Development of Mathematical Models to Predict Weld Bead Geometry of Butt Welded HSLA Steel Plates in a SAW Process

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Abstract - *High Strength Low Alloy Steel is a widely used material and finds application in structural fabrication, cranes and heavy weight vehicles body. HSLA steel is known for its higher strength to low weight ratio. This paper deals with the mathematical modeling of the weld bead geometry based on the welding parameters of submerged arc welding. Weld bead on plate was analyzed and Face centered central composite design was used to construct response surface model. It was found out that wire feed rate was the strongest influencing parameter for all the responses.*

Key Words: SAW, HSLA, Face centered CCD, Response Surface, Weld bead geometry

1. INTRODUCTION

The mechanical properties of SAW weld bead are determined by the weld bead geometrical parameters namely penetration, width and height. The weldment characteristics not only depends on the welding process but also on the process parameters that determine the quality of the weld [1]. Some work on optimization of SAW weld parameters on Structural Steel IS-2062 using Taguchi analyses has been done by [2].

The Face-Centred Central Composite Design method is an efficient design and ensures more effective prediction of the responses in the design space. Highly informative response surface plots can be obtained with the help of this design, demonstrating input parameter's effects and interactions. The Submerged Arc Welding (SAW) process finds wide industrial application due to its easy applicability, high heat input and ability to deposit a large amount of weld metal using more than one wire at the same time. The high-strength, low-alloy (HSLA) steels hold promise of being economical due to reduced fabrication costs. These steels are typically low carbon-manganese steels with small amounts of alloys added such as titanium, aluminium, niobium, or vanadium. Since these steels exhibit high strength and toughness, they are ideally suited for naval shipbuilding [3]. HSLA steel also find heavy application in automotive industries, building and constructions, storage tanks, etc. With such heavy-duty applications a high heat input welding process is required for quality fabrication. SAW provides high heat input and thus is suitable for HSLA welding applications. HSLA steel is preferred over carbon steel due to its superior weather resistance and low weight for the same volume. HSLA steel is also called micro alloyed steel since it is alloyed by Group 5 & 6 elements like V, Mo,W, Cr etc. which result in smaller grain size and thus better mechanical properties. Some work on modelling of weld bead geometry on HSLA for Plasma arc welding is done by [4] with the help of response surface methodology. [5] Shows the importance of HSLA as an engineering material.

Nowadays automated welding is replacing manual welding. This is a fast change in industries and workshop due to the facts that automated and robotic welding offers more uniformity, precise control of welding parameters, and better quality with a higher production rate. Automatic control of welding requires a strong mathematical model which can feed the input variables to produce the desired output.

Gupta and Parmar [6] created a mathematical model to predict weld bead in SAW using multiple regressions. Although work has been done on SAW and HSLA independently, no major work was found on SAW bead modeling on HSLA JCB STD - 5000/0103 steel. The composition of plate material is shown in Table 1.

2. PLAN OF INVESTIGATION

The research work was planned to be carried out in the following steps:

- Identifying the important process control variables and finding their upper and lower limits
- Development of the design matrix and identifying responses
- Conducting the experiment as per the design matrix
- Recording the responses viz., penetration (P), bead width (W), bead height (H)
- Developing mathematical model, determining the coefficients of the regression model

- Checking the adequacy of the model developed
- Testing the significance of coefficients and arriving at the final models.

2.1 Selection of process parameters

Based on the effect on weld bead geometry, ease of control and capability of being maintained at the desired level, three independently controllable process parameters were identified namely, source voltage (V), wire feed rate (F) and trolley speed (S). Trial runs were conducted by varying one of the process parameters at a time while keeping the rest of them at constant value.

Table -1: Composition of the work piece material

Grade	Carbon %	Silicon %	Manganese %	Sulphur %	Phosphorus %	Aluminium %	Vanadium %
5000/0103	0.24	0.55	1.60	0.045	0.035	0.026	0.042

The working range was fixed by inspecting the bead for a smooth appearance and the absence of visible defects. The selected process parameters and their upper and lower limits together with notations and units are given in Table 2.

Table -2: Upper limits and lower limits of parameters

Variables	Notation	Lower limit	Upper limit
Voltage (Volts)	V	32	38
Trolley speed (cms/min)	S	20	40
Wire feed rate (levels)	F	6 (17.6 mm/s)	8 (19.2 mm/s)

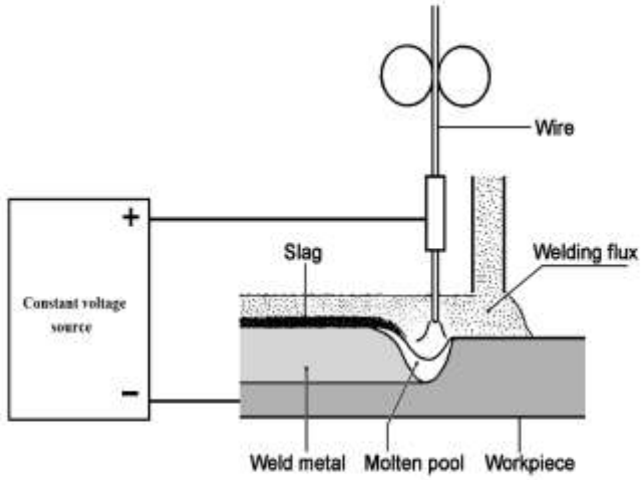

Fig -1: Submerged arc welding process

2.2 Developing the design matrix and selecting the response variables

In the present study, since three factors, each with three levels were selected as controllable variables, a three factor three level face centred central composite design (shown in Table 3) was selected to develop the prediction model in the design space. Penetration, Width and Height of weld were chosen as the response variables.

Face-centred central composite design (Factors – 3, Total runs – 20, single block) specifications are as follows –
Cube points = 8
Centre points in cube = 6
Axial points = 6
Centre points in axial = 0
$\alpha = 1$

2.3 Conducting the experiment as per the design matrix

Samples of HSLA plates (specification mentioned in Table 1.) were prepared having dimensions 150×100×10 mm3 with the help of band-saw machine. All the samples were welded in a single pass on an automatic linear SAW machine with a maximum current capacity of 1400 A. Neutral flux was used for all the experimental runs. Orientation of the welding torch was kept vertical to plates.

Electrode of grade- AWS-SFA 5 23 EG/EF3 having 3.2mm diameter was used. Specimens having dimensions 55*10*10 mm3 were prepared from the welded plate in order to perform polishing and etching operations. Specimens were prepared by using standard metallurgical polishing techniques and etched with 5% Nital solution.

Fig -2: Welded plate specimens

Fig -3: Submerged Arc Welding setup

Table -3: Design matrix and observed responses

Std. Order	Run Order	Voltage (volts)	Trolley Speed (cm/s)	Wire Feed Rate (levels)	Penetration (mm)	Width (mm)	Height (mm)
10	1	38	30	7	3.81	18.42	2.86
6	2	38	20	8	4.64	24.13	4.12
20	3	35	30	7	5.01	18.85	2.64
4	4	38	40	6	3.68	16.73	1.89
19	5	35	30	7	4.00	18.07	2.90
14	6	35	30	8	3.91	20.31	3.57
1	7	32	20	6	3.21	17.95	3.98
2	8	38	20	6	3.06	20.13	3.54
12	9	35	40	7	4.21	12.88	2.53
5	10	32	20	8	5.22	18.40	4.99
3	11	32	40	6	3.03	11.90	2.75
18	12	35	30	7	4.03	17.65	3.11
15	13	35	30	7	3.96	17.61	3.18
8	14	38	40	8	6.24	15.57	3.53
9	15	32	30	7	3.63	17.29	3.50

13	16	35	30	6	2.80	16.33	2.42
7	17	32	40	8	4.50	14.38	3.00
17	18	35	30	7	4.73	18.28	2.64
16	19	35	30	7	4.73	17.09	3.23
11	20	35	20	7	3.29	20.61	4.55

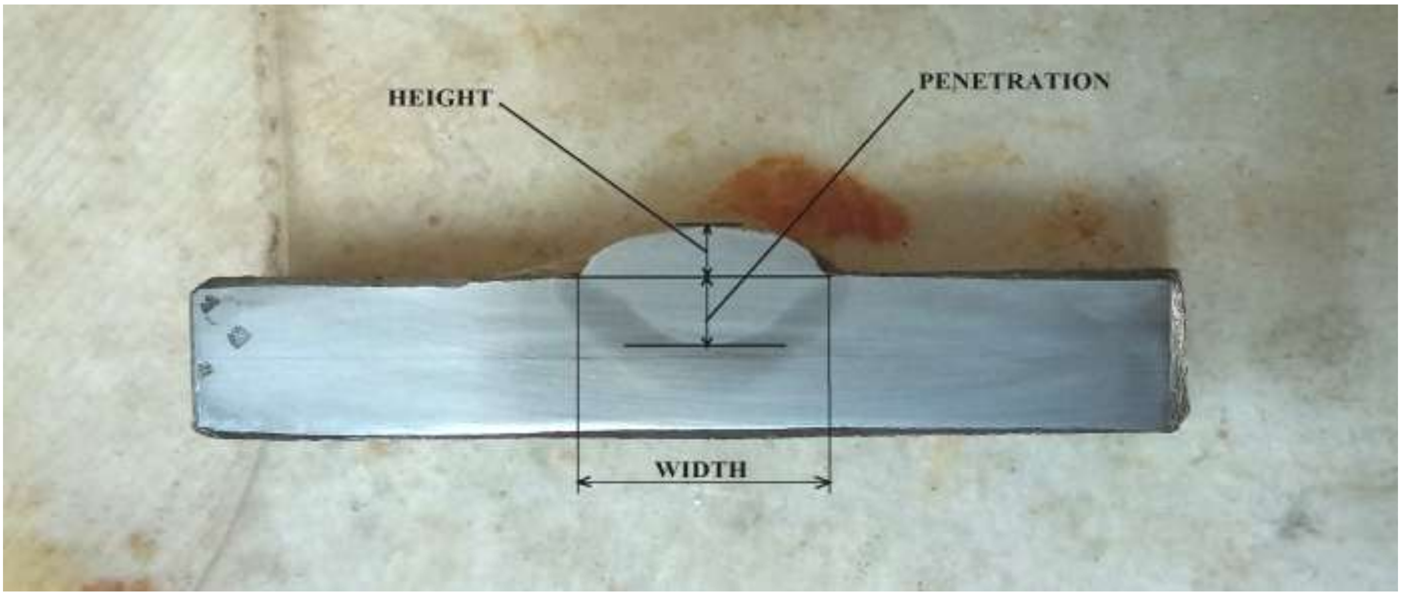

Fig -4: Weld specimen after etching

2.4 Recording the responses

The values of penetration, height and width were recorded after the etching was done. High definition images of etched specimen were taken and imported to image processing software where all the dimensions were accurately measured. The recorded values of penetration, width and height are shown in Table 3.

2.5 Development of mathematical model

Minitab software was used to generate the mathematical model. Regression equations of the responses penetration, width and height were obtained in terms of the input factors viz. Voltage, Wire feed rate and trolley speed. The resulting equations are given below.

Penetration =
19.9 - 1.36 V - 0.553 S + 3.35 F + 0.0119 V2 + 0.00137 S2 - 0.258 F2 + 0.01300 V*S + 0.0275 V*F + 0.0055 S*W

Width =
7.4 + 0.38 V + 0.888 S - 4.9 F + 0.0055 V2 - 0.01060 S2 + 0.515 F2 - 0.0079 V*S - 0.004 V*F - 0.0391 S*F

Height =
34.4 - 1.31 V - 0.524 S + 0.05 F + 0.0118 V2 + 0.00466 S2 - 0.079 F2 + 0.00408 V*S + 0.0400 V*F + 0.0037 S*F

2.6 Checking adequacy of the model developed

2.6.1 Analysis of penetration model

The regression model for the response surface for penetration is significantly good approximation as evident by the S value (standard deviation) which is 0.622. The residual square value (R-sq value) of 71.95% shows that the model explains the actual variations in the result with a good approximation.

2.6.2 Analysis of width model

The S value which shows the standard deviation is 1.2308 which is fairly low indicating that the results are significant. The R-sq value is 89.26% thus the model explains the variation in the results well. The model for weld bead width is a good approximation for the actual process.

2.6.3 Analysis of the height Model

The S value for the response surface model for height is 0.3225 which indicates a very small variation between the actual results and the fitted value. The R-sq value is 90.32% and hence the model very well explains the variation in the results.

3. RESULTS OF DEVELOPED MODEL

3.1 Response surface results for penetration

An ideal fusion welding process is the one where a maximum percentage of supplied energy is utilized in fusing the filler/electrode and base metal, i.e. creating the weld, and minimum energy is wasted in forming the heat affected zone. To achieve a good weld penetration should be high. The results show that the Wire feed rate is the most significant parameter in determining the penetration. This is evident from the p-value of 0.001. The voltage*trolley-speed interaction is also significant with a p-value of 0.107. The important response surface plots are shown in Fig. 5. And Fig. 6.

3.2 Response surface results for width

All factors Voltage, Wire feed rate and trolley speed contribute significantly in the prediction model for width. This is evident by their p-values which are 0.003, 0.0001 and 0.031 respectively. It can be noted that there is no particular interaction between factors that contribute much in determination of the model. The highest contribution among interaction is of trolley speed*wire feed rate which has a p-value of 0.390. The important response surface plots for width are shown in Fig. 7. And Fig. 8.

3.3 Response surface results for height

The height of a weld is a less important response when we consider welding as a fusion joining process since it does not contributes much to strength and in most industrial applications the surface is machined after welding. Though height of weld carries high significance when gap filling capability of a welding process is considered. All factors Voltage, Wire feed rate and trolley speed contribute significantly in the prediction model for height. This is evident by their p-values which are 0.049, 0.0001 and 0.001 respectively. The highest contribution among interaction is of Voltage*trolley speed which has a p-value of 0.308. Response surface plots for weld reinforcement are shown in Fig. 9 and Fig. 10.

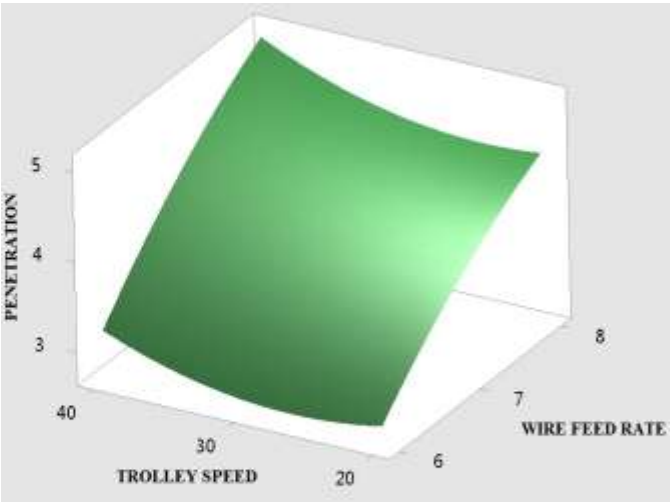

Fig -5: Penetration v/s T.S. v/s W.F.R.

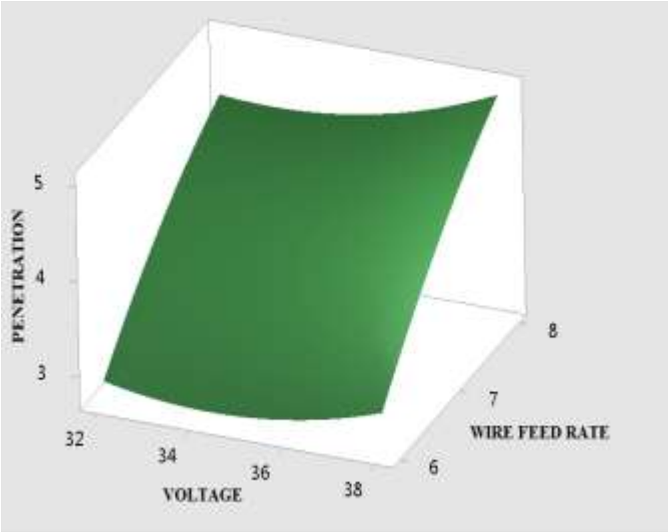

Fig -6: Penetration v/s Voltage v/s W.F.R

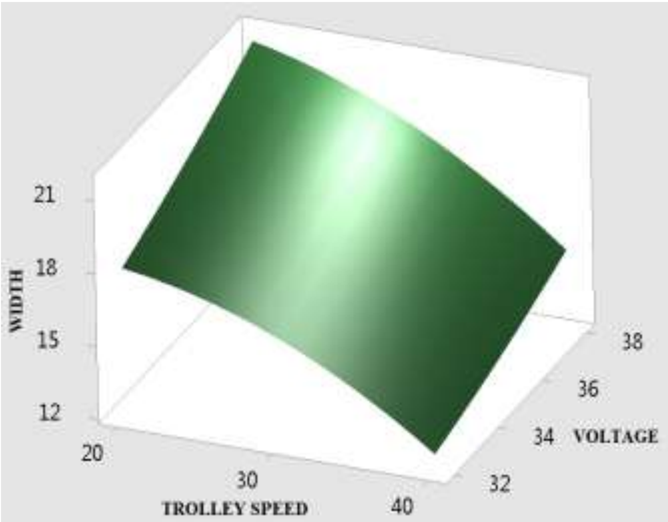

Fig -7: Width v/s T.S. v/s Voltage

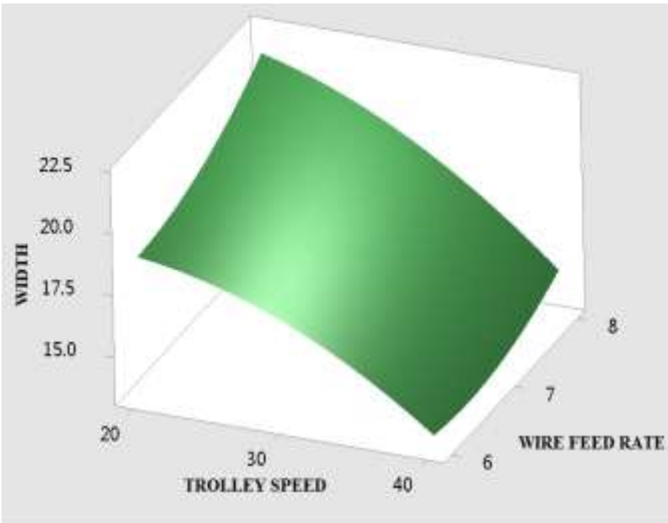

Fig -8: Width v/s T.S. v/s W.F.R.

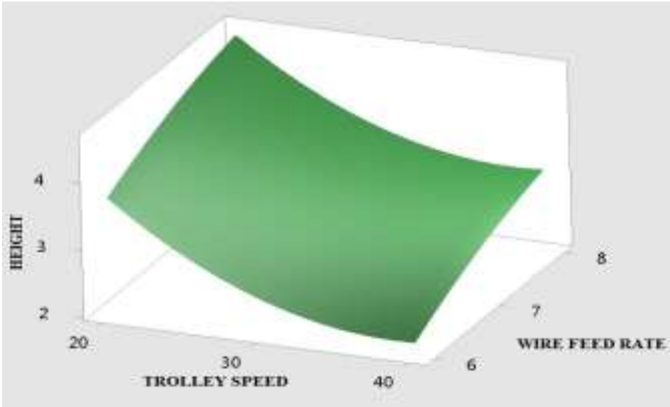

Fig -9: Height v/s T.S. v/s W.F.R

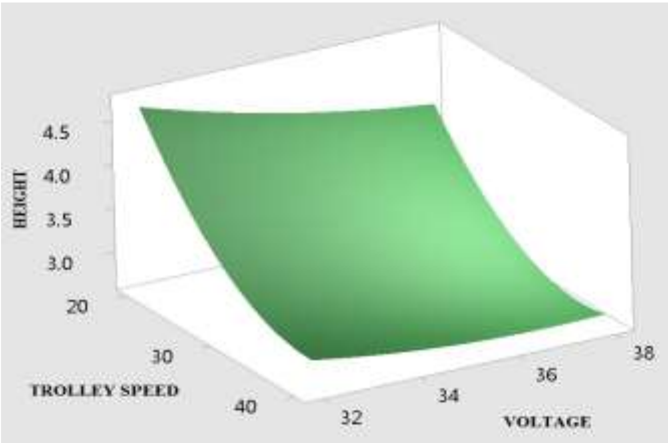

Fig -10: Height v/s T.S. v/s Voltage

4. CONCLUSION

The effects of welding process parameters (voltage, wire feed rate and trolley speed) on weld bead geometry when bead on plate welds are deposited using the SAW process have been studied and quantified using face-cantered CCD. With the help of present study, we can automate and standardize the initial parameter setup process for submerged arc welding of HSLA steel hence resulting in increased productive man hours on the shop floor and reduced manufacturing lead time, eliminating unnecessary reworks and quality control cycles. The time-consuming trial error based method of estimating SAW weld parameters, which was purely based on the expertise of the operator can now be effectively replaced with a meticulously built mathematical model that is able to relate the bead geometry with the weld input parameters. The confirmation experiments were found in close approximation to empirical models with percentage error less than 5 %. The validation results confirmed the capability of empirical models to predict the responses accurately. In the future, these models will be helpful for practitioners to determine input parameters setting for the required optimum weld bead geometry.

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