Int J Adv Manuf Technol (1998) 14:549–554
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The International Journal of Advanced Manufacturing Technology

Optimisation of the Weld Bead Geometry in Gas Tungsten Arc Welding by the Taguchi Method

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In this paper, determination of the welding process parameters for obtaining an optimal weld bead geometry in gas tungsten arc welding is presented. The Taguchi method is used to formulate the experimental layout, to analyse the effect of each welding process parameter on the weld bead geometry, and to predict the optimal setting for each welding process parameter. Experimental results are presented to explain the proposed approach.

Keywords: Gas tungsten arc welding; Optimisation; Taguchi method; Weld bead geometry

1. Introduction

Gas tungsten arc welding (GTAW) is an extremely important arc welding process that uses a non-consumable tungsten electrode and an inert gas for arc shielding. It is commonly used for welding hard-to-weld metals, such as aluminium, stainless steel, magnesium and titanium [1]. Gas tungsten arc weld quality is strongly characterised by the weld bead geometry. This is because the weld bead geometry plays an important role in determining the mechanical properties of the weld [2,3]. In recent years, statistical experimental design, linear regression modelling, and neural networks have been used to study the effect of welding process parameters on the weld bead geometry [4,5]. It has been shown that the welding process parameters are strongly correlated to the weld bead geometry. Therefore, it is very important to select the welding process parameters for obtaining an optimal weld bead geometry. Usually, the desired welding process parameters are determined based on experience or a handbook. However, it does not ensure that the selected welding process parameters can produce the optimal or near optimal weld bead geometry for that particular welding machine and environment. In this paper, the use of the Taguchi method [6–8] to determine the welding process parameters with the optimal weld bead geometry is reported.

The Taguchi method is a powerful tool for the design of high-quality systems. It provides a simple, efficient, and systematic approach to optimise designs for performance, quality, and cost. The methodology is valuable when process parameters are qualitative and discrete. The parameter design based on the Taguchi method can optimise the quality characteristics through the settings of process parameters and reduce the sensitivity of the system performance to the sources of variation. In recent years, many applications of the Taguchi method have been available in a world-wide range of industries and nationalities [9].

In what follows, the Taguchi method is briefly introduced and the gas tungsten arc welding process is described. The front height, front width, back height, and back width of the weld bead are used to describe the weld bead geometry in this study. The optimisation of the weld bead geometry in the gas tungsten arc welding process is then given. A weighting method is then applied to the Taguchi method to consider the front height, front width, back height, and back width of the weld bead together. The paper concludes with a summary.

2. Description of the Taguchi Method

Taguchi proposed that the engineering optimisation of a process or product should be carried out in a three-step approach, that is, system design, parameter design, and tolerance design [6]. In the system design, the engineer applies scientific and engineering knowledge to produce a basic functional prototype design. This prototype design includes the product design stage and the process design stage. In the product design stage, the selections of materials, components, tentative product parameter values, etc., are involved. As to the process design stage, the analysis of processing squences, the selections of production equipment, tentative process parameter values, etc., are involved. Since the system design is an initial functional design, it may be far from optimum in terms of quality and cost. Following the system design is the parameter design. The objective of the parameter design is to optimise the settings of the process parameter values to improve quality character-

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istics and to identify the product parameter values under the optimal process parameter values. In addition, it is intended that the optimal process parameter values obtained from the parameter design are insensitive to the variation of environmental conditions and other noise factors. Finally, the tolerance design is used to determine and analyse tolerances around the optimal settings recommended by the parameter design. The tolerance design is required if the reduced variation obtained by the parameter design does not meet the required product performance. It involves tightening tolerances on the product parameters or proces parameters whose variations result in a large negative influence on the required product performance. Typically, tightening tolerances means purchasing better grade materials, components, or machinery, thus increasing the cost. Based on the above discussion, the parameter design is the key step in the Taguchi method to achieving high quality without increasing cost. To obtain high welding performance in the gas tungsten arc welding process, the parameter design proposed by the Taguchi method is adopted in this paper.

Experimental design methods [10] were originally developed by Fisher [11]. However, classical experimental design methods are too complex and not easy to use. Furthermore, a large number of experiments have to be carried out when the number of process parameters increases. To solve this problem, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments. The experimental results are then transformed into a signal-to-noise (S/N) ratio. The signal-to-noise ratio can be used to measure the quality characteristics deviating from the desired values. Usually, there are three categories of quality characteristics in the analysis of the signal-to-noise ratio, that is, the lower-the-better, the higher-the-better, and nominal-the-better. Regardless of the category of the quality characteristic, the larger signal-to-noise ratio corresponds to the better quality characteristic. Therefore, the optimal level of the process parameters is the level with the highest signal-to-noise ratio. Furthermore, a statistical analysis of variance (ANOVA) is performed to see which process parameters are statistically significant. The optimal combination of the process parameters can then be predicted, based on the above analysis. Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from the parameter design.

To summarise, the parameter design of the Taguchi method includes the following steps:

1. Identify the quality characteristics and process parameters to be evaluated.
2. Determine the number of levels for the process parameters and possible interactions between the process parameters.
3. Select the appropriate orthogonal array and assign the process parameters to the orthogonal array.
4. Conduct the experiments based on the arrangement of the orthogonal array.
5. Analyse the experimental results using the signal-to-noise ratio and statistical analysis of variance.
6. Select the optimal levels of process parameters.
7. Verify the optimal process parameters through the confirmation experiment.

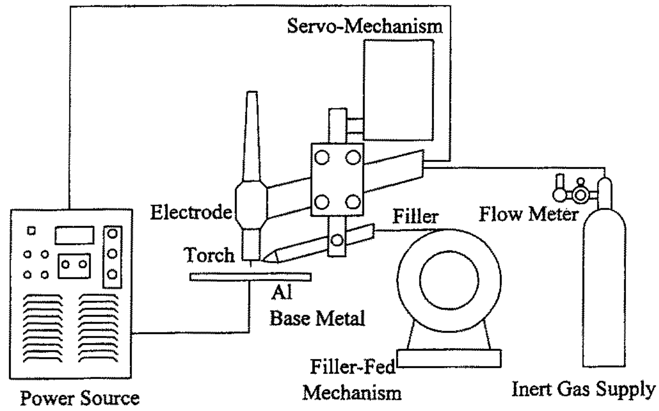

Fig. 1. Experimental set-up for the gas tungsten arc welding process.

3. The Gas Tungsten Arc Welding Process

Figure 1 illustrates the gas tungsten arc welding process with a filler metal. A non-consumable tungsten electrode, shielded by inert gas, is used to strike an electric arc with the base metal. The heat generated by the electric arc is used to melt the base metal and the filler metal. The travelling speed of the torch is controlled by a servo mechanism. In the experiments, the welding power source is provided by a 250 GTSW thermal-arc a.c. welding machine. The shielding gas is argon and the base metal is pure 1100 aluminium plates. A single-pass welding process is performed because the thickness of plates is 1.6 mm. Based on the above discussion, the gas tungsten arc welding process involves a number of welding process parameters such as arc gap, a.c. polarity ratio, welding speed, filler speed, and welding current. The quality of welds is greatly dependent on the selection of the welding process parameters. In the present study, gas tungsten arc welding experiments are carried out by varying the arc gap in the range of 2.4–3.2 mm, the a.c. polarity ratio in the range of 30–70%, the welding speed in the range of 24–46 cm min^{-1}, the filler speed in the range of 1.5–2.5 mm min^{-1}, and the welding current in the range of 80–110 A.

To evaluate the quality of gas tungsten arc welds, measurements of the weld bead geometry are considered (Fig. 2). In this study, the front height, front width, back height, and back width of the weld bead are used to describe the weld bead geometry and are measured by a 3D-Hommelewerk profilometer. Weld penetration at the back face of the base metal must

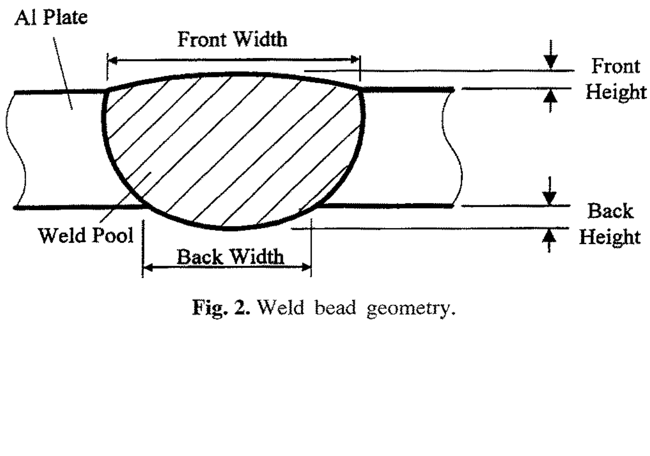

Fig. 2. Weld bead geometry.

be achieved to ensure weld strength. The front height, front width, back height, and back width of the weld bead have a smaller-the-better quality characteristic.

4. Optimal Welding Process Parameters

In this section, the Taguchi method is applied to determining the welding process parameters with an optimal weld bead geometry in the gas tungsten arc welding process. First, the use of an orthogonal array to reduce the number of welding experiments for searching for the optimal welding process parameters is reported. Results of the welding experiments are studied by using the signal-to-noise and analysis of variance. Based on the results of the signal-to-noise and analysis of variance, optimal welding process parameters for the gas tungsten arc welding process are obtained and verified.

4.1 Orthogonal Array Experiment

The experimental design based on an orthogonal array is orthogonal. It allows the effect of each welding process parameter at different levels to be separated out. To select an appropriate orthogonal array for experiments, the total degrees of freedom must be computed. The degrees of freedom are defined as the number of comparisons between process parameters that must be made to determine which level is better and specifically how much better it is. For example, a three-level process parameter counts for two degrees of freedom. The degrees of freedom associated with the interaction between two process parameters are given by the product of the degrees of freedom for the two process parameters. In the present study, the interaction between the welding process parameters is neglected. The value of the welding process parameter at the different levels is listed in Table 1. As shown in Table 1, 8 degrees of freedom are available in the welding experiments.

Once the degrees of freedom required are known, the next step is to select an appropriate orthogonal array to fit the specific task. The degrees of freedom for the orthogonal array should be greater than, or at least equal to, those for the process parameters. In this study, an L_{18} orthogonal array with 8 columns and 18 rows was used. This array has 17 degrees of freedom and it can handle one two-level process parameter and seven three-level process parameters. Each welding process parameter is assigned to a column and 18 welding process parameter combinations are available. Therefore, only 18 experiments are required to study the entire welding process parameter space using the L_{18} orthogonal array. Three columns of the orthogonal array are empty because only five welding process parameters are assigned to the L_{18} orthogonal array. Orthogonality is not lost by letting three columns of the array be empty. The experimental layout for the welding process parameters using the L_{18} orthogonal array is shown in Table 2. Table 3 shows the measurement results of the weld bead geometry based on the experimental layout.

Table 2. Experimental layout using an L_{18} orthogonal array.

Experiment number	Welding parameter level				
	A Arc gap	B Polarity ratio	C Welding speed	D Filler speed	E Welding current
1	1	1	1	1	1
2	1	1	2	2	2
3	1	1	3	3	3
4	1	2	1	1	2
5	1	2	2	2	3
6	1	2	3	3	1
7	1	2	1	2	1
8	1	2	2	3	2
9	1	2	3	1	3
10	2	1	1	3	3
11	2	1	2	1	1
12	2	1	3	2	2
13	2	2	1	2	3
14	2	2	2	3	1
15	2	2	3	1	2
16	2	2	1	3	2
17	2	2	2	1	3
18	2	2	3	2	1

4.2 Signal-to-Noise Ratio

In the Taguchi method, a loss function is defined to calculate the deviation between the experimental value and the desired value. Usually, there are three categories of the quality characteristic in the analysis of the signal-to-noise ratio, that is, the lower-the-better, the higher-the-better, and nominal-the-better. To obtain optimal welding performance, the front height, front width, back height, and back width of the weld bead have a smaller-the-better quality characteristic if the weld penetration at the back face of the base metal is achieved.

The loss function of the lower-the-better quality characteristic can be expressed as:

Table 1. Welding process parameters and their levels.

Symbol	Welding parameter	Unit	Level 1	Level 2	Level 3
A	Arc gap	mm	2.4	3.2*	
B	Polarity ratio	%	30	70*	70*
C	Welding speed	cm min^{-1}	24*	35	46
D	Filler speed	mm min^{-1}	1.5	2.0*	2.5
E	Welding current	A	80	95*	110

*Initial welding parameters.

Table 3. Experimental results for the weld bead geometry.

Experiment number	Front height (mm)	Front width (mm)	Back height (mm)	Back width (mm)
1	0.149	6.090	0.672	5.664
2	0.094	6.665	0.613	6.304
3	0.010	6.396	0.536	6.197
4	0.553	9.757	0.852	9.993
5	0.396	9.652	0.782	10.277
6	0.380	5.231	0.397	2.817
7	0.213	7.424	0.806	7.026
8	0.107	7.055	0.696	7.240
9	0.249	7.719	0.492	7.706
10	0.557	12.348	1.139	12.403
11	0.108	5.173	0.340	3.418
12	0.155	6.002	0.351	4.922
13	0.740	12.273	1.148	12.71
14	0.120	5.850	0.626	4.989
15	0.090	5.892	0.399	5.319
16	0.168	10.348	0.708	10.193
17	0.564	9.670	0.743	9.952
18	0.219	5.538	0.363	2.857

$$L_{ij} = \frac{1}{n} \sum_{k=1}^{n} y_{ijk}^2 \quad (1)$$

where L_{ij} is the loss function of the ith quality characteristic in the jth experiment, n is the number of tests, and y_{ijk} is the experimental value of the ith quality characteristic in the jth experiment at the kth test.

The front height, front width, back height, and back width of the weld bead have different measurement ranges. To consider the four quality characteristics together in the Taguchi method, the loss functions corresponding to the front height, front width, back height, and back width of the weld bead are first normalised. Then, a weighting method is used to integrate the four normalised loss functions into a total loss function, that is:

$$TL_j = \sum_{i=1}^{m} w_i S_{ij} \quad (2)$$

where TL_j is the total loss function in the jth experiment, m is the number of the quality characteristics, w_i is the weighting factor for the ith quality characteristic and S_{ij} is the normalised loss function for the ith quality characteristic in the jth experiment, which can also be expressed as:

$$S_{ij} = \frac{L_{ij}}{\overline{L}_i} \quad (3)$$

where L_{ij} is the loss function for the ith quality characteristic in the jth experiment and $\overline{L}_i$ is the average loss function for the ith quality characteristic.

The total loss function is further transformed into a multi-response signal-to-noise (S/N) ratio. In the Taguchi method, the S/N ratio is used to determine the quality characteristic deviating from the desired value. The multi-response signal-to-noise (S/N) ratio η_j in the jth experiment can be expressed as:

$$\eta_j = -10 \log(TL_j) \quad (4)$$

In the present study, the weighting factor of the front height, front width, back height, and back width of the weld bead is equal to 0.25. Table 4 shows the experimental results for the multiresponse signal-to-noise (S/N) ratio. Since the experimental design is orthogonal, it is then possible to separate out the effect of each welding process parameter at different levels. For example, the mean of the multiresponse signal-to-noise ratio for the arc gap at levels 1 and 2 can be calculated by averaging the multiresponse signal-to-noise ratios for experiments 1 to 9 and 10 to 18, respectively (Table 2). The mean of the multiresponse signal-to-noise ratio for each level of the other welding process parameters can be computed in a similar manner. The mean of the multiresponse signal-to-noise ratio for each level of the welding process parameters is summarised and called the multiresponse signal-to-noise table (Table 5). In addition, the total mean of the multiresponse signal-to-noise ratio for the 8 experiments is also calculated and listed in Table 5. Figure 3 shows the multiresponse signal-to-noise graph and the dashed line in Fig. 3 is the value of the total mean of the multiresponse signal-to-noise ratio. The larger the multiresponse signal-to-noise ratio, the smaller the variance of quality characteristics around the desired value. However, the relative importance among the welding process parameters of the multiple quality characteristics must still be known so that the optimal combinations of the welding process parameter levels can be determined more accurately. This will be discussed in Section 4.3 using the statistical analysis of variance.

4.3 Analysis of Variance

The purpose of the analysis of variance (ANOVA) is to investigate which process parameters significantly affect the quality characteristic. This is accomplished by separating the total variability of the multiresponse signal-to-noise ratios, which is measured by the sum of the squared deviations from the total mean of the multiresponse signal-to-noise ratio, into contributions by each of the process parameter and the error. First, the total sum of the squared deviations SS_T from the

Table 4. Multi-response signal-to-noise ratio for the welding performance.

Experiment number	Multi-response S/N ratio (dB)
1	−3.497
2	−3.424
3	−2.700
4	−8.625
5	−7.643
6	−3.303
7	−5.334
8	−4.378
9	−4.679
10	−10.12
11	0.234
12	−1.520
13	−10.97
14	−2.746
15	−1.468
16	−6.671
17	−8.444
18	−1.140

Table 5. Signal-to-noise response table for the welding performance.

Symbol	Welding parameter	Mean multi-response S/N ratio (dB)			
		Level 1	Level 2	Level 3	Max–Min
A	Arc gap	−4.842	−4.761		0.082
B	Polarity ratio	−3.505	−5.450		1.945
C	Welding speed	−7.536	−4.400	−2.468	5.068
D	Filler speed	−4.413	−5.005	−4.987	0.592
E	Welding current	−2.631	−4.348	−7.426	4.795
	Total mean multi-response S/N ratio = −4.802 dB				

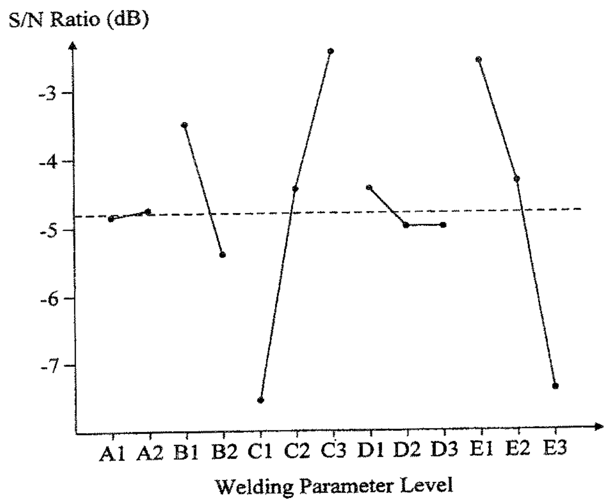

Fig. 3. Signal-to-noise graph for the welding performance.

total mean of the multi-response signal-to-noise ratio η_m can be calculated as:

$$SS_T = \sum_{j=1}^{p} (\eta_j - \eta_m)^2 \tag{5}$$

where p is the number of experiments in the orthogonal array, η_m is the total mean of the multiresponse signal-to-noise ratio, and η_j is the mean of the multiresponse signal-to-noise ratio for the jth experiment.

The total sum of the squared deviations SS_T is decomposed into two sources: the sum of the squared deviations SS_d due to each process parameter and the sum of the squared error SS_e. The percentage contribution ρ by each of the process parameters into the total sum of the squared deviations SS_T can then be obtained.

Statistically, there is a tool called an F-test, named after R. A. Fisher [11], to see which process parameters have a significant effect on the quality characteristic. In performing the F-test, the mean of the squared deviations SS_m due to each of the process parameters must be calculated. The mean of the squared deviations SS_m is equal to the sum of the squared deviations SS_d divided by the number of degrees of freedom associated with the process parameter. Then, the F-value for each process parameter is simply a ratio of the mean of the squared deviations SS_m to the mean of the squared error. Usually, when the F-value is greater than 4, it means that a change in the process parameter has a significant effect on the quality characteristic.

Table 6 shows the results of analysis of variance. It can be found that welding speed, welding current, and polarity ratio have a significant effect on the defined multiple quality characteristics, but, the changes of arc gap and filler speed in the range given by Table 1 have an insignificant effect on the defined multiple quality characteristics. Therefore, based on the signal-to-noise ratio and analysis of variance, the optimal welding process parameters are the arc gap at level 2, the polarity ratio at level 1, the welding speed at level 3, the filler speed at level 1, and the welding current at level 1.

4.4 Confirmation Tests

Once the optimal level of the process parameters is selected, the final step is to predict and verify the improvement of the quality characteristic using the optimal level of the process parameters. The estimated signal-to-noise ratio $\hat{\eta}$ using the optimal level of the process parameters can be calculated as:

$$\hat{\eta} = \eta_m + \sum_{i=1}^{q} (\bar{\eta}_i - \eta_m) \tag{6}$$

where $\bar{\eta}_i$ is the mean of the multiresponse signal-to-noise ratio at the optimal level and q is the number of process parameters that significantly affect the multiple quality characteristics.

Based on equation (6), the estimated multiresponse signal-to-noise ratio using the optimal welding process parameters can then be obtained. Table 7 shows the results of the confirmation experiment using the optimal welding process parameters. The increase of the multiresponse signal-to-noise ratio from the initial welding process parameters to the optimal welding process parameters is 9.45 dB. It is clearly shown that the front height, front width, back height, and back width of the weld are greatly reduced by using the optimal welding process parameters.

5. Conclusions

This paper has described an application of the Taguchi method to the optimisation of the weld bead geometry in the

Table 6. Results of the analysis of variance for the welding performance.

Symbol	Welding parameter	Degree of freedom	Sum of square	Mean square	*F*	Contribution per cent
A	Arc gap	1	0.03	0.03	0.02	1.66
B	Polarity ratio	1	15.1	15.1	8.56	8.34
C	Welding speed	2	78.5	39.3	22.7	43.3
D	Filler speed	2	1.36	0.68	0.39	0.75
E	Welding current	2	70.8	35.4	20.5	39.0
Error		9	15.5			8.57
Total		17	181.4			100

Table 7. Results of the confirmation experiment for the welding performance.

	Initial welding parameters	Optimal welding parameters	
		Prediction	Experiment
Level	A2B2C1D2E2	A2B1C3D1E1	A2B1C3D1E1
Front height (mm)	0.448		0.168
Front width (mm)	10.523		4.898
Back height (mm)	1.005		0.277
Back width (mm)	11.088		2.998
S/N ratio (dB)	−9.108	0.999	0.347
	Improvement multi-response S/N ratio = 9.45 dB		

gas tungsten arc welding process. It has been shown that the Taguchi method provides a systematic and efficient methodology for searching the welding process parameters with an optimal weld bead geometry. The optimal weld bead geometry has a smaller-the-better quality characteristic for the front height, front width, back height, and back width of the weld bead. Through the analysis of variance, it is seen that welding speed, welding current, and polarity ratio are the important welding process parameters for the determination of the weld bead geometry. The confirmation experiments were conducted to verify the optimal welding process parameters. It has been shown that the front height, front width, back height, and back width of the weld bead in the gas tungsten arc welding process are greatly improved by using this approach.

Acknowledgements

Financial support from the National Science Council of the Republic of China under grant number NSC84-2212-E011-005 is gratefully acknowledged.

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