidence level.

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