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TIG Welding Al6061 using Taguchi and Regression analysis methods

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Abstract— ***Design of experiments is a technique to determine and represent the cause and effect relationship between true mean responses and input control variables influencing the responses as a two or three-dimensional hyper surface. TIG welding is used extensively in industry to join similar metals. The main problem faced in the TIG welding process is the selection of the optimum combination of input variables for achieving the required qualities of weld. This problem can be solved by the development of mathematical models through effective and strategic planning and the execution of experiments by Taguchi techniques and Analysis of variance (ANOVA). This paper highlights the use of Taguchi techniques by designing a three-factor two-level orthogonal array with full replication for planning, conduction, execution and development of mathematical models. These are useful not only for predicting the weld bead quality but also for selecting optimum process parameters for achieving the desired quality and process optimization. The correlation was obtained by regression analysis and compared with the experimental results.***

Key words: TIG Welding, Al6061, Taguchi Techniques, ANOVA, Regression analysis.

I. Introduction

The Design of Experiments (DOE) is a set of techniques that encompasses [1] (i) the designing of a set of experiments for adequate and reliable measurement of the true mean response of interest; (ii) the determining of mathematical model with best fits; (iii) finding the optimum set of experimental factors that produces maximum or minimum value of response; and (iv) representing the direct and interactive effects of process variables on the bead parameters through two dimensional and three dimensional graphs. The accuracy and effectiveness of an experimental program depends on careful planning and execution of the experimental procedures [2]. In the TIG (tungsten inert gas) welding process, an essentially non-consumable tungsten electrode is used to provide an electric arc for welding. A sheath of inert gas surrounds the electrode, the arc, and the area to be welded. This gas shielding process prevents any oxidization of the weld and allows for the production of neat, clean welds.
TIG welding is an arc-welding process that produces coalescence of metals by heating them with an arc between a non-consumable tungsten electrode and the base metal. His process was originally developed for hard-to-weld lightweight metals such as aluminum, magnesium and titanium. Many delicate components in aircraft and nuclear reactors are TIG welded and therefore TIG weld quality is of extreme importance. Basically, TIG weld quality is strongly characterized by the weld pool geometry. This is because the weld pool geometry plays an important role in determining the mechanical properties of the weld [3]. To ensure TIG weld quality, several on-line monitoring techniques have been studied [4]

II. Experimental Procedure:

Material and testing

In our project we have performed TIG welding on Aluminum 6061, which is the base metal and the filler material used is Aluminum 4043. Although many metals are TIG welded, the metal most frequently associated with the process is aluminum, especially with metals of a smaller thickness. Many other processes, of course, can join aluminum, but in the lighter gauges the most applicable process is TIG. The popularity of aluminum in automotive applications has brought TIG welding to a new golden age. Mechanically strong and visually appealing, TIG welding is the number one process chosen by professional welders for professional racing teams, and the avid auto enthusiast or hobbyist.

Specimen Preparation

Specimens were prepared manually according to ASTM (American Society for Testing Materials) E8 M standards. The templates of the specimen are as shown below 8 such specimens were prepared and split at its center for joint preparation These were then TIG welded under varying conditions of current, voltage, and inert gas flow rate and arc gap between the electrode tip and the surface of the specimen. This procedure is based on Taguchi methods to determine the response or quality characteristic of the weld these specimens relative to the input parameters chosen.

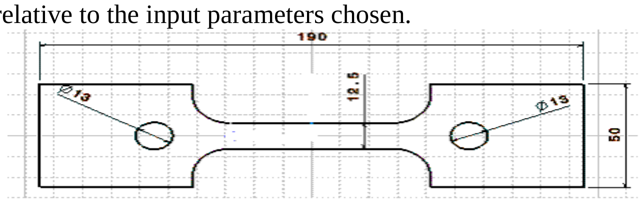

Figure 1 Welding specimen

Joint Design

The basic types of joints butt, lap, corner, edge, and T are all used in GTAW. Variations of these joints can be made to meet special requirements. Selection of the proper design for a particular application depends primarily on:

- Mechanical properties desired
- Cost of preparing the joint and making the weld
- Type of metal being welded
- Size and configuration of the components to be welded
- Edge and joint preparation are critical to obtain sound welds, because proper joint fit up is necessary particularly for square groove butt joints and any other joint to be made without adding filler metal.

Butt Joints

A square groove butt joint is the easiest to prepare, and can be welded with or without filler metal, depending on the composition and thickness of the pieces being welded. A single V groove butt joint is used where complete penetration is required on work metal more than 3/16 in. to 3/8 in. thick. A double V groove butt joint is generally used on stock thicker than 1/2 in., when design of the weld element permits access to the back of the joint. Butt joints of special design are sometimes used for very thick work metal, which may require many welding passes (often by other processes in addition to GTAW).

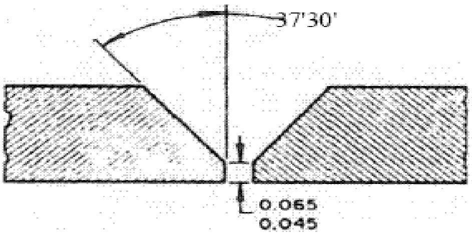

Figure 2 Edge preparations for butt joint.

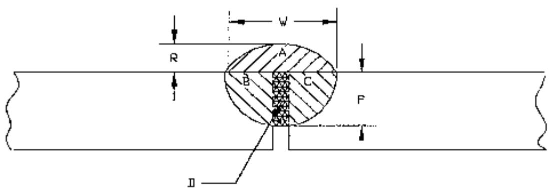

Figure 3 Weld bead geometry.

Table:Experimental conditions and Results

Exp No	Current (amps)	Voltage (Volts)	Gas flow rate (l/min)	Tensile strength (Mpa)	Bead width (mm)	Bead length (mm)
1	50	80	8	78.48	5.23	2.46
2	50	80	10	41.85	5.5	2.85
3	50	100	8	136.03	4.8	2.34
4	50	100	10	99.4	7.86	4.51
5	60	80	8	94.17	5.73	3.58
6	60	80	10	88.94	4.92	2.74
7	60	100	8	78.48	5.28	3.41
8	60	100	10	83.71	6.6	2.04

ANOVA (Analysis Of Variance)

Analysis of Variance is a statistical procedure for breaking out (decomposing) the contributions of individual sources of variance to the total variance in a study. For the ANOVA table, we isolate possible sources of variation (factors) and sum of squares of the deviations around the mean (or target value) for each source. Next we convert the sums of squares of the deviations for all sources, including our error estimate, into one degree of freedom each.

III. Results and Discussions

Plan of experiments: The methods of Taguchi for three factors at two levels are taken. The table1 below indicates the factors to be studied and assignment of corresponding level.

The array chosen was the L8 Orthogonal array (2^3), which has 8 rows corresponding to the number of tests (7 degrees of freedom) with 7 columns at 2 levels as shown in **table 1.**

Table 1 Input parameters

Level	Current (amps)	Voltage (volts)	Gas flow rate (l/min)
1	50	80	8
2	60	100	10

The factors and interactions are assigned to the columns. The plan of experiments is made of 8 tests in which the first column was assigned to the current (A) and the second column to the voltage (B) and the fourth column to the gas flow rate (C) and the remaining were assigned to the interactions. The outputs to be studied are tensile strength, bead length and bead width.

Table 3 ANOVA table for Tensile strength

Source	DF	S	V	F	S'	P
A	1	0.5408	0.5408			
B	1	1,423.64	1,423.64	2,632.48	1,423.10	31.36
AXB	1	1,628.49	1,628.49	3,011.27	1,627.95	**35.87**
C	1	412.7064	412.7064	763.1406	412.1656	9.08
AXC	1	920.205	920.205	1,701.56	919.6642	20.27
BXC	1	66.125	66.125	122.2726	65.5842	1.45
ERROR	1	86.1984	86.1984	159.3906	85.6576	1.89
(e)	1	0.5408	0.5408		3.7856	0.08
Total	**7**	**4,537.91**	**648.2733**			**100**

Data Analysis

The plan of tests was developed with the aim of relating the influence of the current (A), voltage (B), and gas flow rate (C), with the tensile strength, bead width and length. The statistical treatment of the data was made in two phases. The first phase was concerned with the ANOVA and the effect of the factors and interactions. The second phase was to obtain correlation between the parameters. Afterwards, results were obtained through confirmation tests.

It was done an ANOVA of the data with the tensile strength, bead width and length with the objective of analyzing the influence of the current (A), voltage (B), and gas flow rate (C) on the total variance of results. Table 5.3.1, 5.3.2 and 5.3.3 shows the results of ANOVA with the tensile strength, bead width and bead length. This analysis was undertaken for a level of confidence of 95%. The last column indicates the percentage of contribution (P) of each factor on the total variation indicating then, the degree of influence on the result.

We find out DF=degrees of freedom f, S=Source variation, V= Source variance.i.e. V=S/f, F=Source variance ratio i.e. $F=V / V_e$, S'=Source pure variation.i.e S'=S-Ve X f and P=Percentage contribution.

From **table 3** one can observe that the interactions of current (A) and voltage (B) (35.87%) have great influence on the tensile strength of the material. The current (A) (31.36%) and the interactions of current (A) and the gas flow rate(C) (20.27%) are the next most contributing factor. Gas flow rate (9.08%) has a lower percentage of significance of contribution on the tensile strength

Table 4 ANOVA table for bead width

Source	**DF**	**S**	**V**	**F**	**S'**	**P**
A	1	0.019	0.019	1.2416	0.0037	0.08
B	1	0.0561	0.0561	3.6645	0.0408	0.9
AXB	1	0.726	0.726	47.4131	0.7107	15.71
C	1	0.0153	0.0153			
AXC	1	2.8441	2.8441	185.738	2.8288	**62.54**
BXC	1	0.1953	0.1953	12.7551	0.18	3.98
ERROR	1	0.667	0.667	43.56	0.6517	14.41
(e)	1	0.0153	0.0153		0.1072	2.37
Total	**7**	**4.5229**	**0.6461**			**100**

From **table 4**, we can see that the interactions of voltage (B) and gas flow rate (40.33%) and the gas flow rate alone (24.42%) are the most influencing factors on the bead width. The voltage and the interactions of current and gas flow rate are also contributing to the bead width. The current has no influence on the bead width
From **table 5** we can observe that the interactions of current (A) and gas flow rate(C) (62.54%) are the most influencing factor with respect to bead length. The interactions of current and voltage (15.71%) influences to a smaller extent.

Table 5 ANOVA table for bead length

Source	**DF**	**S**	**V**	**F**	**S'**	**P**
A	1	0.0935	0.0935	1.692	0.0383	0.52
B	1	1.2522	1.2522	22.6519	1.1969	16.3
AXB	1	0.0621	0.0621	1.1239	0.0069	0.09
C	1	1.848	1.848	33.431	1.7927	24.42
AXC	1	0.9976	0.9976	18.0465	0.9423	12.84
BXC	1	3.032	3.032	54.8491	2.9767	**40.55**
ERROR	1	0.0553	0.0553			
(e)	1	0.0553	0.0553		0.3869	5.27
Total	**7**	**7.3406**	**1.0487**			**100**

Confirmation tests and the comparison with the results.

The **table 6** shows the values of the input parameters that were obtained as optimum experimental values. These values were used in the confirmation tests and the error percentage was calculated by comparing with the model experimental values.
The Model Equation that is used for the confirmation tests is :
Output =A + B * X + C * Y + D * Z + E * X * Y + F * Y * Z + G * Z * X
Where A, B, C, D, E, F and G are constants
X, y, z are the input paramètres respectively

The correlation between input factors and the measured output parameters are obtained by linear regression analysis and presented in the subsection below.

Table 6 Values of input parameters used in the welding confirmation tests

Test	Current (Amps)	Voltage (volts)	Gas flow rate(L/min)
1c	50	90	8
2c	60	90	10

Linear regression equation for tensile strength

TS (max)= -592.26 + 13.85 * X + 18.70 * Y -121.65 * Z - 0.34 * X * Y +0 .13 * Y * Z + 1.831 * Z * X.

R^2 = 1-residual SS / corrected SS (SS is sum of squares)

R2 value for tensile test = 0.9915

Table 7 Confirmation tests for Tensile Strength

Test	Experimental values	Model Equation values	Error (%)
1c	72.34	69.5	3.9
2c	89.8	85.28	5.03

Linear regression equation for bead length

WL (max)= -73.81 + 1.60 * X +0 .19 * Y +5.19 * Z -0.006 * X * Y + 0.015 * Y * Z –0.119 * Z * X.
R^2 = 0.8525

Table 8 Confirmation Tests for Bead Length

Test	Experimental values	Model Equation values	Error (%)
1c	2.4	2.19	8.75
2c	2.04	2.09	2.4

Linear regression equation for bead width

WW (max)= 5.30 +0.77 * X - 0.417 * Y -1.17 * Z -0.0017 * X * Y + 0.0615 * Y * Z-0.070 * Z * X.
R^2 = 0.9926

Table 9 Confirmation Tests for Bead Width

Test	Experimental values	Model Equation values	Error (%)
1c	7.96	7.27	8.66
2c	8.85	6.11	8.25

Linear regression equation for reinforcement
RE IN (max)= -9.63 +0.2867 * X +0.092 * Y -0.683 * Z - 0.0029 * X * Y +0.0093 * Y * Z - 0.0012 * Z * X.
R^2 = 0.9926

IV. Discussion

We can see from the results that inert gas flow rate has a substantial effect on weld bead width but has lesser effect on the tensile strength and the weld bead length. it may be due to the following reasons.

Gas flow rate affects the heat input by trying to spread over the region of the molten metal. This increases the heat addition over that small area of the weld to increase the penetration and decrease the metal deposition rate. Also since the metal is in a liquid state for a greater amount of time it spreads over the base metal and thus the bead width increases.

Voltage and current both have a combined effect on both tensile strength and weld bead length. This is because voltage and current increase the arc length and hence the heat input. This increase in heat input causes the spreading of arc cone at its base, which leads to an increase in length and penetration.

Penetration thus joins the base metal very firmly and evenly at the joint area and thus increases the strength of other factors like gas flow rate shows a downward trend since it increases the air gaps in the molten metal and these when solidifying act as voids to reduce the strength although not considerably but to a very smaller extent.

V. Conclusion

The Taguchi approach has been built on traditional design of experimental methods to improve the design of products and processes. These unique and relatively simple concepts result in substantial improvements in quality at lower costs.

The present approach involves design of experiments to develop the process knowledge base and a quadratic regression analysis technique to account for the major contribution of the selected factors on the response of quality process evaluators.

- The Gas flow rate is found to be a major contributing factor
- The interactions of current and gas flow rate are the most influencing factor with respect to bead length.
- The interactions of voltage and gas flow rate and the gas flow rate alone influence the bead width.

The interactions of current (A) and voltage (B) greatly influences the tensile strength of the material.

The confirmation tests demonstrated a closer agreement of prediction with experimental results as evident from the results that the error is within 11%. It proves the effectiveness of the selected regression analysis for prediction Predictive regression network models are found to be capable of better predictions for tensile strength, bead width, bead length.

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