Optimising Process Conditions in MIG Welding of Aluminum Alloys Through Factorial Design Experiments

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Abstract: - MIG welding is among the most important processes in assembly operations for aluminum alloys. The success of this process in terms of providing weld joints of good quality and high strength depends on the process conditions used in the setup. This study aims at identifying and optimising the main factors that have significant effect on weld joint strength through factorial design experiments. The factors that were studied are arc voltage, filler feed rate, gas flow rate, specimen edge angle and preheat temperature. Results of factorial design experiments and the analysis of variance (ANOVA) showed that arc voltage and filler feed rate are the only significant factors of the five. Optimal settings of arc voltage and filler feed rate were reached using regression analysis at 24 V and 7 in/s, respectively, at which the mean weld strength is maximum.

Key-Words: - MIG welding; ANOVA; Factorial design; Regression analysis

1 Introduction

Welding of aluminum alloys has significant importance in joining applications in industry. It is widely used in the construction of aluminum boats, transport equipment, storage tanks, and general metal sheet works. Two main processes are used in the welding of aluminum alloys. One is the Metal Inert Gas (MIG) welding process, also known as Gas Metal Arc Welding (GMAW). This process generates a constant electric arc between an automatically fed consumable wire electrode and a workpiece in the presence of an inert gas shield (AFSA, 2004). The second process is the Tungsten Inert Gas (TIG) welding process, which is also known as Gas Tungsten Arc Welding (GTAW). This process typically applies a constant electric arc between a permanent tungsten electrode and a workpiece, while an inert gas is used for shielding the molten metal to minimize oxidation. Compared to TIG welding, MIG welding is much faster, more versatile, requires less skill and training, and can be used for welding thicker sections. In addition, MIG welds are generally stronger than TIG welds due to better penetration.

Strength and quality of welded joints depends largely on the parameter settings used in the welding process. Optimising these process conditions is very important for achieving good weld characteristics. In the literature, some studies have addressed certain aspects of parameter optimisation in welding operations. Most of these studies have considered welding of steel, but few of them have addressed welding of aluminum alloys. Singla et al. (2010) implemented an experimental study to optimise various GMAW parameters including welding voltage, welding current, welding speed and nozzle to plate distance (NPD) by developing a mathematical model for sound weld deposit area of a mild steel specimen. They applied a factorial design approach for finding the relationship between the various process parameters and weld deposit area. Pal and Pal (2010) focused on the influence of pulse parameters at various torch angles on the tensile properties of low carbon steel butt weld in pulsed metal inert gas welding. The interface of weld zone and heat affected zone was found to be the weakest area due to significant variation of weld microstructure.

In addition, Karadeniz et al. (2007) investigated the effect of welding current, arc voltage and welding speed on welding penetration in Erdemir 6842 steel having 2.5 mm thickness welded by robotic GMAW process. They concluded that higher depth of penetration can be achieved by increasing the welding current. Correia et al. (2005) compared the response surface methodology (RSM) genetic algorithm (GA) in the optimisation of a GMAW welding process of mild steel. The situation was to choose the best values of three control variables (reference voltage, wire feed rate and welding speed) based on four quality responses (deposition efficiency, bead width, depth of penetration and

reinforcement), inside a previous delimited experimental region. Results indicated that both methods are capable of locating optimum conditions, with a relatively small number of experiments.

In an attempt to address parameter optimisation in aluminum welding, Kumar and Sundarrajan (2009) employed Taguchi method to optimise process parameters for the pulsed TIG welding of AA 5456 Aluminum alloy. Their aim was to increase the mechanical properties of welded joints. Benyounis and Olabi (2008) reviewd different optimisation approaches including artificial neural networks (ANNs), genetic algorithm (GA), response surface methodology (RSM), Taguchi and factorial designs, as applied to certain weld joint properties. They provided a comparison between the studied techniques in terms of computational time, optimisation, model development, accuracy level and application. Palani and Murugan (2006) studied the pulsed GMAW process to optimise process parameters such as average current, peak current, peak time, base current, feed rate, frequency and shielding gas. They adopted emperical approaches to select the optimal parameter values that give the best quality.

This study aims at optimising the main factors that have effect on weld joint strength. Although quality may be different from strength, in the case of welds these are related. Accordingly, weld joint strength is the one selected as the objective variable in this study. This study is motivated by the lack of information available on the best combination of process conditions to be used in MIG welding of aluminum alloys that yield weld joints of high quality and strength. It is also motivated by the fact that MIG welding is increasingly used in industry due to being very productive and economical.

Factorial design experiments are conducted in this work based on design of experiments (DOE) methodology. ANOVA is used to identify the relevant factors whose effect on weld joint strength is significant. Then, linear regression analysis is applied to develop a first-order relationship between weld joint strength and the factors that are determined as significant ones. Ultimately, the optimal settings of process conditions that are significant are determined based on the data from factorial design experiments. In this study, five factors have been investigated. These are arc voltage, filler feed rate, gas flow rate, specimen edge angle and preheat temperature.

2 Description of Experiments

Welding experiments were carried out using Butters 400 MIG welding machine. An ER1100 filler wire with 1.2 *mm* in diameter was used as a consumable electrode. The shielding gas used was 100% pure Argon. Test specimens were composed of two pieces each, and each piece was 100 *mm* × 50 *mm* × 8 *mm* in size and made of 1070 aluminum alloy. The specimens were prepared according to the joint geometry shown in Fig. 1. Joint spacing between specimens was fixed at 2 mm in all welding experiments. Prior to welding, specimens were degreased using an aerosol degreaser to remove lubricants and other contaminants. Surface oxides were removed with a stainless wire brush used only on aluminum. A forehand (push) travel technique, as shown in Fig. 2, was employed with a 10° to 15° degrees in push travel angle.

Once a two-piece specimen is welded, a *wrap-around* bending test was used, as shown in Fig. 3, to determine the strength of the welded joint. In this figure, a V-shaped line load is applied against the weld line, also the center line, of the specimen. As the specimen is supported on the sides by a steel fixture, it begins to yield due to bending. This test was conducted out on a 100-kN Instron UTM machine at a speed of 50 mm/min. The maximum load registered by the machine during bending was used to indicate the strength of the weld joint.
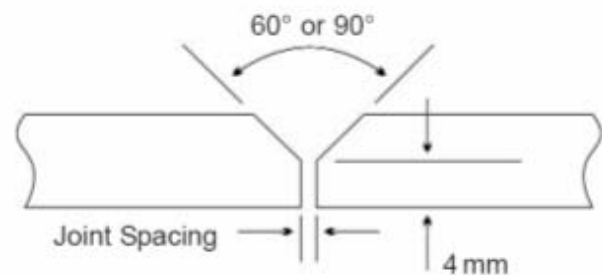

Fig. 1: Joint geometry for the welding specimens
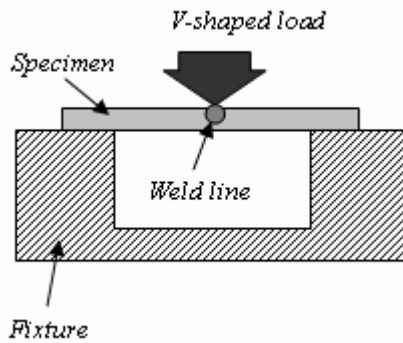

Fig. 2: Push travel technique

Fig. *3*: Representation of the wrap-around bend test

3 Factorial Design Experiments

Factorial design experiments refer to the implementation of design of experiments (DOE) methodology to the design and analysis of experiments with multiple factors being studied. This methodology is very useful in helping to reach valid and reliable conclusions based on a set of experiments. Although in MIG welding of aluminum alloys numerous factors have an effect on weld joint strength and quality, few of these effects can be considered significant. In this study, five factors that have supposedly significant effects on weld joint strength and quality will be screened first (screening phase). Once the factors with significant effects are determined, then these factors will be further studied and optimised (optimisation phase) to find the optimal conditions for generating maximum weld joint strength.

3.1 Screening Phase

Five factors were screened in this phase, as summarized in Table 1. These factors are arc voltage (Volt, V), filler feed rate (in/s), gas flow rate (cubic foot per hour, cfh), specimen edge angle (deg) and preheat temperature (oC). Further in this paper, these factors will be denoted as V, F, G, A and T, respectively. To study the mentioned factors, a 25×1 (2 refers to the number of levels for each of the 5 factors, and 1 refers to the number of replicates) factorial design of experiments was implemented. The levels of each of the five factors are listed in Table 1. For each combination of the five factors, a single reading of weld joint strength was produced through the bending test. This corresponds to a total of thirty two experiments that need to be conducted.

Table 1: Study factors and their levels in the screening phase

Factor	Arc voltage	Filler feed rate	Gas flow rate	Edge angle	Preheat temp.
Level	(V)	(in/s)	(cfh)	(°)	(°C)
Low (–)	21	4	24	60	25
High (+)	27	6	32	90	70

3.2 Optimisation Phase

In this phase, two factors were further studied because they have significant effects on weld joint strength, as will be shown later in the next section. The two factors were arc voltage and filler feed rate. Since the main objective at this stage is to optimise the welding process by finding the best combination of significant factors that yields the maximum weld joint strength, it is important to increase the number of levels for each factor. Thus, the number of levels has been increased to four levels for each factor, as shown in Table 2. In addition, two replicates of each combination of factor levels were produced. The corresponding factorial design can be abbreviated as $4^2 \times 2$. The total number of experiments needed for this design is thirty two. The other factors that were eliminated in this phase were fixed at the levels that led to higher values of weld joint strength. Accordingly, the gas flow rate, specimen edge angle and preheat temperature were fixed at 24 cfh, 90° and 25 °C, respectively.

Table 2: Study factors and their levels in the screening phase

Design Factor		
Level	Arc voltage (V)	Filler feed rate (in/s)
1	21	4
2	24	5
3	27	6
4	30	7

4 Results and Discussion
4.1 Screening Phase Results

The weld strength results of the screening phase experiments are summarized in Table 3. This table also shows the random order (run order) in which the thirty two experiments were conducted. A randomized run order is useful for avoiding the effect of time/sequence related nuisance factors, e.g.

machine warm-up and technician fatigue (Hassan et al., 2008). To analyze the data shown in Table 3, a normal probability plot of the factorial effects is generated with the aid of MINITAB™ using Daniel's method (Montgomery, 2005), as shown in Fig. 4. An effect is generally defined as the average change in response (which is here the weld strength) caused by the change in the level of a process variable (Bataineh and Dalalah, 2010). Based on Daniel's method, if all the effects of a factor fall approximately close to the fitted line, then this factor is considered insignificant. It can be seen in Fig. 4 that the factorial effects of arc voltage and filler feed rate (denoted as A and B, respectively, by MINITAB™) are located far away from the fitted line, and thus these two factors are considered the only significant factors. It should be noted here that when a factorial effect is considered far enough from the fitted line to be treated as significant, this depends on the significance level $(1 - \alpha)\%$ defined in MINITAB™.

Table 3: Weld strength results from the screening phase experiments

| Run Order	Arc voltage (V)	Filler feed rate (in/s)	Gas flow rate (cfh)	Edge angle (°)	Preheat temp. (°C)	Weld strength (N)
1	27	4	24	60	25	2,490
2	27	4	24	90	70	2,685
3	27	4	32	60	70	2,180
4	21	4	24	60	25	2,895
5	21	6	32	90	25	9,820
6	27	6	32	60	70	2,735
7	27	4	32	60	25	2,235
8	27	6	24	60	70	4,120
9	21	4	24	90	25	3,720
10	27	6	24	90	25	4,990
11	27	6	32	90	25	2,265
12	21	6	24	60	25	7,420
13	21	4	32	60	25	2,685
14	27	6	32	90	70	5,050
15	27	6	24	60	25	3,535
16	21	4	32	90	25	4,440
17	27	6	24	90	70	4,690
18	21	6	24	90	70	8,440
19	27	4	32	90	25	1,885
20	27	4	24	60	70	3,995
21	21	4	24	60	70	3,830
22	27	6	32	60	25	5,190
23	21	6	32	90	70	11,260
24	21	6	24	90	25	10,120
25	27	4	24	90	25	1,650
26	21	4	32	90	70	2,795
27	21	6	32	60	70	5,070
28	27	4	32	90	70	3,485
29	21	4	24	90	70	3,740
30	21	6	24	60	70	5,910
31	21	6	32	60	25	6,790
32	21	4	32	60	70	2,630
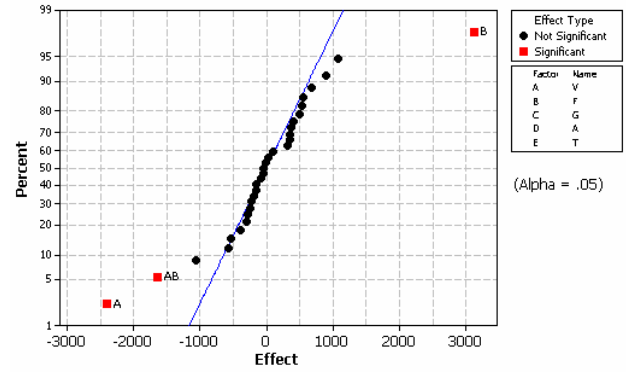
Fig. 4: Normal probability plot of the factorial effects

4.2 Optimisation Phase Results

The weld strength results of the optimisation phase experiments are summarized in Table 4. This table shows the random order of the thirty two experiments when arc voltage and filler feed rate are the only study factors. It can be noted from Table 4 that the maximum mean weld strength occurs when arc voltage and filler feed rate are set at 24 V and 7 in/s, respectively.

Since the data in Table 4 are replicated, it can be analyzed using the analysis of variance (ANOVA) approach accompanied with linear regression analysis (Montgomery and Runger, 2007). The results of ANOVA and linear regression analysis generated for the data with the aid of MINITAB™, are shown in Fig. 5. Considering a significance level of 95%, it can be inferred from Fig. 5 that the following linear regression equation

$$W = 6993 - 1271V + 3272F \qquad (1)$$

can be used to model the relationship between weld strength (W) as a function of the significant factors, i.e. arc voltage (V) and filler feed rate (F). The interaction component ($V*F$) was not included in equation (1) because the corresponding P-value from ANOVA (equals 0.12) is greater than $\alpha = 0.05$.

The calculated R^2 (also called *coefficient of multiple determination*) value is 76.6%, as shown in Fig. 5. This value represents the percentage of variability in the data accounted for by the model in equation (1). The remaining 23.4% of unexplained variability is due to both pure error and lack-of-fit. Since the P-value of ANOVA that corresponds to lack-of-fit (approximately zero) is less than $\alpha = 0.05$, this indicates that nonlinearities exist in the relationship between weld strength (W), arc voltage (V) and filler feed rate (F).

Table 4: Weld strength results from the optimisation phase experiments

Run Order	Arc voltage (V)	Filler feed rate (in/s)	Weld strength (N)
1	27	4	2,685
2	24	4	5,040
3	21	4	3,720
4	30	5	5,190
5	24	6	9,620
6	24	4	5,310
7	21	6	10,120
8	24	7	12,880
9	27	6	4,990
10	30	6	7,110
11	21	5	7,790
12	21	7	10,520
13	30	7	8,170
14	21	6	8,440
15	27	7	11,620
16	27	7	11,320
17	27	5	2,910
18	30	4	4,760
19	21	4	3,740
20	30	7	6,740
21	24	6	11,600
22	30	6	6,400
23	27	5	4,550
24	27	4	1,650
25	30	4	4,200
26	24	5	6,840
27	30	5	5,040
28	24	7	10,900
29	21	5	5,810
30	24	5	7,920
31	21	7	11,500
32	27	6	4,690

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Estimated Regression Coefficients for Weld strength (N)

Term        Coef    SE Coef     T       P
Constant   6993.0    277.3   25.219   0.000
V         -1271.0    372.0   -3.416   0.002
F          3272.9    372.0    8.798   0.000
V*F        -801.5    499.1   -1.606   0.120

S = 1568.60   R-Sq = 76.60%   R-Sq(adj) = 74.09%


Analysis of Variance for Weld strength (N)

Source          DF     Seq SS      Adj SS      Adj MS      F       P
Regression       3   225496402   225496402    75165467   30.55   0.000
  Linear         2   219151589   219151589   109575795   44.53   0.000
  Interaction    1     6344813     6344813     6344813    2.58   0.120
Residual Error  28    68894341    68894341     2460512
  Lack-of-Fit   12    57089529    57089529     4757461    6.45   0.000
  Pure Error    16    11804813    11804813      737801
Total           31   294390743
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Fig. 5: ANOVA output for the $4^2 \times 2$ factorial design

5 Conclusions

MIG welding often has the upper edge over TIG welding of aluminum alloys due to being more productive and economical. In this paper, it was established that several factors affect quality and strength of joints welded by the MIG welding process. These factors include arc voltage, filler feed rate, gas flow rate, specimen edge angle and preheat temperature. Factorial design experiments have shown, based on Daniel's method, that arc voltage and filler feed rate are the only significant factors of the five.

Utilizing the analysis of variance (ANOVA) approach in the optimization phase experiments, it was determined that setting arc voltage and filler feed rate at 24 V and 7 in/s, respectively, yields the maximum mean weld strength. In addition, it was possible to fit the relationship between weld strength as a function of arc voltage and filler feed rate using a linear regression model. However, this model is only approximate as a lack-of-fit was evident due to the presence of nonlinearities in the actual relationship.

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