Factorial Technique—An Approach for Prediction of Bead Geometry & Shape Relationships of Hyperbaric Welding

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Factorial technique is a statistical method used for designing of experiments. This paper contains various techniques generally used in designing the experiments, their merits and limiations. It has included the system of designing of five level Factorial technique with four welding variables to be used for PULSE MIG HYPERBARIC welding. Finally, the application of Factorial design to study the weld bead geometry and shape relationship has been explained.

A. INTRODUCTION

To study the weld bead dimensions and shape relatioships and to develop mathematical models, it is imperative to generate the data by carrying out the experiments to corresponding actual conditions of fabrications. The experiments should provide the required informations within the minimum amount of time and effort. Therefore, to conduct useful experiments, the experimental plan and programme must be well prepared and designed. The design of experiments is the procedure of selecting the number of trials and conditions for running them.

In widely diverse field of research, the effects of experimental treatment vary from trial to trial. It becomes more critical wherein a large number of variables are involved. It is imperative to know the effect of individual variable on the product to control the quality as well as to reduce the cost and labour. Therefore, the the design of experiments with required degree of precision and accuracy is essential for carrying out the research activity.

This paper describes the various techniques of design of experiments, factorial technique and its application to study the weld bead geometry and shape relationships of hyperbaric welding (Dry Underwater Welding).

B. Techniques used for design of experiments

Besides the trial & error method of investigations, the following techyniques are generally employed by the investigator with varying degree of success.

- Theoretical Approach
- Dimensional Analysis
- Classical Method
- Statistical Method

The theoretical approach is based on the predictions on the basis of mathematical models developed by Resenthal. It was first applied for determining the temperature fields for welding an infinite plate, semi-infinite and finite plate. But this technique can not be utilised to predict accurately the weld bead dimensions because of the numerous assumptions made in developing these equations. Thus the theoritical approach has rarely been used alone to predict the weld bead geometry and shape relationships due to the complexities caused by the interactions of different parameters involved, in hyperbaric welding.

In dimensional analysis technique all the parameters are converted to M.L.T., φ system where these symbols refer to fundamental units of mass, length, time and temperature respectively. There relationship so developed can be used even for predicting the weld dimensions beyond the limits of the ranges of the parameters investigated. In this technique, the optimisation of parameters and prediction of interactions between the parameters are not possible as the experiments are done on tiral and error basis within the narrow experimental range.

In classical method of experiments, the effect of each method is studied by varying one factor at a time while the others are held constant. More the number of variables, more the experimentations are required and thus this technique is more time consuming and expensive. Moreover, with this technique, it is not possible to find out the interaction between two or more variables.

The statistical method has a number of advantage over classical method. The most important advantage of this method is that several variables can be simultaneously studied and in addition to optimisation of process, the interaction between two or more factors can be evaluated. In general, the statistical method helps in minimising the cost and time of testing and at the same time increases the chances of success.

There are various techniques available from the statistical theory of experimental design which are well studied to engineering investigations[2,3]. One such important technique is a factorial design.

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C. Factorial Design

Factorial design means that in each complete trial or replication of the experiment, all combinations of the levels of the factors are studied. It involves simultaneously more than one factor each at two or more levels. The treatments consist of all combinations that can be formed from the different factors[4].

This technique provides an opportunity to study not only the individual effects of each factor but also their interactions. When experiments are conducted factor by factor, changing the level of one factor at a time and keeping the other factor at a constant levels, the effect of interaction can not be investigated. Therefore, factorial design is more informative in such investigation. But the success of this design depends on selection of the parameters which can affect the weld dimension.

The experimental plan is to first choose fixed number of levels of each the parameters believed to affect the system under study. If there are P levels and k number of the factors then the full factorial design consists of p^K runs at all possible combinations of the testing conditions.

D. Selection of Design

Under the present investigation, it has been decided to study the welding parameters on weld bead geometry and shape relationship under hyperbaric conditions. The welding bead geometry is well known to be affected by the welding mean current (I_m), nozzle-to-plate distance(L), speed of the welding (S) and pressure of the welding chamber (P_r). It was, therefore, decided to take all these parameters into the account to design the experiments. The experimental design chosen was a thirty point central composite rotatable design. Such an experimental design comprises a full replica of 2^4 factorial design plus 6 centre points and 10 star points. Combinations of the welding parameters at the low level (-1) and high (+1) levels constitute the 16 factorial points. All the welding parameters at the intermediate level (0) constitute the centre points. Combinations of each welding parameters at either its lowest (-2) or highest (+2) level with other three factors of the intermediate levels constitute the star points. The design matrix thus formed is shown in the table I.

E. Selection of Mathematical Model

y represents the weld bead dimensions and shape relationship, the response function can be represented as

$y = f(I_m, L, S, P_r)$

The relation selected was a second degree response surface expressed as follows[5] :

$$y = b_0+b_1x_1+b_2x_2+b_3x_3+b_4x_4+b_{11}x_1^2+b_{22}x_2^2+b_{33}x_3^2+b_{44}x_4^2+ b_{12}x_1x_2+b_{13}x_1x_3+b_{14}x_1x_4+b_{23}x_2x_3+b_{24}x_2x_4+b_{34}x_3x_4 \quad \ldots (1)$$

where I_m, L, S and P_r were represented by x_1, x_2, x_3, and x_4 respectively

TABLE-1
DESIGN MATRIX

Experimental Run	Mean current (I) (Im)	Nozzle to Plate Distance (L)	Speed of the weld (S)	Pressure of the chamber (Pr)
1	+1	+1	+1	+1
2	-1	+1	+1	-1
3	+1	-1	+1	-1
4	-1	-1	+1	+1
5	+1	+1	-1	-1
6	-1	+1	-1	+1
7	+1	-1	-1	+1
8	-1	-1	-1	+1
9	+1	+1	-1	-1
10	-1	+1	+1	+1
11	+1	-1	+1	+1
12	-1	-1	+1	-1
13	+1	+1	-1	+1
14	-1	+1	-1	-1
15	+1	-1	-1	-1
16	-1	-1	-1	+1
17	0	0	0	0
18	0	0	0	0
19	0	0	0	0
20	0	0	0	0
21	0	0	0	0
22	0	0	0	0
23	+2	0	0	0
24	-2	0	0	0
25	0	+2	0	0
26	0	-2	0	0
27	0	0	2	0
28	0	0	-2	0
29	0	0	0	+2
30	0	0	0	-2

Analysing the equation :

$$b_0 = \frac{\lambda_4(c+v-1)\ y^{-2(X12y)}}{N\ [(c+v-1)-v\lambda_2^2]}$$

$$b_i = \frac{\Sigma x_i y}{N\lambda_2} \quad \text{where } i = 1,2,3,4$$

$$b_{ij} = \frac{\Sigma x_i x_j y}{N\lambda_4} \quad \text{where } i = j$$

$$b_{ii} = \frac{\Sigma x_i 2^y}{(c-1)N\lambda_4} - \frac{\lambda_2\lambda_4(c-1)\Sigma y-\Sigma(x_i^2{}_y)(\lambda_2^2-\lambda_4)}{(c-1)N\lambda_4\Delta}$$

Where $= \lambda_4(c+v-1)-v\lambda_2 \quad \ldots\ldots\ldots (2)$

and N = Total nos. of experiment.

$$\lambda 2 = \frac{24}{N}, \qquad c = 3$$

Thus the values of all coefficients are formed out. A computer programme is necessary to be developed to find out the values of the coefficients.

F. Estimation of the Coefficient of the Model

All the coefficients of the models expressed by the equation. (1) were estimated for different responses viz. weld width (W), reinforcement height (H), penetration (P) WPSF (W/p), WRFF (W/H) and dilution (D). Since the method of least square technique has been used, these estimates also possess the property of minimum variance.

G. Checking the Adequacy of the Model

The adequacies of the models are generally done by applying the analysis of variance technique (ANOVA). As per this technique, the F-ratio of the developed model is calculated and compared with the corresponding F-value from the tables at a certain value of confidence.

The F-ratio for the model is the ratio of the variance of adequacy also known as residual variance (S_{ad}^2) to the variance of reproducibility also known as variance of optimisation parameter (S^2_e).

$$\text{Therefore, F-model} = \frac{S^2_{ad}}{S^2_e}$$

$$\text{where } S_{ad}^2 \quad \frac{\Sigma(y-\lambda y)}{n_2 - V\frac{(v+3)}{2}} \quad \text{and } S_e^2 \quad \frac{(yiu-y)^2}{ni-l}$$

where v = no. of factors, n_1 = no. of centre points
y_{iu} = response at the centre points and u = 1 6
y = Estimated response

$$\text{and degree of freedom} = n_2 - \frac{v(v+3)}{2}$$

H. Test for Significant Regression Coefficient

The values of the regression coefficients give an idea as to what extent the control variables affect the responses quantitatively. It is evident that those coefficients which are not significant can be eliminated, along with responses with which they are associated, without sacrifycing much of the accuracy thereby, reducing the mathematical labour. To enable this, the 't' test is used[6]. As per ths test the calculated value of 't' corresponding to a coefficient is compared with the standard tabulated value of specific level of probability, and if the calculated value of 't' exceeds the tabulated one, then with the corresponding confidence probability the coefficient is said to be significant.

For this purpose, the value of t is given by

$$t = \frac{|\lambda \hat{b}_j|}{Sb_I}$$

where $|\hat{b}_i|$ = absolute value of the estimated coefficient whose significance is being tested.

$S(b)$ = $vS(b_i)$standard deviation of coefficient.

$$\text{Now } V(\lambda b_o) = \frac{\lambda 4(C+v-l)}{N\Delta}$$

$$v(b_{ij}) = \frac{\sigma^2}{N\lambda 2}$$

$$v(bii) = \sigma^2 \left[\frac{l}{(c-1)N\lambda_4} \times \left\{ \frac{\lambda_4(c+v-2)-(v-1)^2_2}{\Delta} \right\} \right]$$

where σ^2 = error variance.

I. Application of Factorial Technique for Prediction of Weld Bead Geometry

With the help of aforesaid equation, the mathematical models for hyperbaric welding within the range of 10 to 40 bars based on experimental observations made during pulsed MIG welding of low carbon steel by bead-on-plate-technique have been developed.

In the experiment, it was planned to investigate the effects of welding variables viz mean current, nozzle-to-plate-distance, speed of welding and chamber pressure on weld bead dimension in 6mm thick plate of low carbon structural steel.

J. Development of Mathematical Models

A computer programme was developed to calculate the values of coefficients as mentioned in the euation (1). After calculation of the coefficients the models for Width, Height and WRFF (W/H) have been developed. They are represented as follows :

$W = 6.30-0.25I_m-0.20L-0.42S+0.14P_r-0.22I_m2-0,09L2-0.10S2-0.16P_r+0.04I_mL+0.08I_mS-0.01I_mP_r-0.006LS-0.0.6LP_r-0.16SP_r$

$H = 3.70+0.17I_m+0.27L-0.28S-0.11P_r+0.21I_m^2+0.11L^2+0.04S^2+0.08P_r^2+0.16I_mL+0.05I_mS+0.15I_mP_r+0.06LS+0.11LP_r-0.16SP_r$

$W/H = 1.71-0.12I_m-0.11L+0.004S+0.09P_r-0.13I_m^2-0.06L^2-0.04S^2-0.07P^{-2}-0.01I_mL-0.02I_mS-0.02I_mP_r-0.04LS-0.07LP_r+0.03SP_r$

Non-significant coefficients were eliminated alongwith the response with the help of 't' test thereby reducing the mathematical labour.

The models so developed were utilised to determine the values of response parameters for each givenset of welding variables. Redeveloped final models are represented as follows :

$W = 6.3-0.025I-0.42S-0.22I^2-0.16P_r^2$
$H = 3.7+0.17I+0.27L-0.28S+0.21I^2$
$W/H = 1.71+0.12I-0.11L-0.13I^2$

K. Prediction of Weld Bead Dimensions and Shape Relationships :

These final models were used to produce predictive data which are represented graphically. These are shown in figs. 1 to 4. These show the general trands between cause and effect.

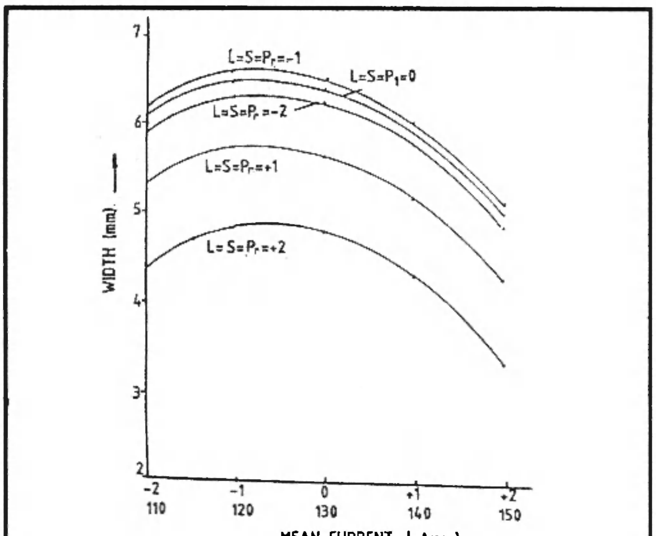

Fig. 1. Effect of Mean Current on width

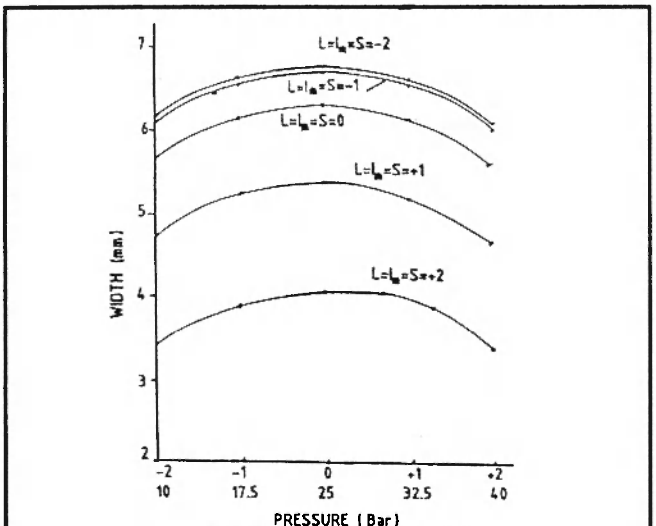

Fig. 2. Effect of Pressure on width

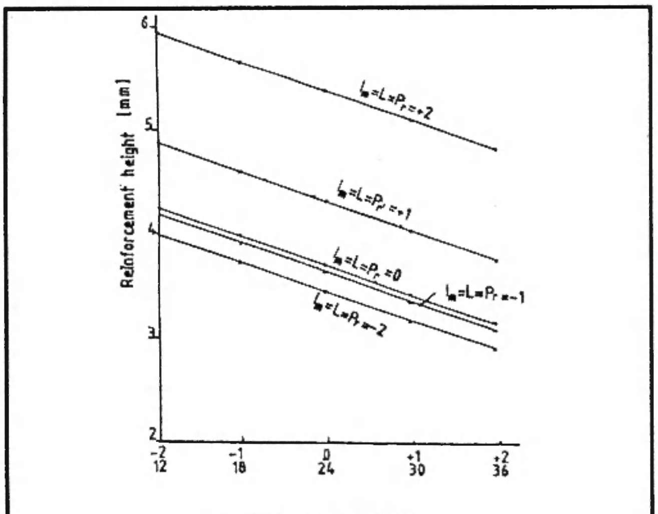

Fig. 3. Effect of welding Speed on Reinforcement height

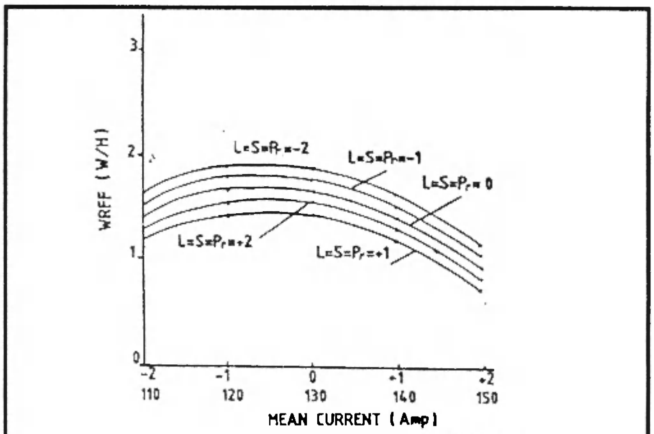

Fig. 4. Effect of Mean Current on WRFF (W/H)

From the graphs it is possible to study and predict the trend. From fig.1, it would be seen that width has increased upto -1 (120 amps) level of current and then it has decreased with increase of current when the other conditions were kept fixed at certain level. In a similar pattern, width of the weld bead has increased upto 0 (25 bar) level of pressure and then it has decreased. From fig. 3, it appears that in all conditions of hyperbaric welding the reinforcement height of bead had remained maximum at the lowest level of speed (-2). From fig. 4, it is evident that WRFF (W/H) has reached maximum at (-1) level of mean current.

CONCLUSIONS

1. Factorial Technique is a useful technique to develop mathematical models of weld bead dimension and shape relationships.
2. With this technique, it is possible to find out the interactions between two or more variables.
3. By using the Factorial technique, the numbers of experiments can be restricted.
4. This technique is less time consuming and less expensive as several variables can be studied at a time.
5. From the experimentation conducted, it is evident that five level factorial technique can be employed to predict the main effects and the interaction effects of different combinations of welding parameters within the ranges of investigation on the weld bead and shape relations for pulsed MIG hyperbaric (Dry Underwater) Welding.

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