Optimising MIG Weld Bead Geometry of Hot Rolled Carbon Steel Using Response Surface Method

Junita Mohd Said and Faiz Mohd Turan

Abstract This paper presents the optimisation of weld bead geometry, through Metal Inert Gas butt-welding. Many failures occur in joints due to the bad quality of welding, influenced by a range of parameters across the welding process. With the rapid advancement of computer and automated technologies, new statistical methods for modelling and optimising have been developed. These have eliminated the need for performing experiments on the basis of conventional trial and error, for performance and quality. Experimental methods were set by selecting process parameters, which include the welding current, arc voltage and welding speed and employing a central composite design of Response Surface Methodology method. These methods were adopted as the statistical design of experimental techniques to analyse the performance of the weld bead geometry, i.e. bead height, bead width and penetration, in order to expound the numerical expression between the welding process parameters and the output variable. The results obtained from developing these models indicate that the model predicts weld bead geometry adequately. The effectiveness of process parameters can be estimated by applying the developed mathematical models to a given bead geometry, indicating the change of parameters influences the bead height and width more significantly than penetration alone.

Keywords Failure · Weld bead geometry · RSM · Optimisation

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1 Introduction

Welding is known as a fabrication process to joining parts. It is a complex process with successful outcomes dependent on a range of input parameters. However, it is very difficult to obtain relationship between welding quality and process parameters due to the high nonlinearity [1]. Fatigue failures in engineering structures occur predominately at component connections especially welding, due to variable stresses in the material. It is become the largest parts of failure on metallic components and leads to a major threat to many structures [2–4]. The result from various discontinuities influence by many factors, hence will affect the quality of welding joint, these characteristics include a lack of penetration at the weld root, undercutting at weld toes, and slag inclusion or gas pores. The rate of energy input will also affect the weldment characteristic, which reduces the welding quality and productivity, whilst increasing the cost of the welding joint [5–8].

Metal Inert Gas (MIG) is one of the arc welding process types and the most widely used in today's world. It became an important, easiest and strongest welding techniques used in manufacturing industries, oil and gas industries, and in building construction [9–11]. During MIG welding process, the transient heat source is supplied between filler metal and parent metal in a localized fusion zone. This heating melts and solidifies the filler metal and parent metal. The process involves critical parameters or criteria, such as welding speed, current, voltage, nozzle-plate distance, torch angle and the electrode diameter [12].

Rapid development in the advancement of computer and technologies in the manufacturing-based optimisation procedure, i.e. Design of Experiments (DoE), optimisation technique has been significantly exploited to represent and optimise the manufacturing processes to enhance performance, quality and lower costs [13]. Numerous weldment characteristic methods have been studied, leading to research in theoretical developments, statistical analysis and numerous experiments by various researchers [14–17], with the aim of enhancing productivity, the optimisation of welding parameters must be considered in order to achieve optimal welding quality to predicting weld bead geometry, mechanical properties, and Heat Affected Zones (HAZ) and others [18, 19].

Conventionally, it is time consuming to define suitable weld input parameters when producing a new welded joint product, with required specifications, through trial and error. Fortunately, one of the best-known optimisation techniques of experimental design is the Response Surface Methods (RSM) technique, which aids analysis of experiments with the least experimental effort [20, 21]. RSM is an accepted study method for the collection of mathematical and statistical techniques to facilitate the developing, improving and optimisation of this process. The response of interest is influenced by several variables and the objective is to optimise the variables [22]. At the same time, it is also possible to estimate linear, interaction and quadratic effects of the factors and to develop a prediction model for the response. With these vigorous methods, it is possible to not only cover prediction of the system responses, but also to assist in conducting the analysis of experiments in order to define the optimum quality process of parameter settings with minimised experimental effort [23].

Based on the above overview, the effects of welding parameters through experimental investigations have been discussed in this article, focusing on a weld bead of 3 mm thick hot rolled carbon steel plates JIS G3131. According to the relevant scope of work, the experiments were performed based on the Central Composite Design (CCD) matrix that led to the main objective of this study, i.e. to optimise the process parameters by maximising the aspect ratio of the weld bead under the premise of acceptable weld bead dimensions. Therefore, the limits of welding parameters will also be obtained. RSM was then used to develop mathematical models to predict the relationship between the processing parameters and the weld bead profile. Based on regression models, the optimal welding conditions can be identified, providing valuable guidance for production.

2 Methodology

The welding experimental procedure was designed based on RSM as the statistical DoE technique. The overall experimental methodology process flow of the research work is planned to be carried out as shown in Fig. 1. It was chosen as an effective way to model a quadratic relationship and would reveal good results for identifying the optimal welding conditions. RSM has widely been used to predict the weld-bead properties and to find the optimum responses of interest in many welding processes [24–26].

The ultimate objective of the RSM method is to establish the optimal operating conditions of experimental requirement. For the analysis, the relevant statistical-based software was then used to create the design matrix and analyse the experimental data.

2.1 Process Selection for RSM Procedure

All the regression model building methods and tools are significant to ensure the adequacy of the model, and therefore it is appropriate in RSM [27]. In order to define limitations of the selected process input welding parameter, three-factor and three levels (33) independent variables of the welding process parameter were identified and evaluated in random design. A pilot experimental test setting, based on the welding standards recommended by the American Welding Society (AWS), and the manuals for MIG welding equipment were consulted. In MIG welding, the variable parameter affecting the weldment quality are welding current (C), welding speed (S) and welding voltage (V) and were run according to CCD. The values of the independent process variable and experimental design levels, with their limits and notations are given in Table 1.

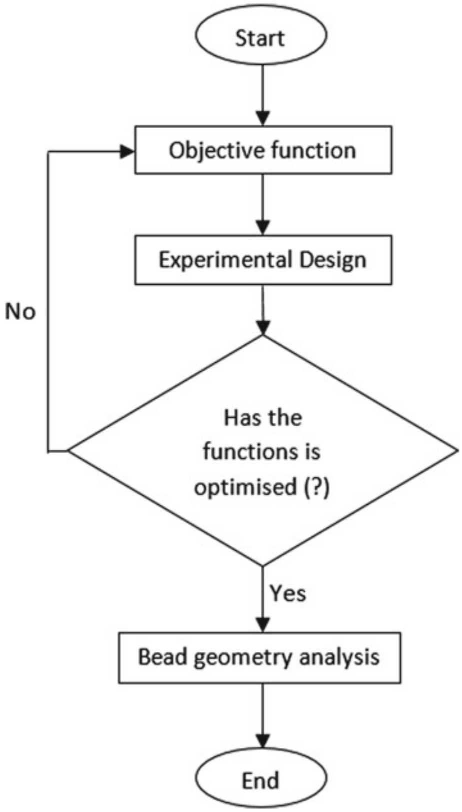

Fig. 1 The experimental process flow for the research

Table 1 Independent process variables and experimental design levels

Variable	Code			
	Unit	Low	Medium	High
		−1	0	+1
Welding current (C)	Amps	100	110	120
Welding speed (S)	Cm min^{-1}	20	25	30
Arc voltage (V)	Volts	17	18	19

The experimental measured responses are defined as heat input and weld bead geometry, contained weld width, penetration, and weld height. Figure 2 illustrates the criterion of weld bead geometry which normally occurs during the welding process. The welding quality criteria was defined and set as a goal to establish the optimal setting of welding parameters.

The aim of the experiment is to measure the possible reaction and then to generate a design matrix, as shown in Tables 2 and 3, respectively. The total generated design by software can also be defined by a matrix form as Eqs. 1 and 2.

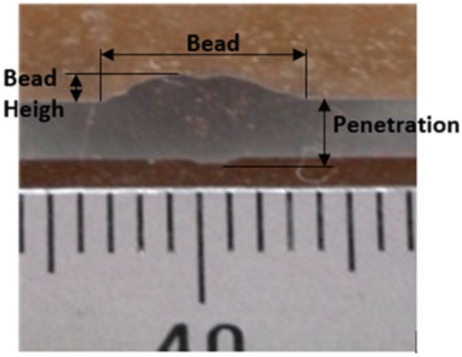

Fig. 2 Experimental weld bead geometry and illustration of measured responses

Table 2 Goals of experimental measured responses

Responses	Unit	Goal
Heat input (HI)	J/mm	Minimum
Weld penetration (WP)	mm	Minimum
Weld width (WW)	mm	Minimum
Weld height (WH)	mm	Minimum

$$y = X\beta + \varepsilon \tag{1}$$

$$y = \begin{bmatrix} y_1 \\ y_2 \\ \cdots \\ y_n \end{bmatrix}, \quad X = \begin{bmatrix} 1 & x_{11} & \ldots & x_{1k} \\ 1 & 1 & \ldots & x_{2k} \\ \cdots & \cdots & \cdots & \cdots \\ 1 & & \ldots & x_{nk} \end{bmatrix},$$

$$\beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \cdots \\ \beta_k \end{bmatrix}, \quad \text{and} \quad \varepsilon = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \cdots \\ \varepsilon_n \end{bmatrix} \tag{2}$$

where y is the monitored value of response function, depending upon the levels $x_1, x_2, \ldots, x_k$ of some k quantitative factors of design variable, β is the regression coefficient vector and ε is the noise of error in term of monitoring the response. The quadratic response model consists of all the linear terms, square terms and linear interactions.

Table 3 Design matrix with actual independent process variables

Std	Run	Value		
		C (Amp)	*S* (cm/min)	*V* (volts)
1	16	100	20	17
2	7	120	20	17
3	12	100	30	17
4	10	120	30	17
5	1	100	20	19
6	2	120	20	19
7	3	100	30	19
8	17	120	30	19
9	6	100	25	18
10	19	120	25	18
11	18	110	20	18
12	11	110	30	18
13	9	110	25	17
14	4	110	25	19
15	5	110	25	18
16	14	110	25	18
17	15	110	25	18
18	8	110	25	18
19	13	110	25	18
20	20	110	25	18

2.2 *Materials and Experimental Work*

The material used in this experiment was hot rolled carbon steel plates with the standard serial number of JIS G3131 SPH270C. The inert gas used was carbon dioxide (CO_2) and the electrode wire ER70S-6 was selected based on the properties and characteristic of the base material, weld dimension and existing filler wire inventory. The material composition and filler metal are tabulated in Table 4.

Welding assemblies were prepared by the MIG butt joint welding process of a 3 mm thick sheet and was conducted on the two plates with dimensions of 200 × 80 widths respectively. Basic geometry of the specimens was prepared according to the AWS D1.1 standard [28], as illustrated in Fig. 3. The experimental work was carried out using the MIG robot welding procedure and according to the total 20 conditions of design matrix as tabulated in Table 3. These design matrixes were generated by statistical software in a random order. To minimise any systematic error in the experiment, the welded plates were cleaned in order to make sure all solidified molten drops were removed from the intended test surface. To obtain and record an average value of the measured responses of weld bead geometry, at least two

Table 4 Nominal composition of carbon steel G3131 and filler wire Er70s-6 (weight in %)

Elements	Nominal carbon steel G3131	ER70S-6
C	0.13	0.06–0.15
Si	0.05	0.80–1.15
Mn	0.5	1.40–1.85
P	0.035	0.025 max
S	0.035	0.025 max
Cu	…	0.50
Alt	0.010	…

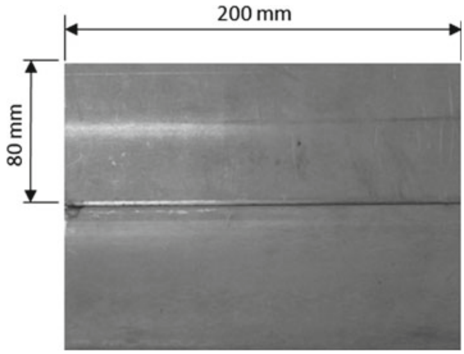

Fig. 3 The geometry of the tested specimen

transverse sections of the specimen were cut from each respective welded specimen, according to AWS D1.1 standard [28].

The specimen was then grinded to remove the cold work, and cut and polished as per standard metallographic procedures to obtain better edge flatness by silicon carbide abrasive paper of grades 100, 240, 400, 800 and 1200 grit, on a rotating polishing wheel machine. The resulting weld bead geometry profile was attained through the measurement process described in Fig. 2, after cutting and polishing according to the welded specimen perpendicular to the direction of welding process.

3 Preliminary Result

The measures responses result of experiments from every test material are tabulated in Table 5. The RSM was used on the experimental data to obtain the impact of the regression models on the individual model, and to determine the mathematical models with best fits. The associated p-value of less than 0.05, (i.e., α is Equal to 0.05 or 95% confident level) indicates that the model terms can be considered as statistically significant. The coefficients and their lack-of-fit through the step wise regression method were used, which Eliminated the irrelevant model term. The indicated variance Value and the significance of each model terms respectively. The

Table 5 The measures responses results of experiments

STD	Responses			
	HI (J/mm)	Weld bead geometry		
		WP (mm)	WW (mm)	WH (mm)
1	5100	3.320	8.820	1.960
2	6120	3.220	9.210	1.750
3	3400	2.930	7.040	1.470
4	4080	3.500	7.810	1.680
5	5700	3.230	8.820	1.960
6	6840	3.730	9.120	1.040
7	3800	2.930	7.560	2.010
8	4560	4.250	8.480	1.220
9	4320	3.280	8.100	1.740
10	5184	4.150	7.570	1.770
11	5940	4.200	9.260	1.910
12	3960	3.420	8.590	2.560
13	4488	3.550	7.500	1.850
14	5016	4.470	8.600	0.820
15	4752	3.460	8.560	1.510
16	4752	3.330	8.230	1.950
17	4752	3.200	8.230	1.660
18	4752	2.750	8.810	2.200
19	4752	3.810	8.050	1.780
20	4752	3.670	7.920	1.750

complete model was checked through the verification coefficient (R^2) where its value was always in a range of 0–1. This value was defined as the indicator to calculate an optimal choice of the responses. The nearer its value is to 1, the more accurate the developed model is [29].

4 Conclusion

The detailed methodology of the RSM optimisation technique for MIG butt welding of hot rolled carbon steel plates JIS G3131 SPH270C was studied and statistically will be analysed. The purpose of this was to evaluate a combination of optimal parameters with acceptance responses of penetration and weld bead of HAZ. This has important criteria for welded joints through reducing the weld metal consumption by providing deeper penetration and lower bead height and width, where the mechanical metallurgical characteristics of the weld joint is influenced by HAZ sizes. This is therefore expected to minimise HAZ width and depth, which is necessary to avoid drastic micro-structure changes between HAZ and the parent metal.

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