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Application of Taguchi Methods and ANOVA in GTAW Process Parameters Optimization for Aluminium Alloy 7039

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Abstract*— Aluminium alloy 7039 is an Al-Mg-Zn alloy employed in aircraft, automobiles, infantry combat vehicles and high speed trains due to their low density, high specific strength and excellent corrosion resistance. Pulsed Gas Tungsten Arc Welding is used in this study for welding AA7039. The influence of the various GTAW process parameters, i.e. Pulse Current, Base current and Pulse Frequency on welds were studied for properties of weld like microhardness, ASTM grain size number and heat affected zone (HAZ) width. The settings of the process parameters were determined by using Taguchi's experimental design method. Orthogonal arrays of Taguchi, the signal-to-noise (S/N) ratio, the analysis of variance (ANOVA), and regression analyses are employed to find the optimal process parameter levels and to analyze the effect of these parameters on the weld properties. Confirmation test with the optimal levels of welding parameters was carried out in order to illustrate the effectiveness of the Taguchi optimization method.

***Index Terms*— AA7039, GTAW, Microhardness, Taguchi optimization methods, ANOVA.**

I. INTRODUCTION

Aluminium alloys find wide applications in aerospace, automobiles, railway vehicles, bridges and high speed ships due to its light weight and higher strength to weight ratio [1]. A demand for lighter and stronger aluminium armor for protection against high explosive shell fragments led to the introduction of aluminium alloy 7039. It is heat treatable and weldable aluminium-magnesium-zinc alloy. Magnesium is alloyed with aluminium for increasing mechanical properties, corrosion resistance and easy machinability. In these alloys, as long as possible the weld metal contains 3% Mg or more, hot cracking is not a serious problem [2]. Zinc is usually added to improve mechanical properties through formation of hard intermediate phase, such as Mg_2Zn. Welding of aluminum is generally performed either by gas metal arc welding (GMAW) or gas tungsten arc welding (GTAW). Lots of difficulties are associated with this kind of joining process, mainly related to the presence of a oxide layer, high thermal conductivity, high coefficient of thermal expansion, solidification shrinkage, high solubility of hydrogen in the molten state. Further problems occur when attention is focused on heat-treatable alloys, since heat provided by the welding process, is responsible for the decay of mechanical properties, due to phase transformations and softening. Vainarman et al. [2] reported that the use of pulsed arc welding in place of conventional GTAW increases the output by 200–400%, reduces consumption of argon by three to ten times, and also reduces the cost of 1 m weld deposition by three to five times. The aim of pulsing is mainly to achieve maximum penetration without excessive heat build-up, by using the high current pulses to penetrate deeply and then allowing the weld pool to dissipate some of the heat during relatively longer arc period at a low current. The increased numbers of variables in the pulsed GTAW process also support the possibility of increased control of the solidification process. Arc pulsation is responsible for the grain refinement, lesser risk of cracking, reduction in width of HAZ (heat affected zone) and less distortion. A. Kumar et al [3] developed a method to use Taguchi method to optimize the magnetic arc oscillation welding process parameters of non-heat treatable aluminum alloy 5456 welds for increasing the mechanical properties. P. K. Giridharan [4] et al developed optimization of pulsed GTAW process parameters to obtain optimum bead geometry using the developed models. M. Balasubramanian [5] et al used traditional Hooke and Jeeve's algorithm for optimizing process parameters to obtain maximum impact toughness properties in the pulsed GTA welding of titanium alloy. In this paper, AA7039 samples were welded by pulsed GTAW process and testing was carried out on various machines or equipments. The setting of the pulsed GTAW process parameters were determined by using Taguchi's experimental design method. Orthogonal arrays of Taguchi, the signal-to-noise (S/N) ratio, the analysis of variance (ANOVA), are employed to find the optimal levels and to analyze the effect of the GTAW process parameters on properties of welds like microhardness, ASTM grain size number and HAZ width. Confirmation test with the optimal levels of welding parameters was carried out in order to illustrate the effectiveness of Taguchi's optimization method.

II. WELDING OF AA7039

The experiments were performed on a Digital Pulse GTAW TRITON-220 AC/DC welding machine. The aluminium alloys selected for experimentations were AA7039 in T6 condition and filler rod as AA5356 for better penetration and elongation. The chemical composition of the base and filler material is given in table 1.

The 5.0 mm thick samples of aluminium alloy 7039 were cut into the standard sizes (AWS Standard) of 300x 150mm by EDM Wire-cut machine. All samples and filler rods were cleaned by stainless steel wire brush / with acetone for removing the dust, oil, grease and thin oxide coating before welding. A non-consumable tungsten electrode of 2.4mm diameter was used with 30% helium plus 70% argon as a shielded gas. V grove butt weld joints were prepared with AC sinusoidal wave at various currents and frequencies. These welded samples were used to measure the ASTM grain size, weld microhardness and HAZ width.

Table 1 Chemical Composition of Base and Filler Metal (Weight %)

Alloy	Al	Mg	Zn	Others
7039	93.0	2.80	4.00	Rest
5356	95.2	4.8	-	-

III. DOE TAGUCHI METHODS

Full factorial method in the Design of Experiments is having experimental design procedures which are too complicated and not easy to use. A large number of experimental works 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 (OA) to study the entire parameter space with only a small number of experiments [6]. Taguchi methods [7] have been widely utilized in engineering analysis and consist of a plan of experiments with the objective of acquiring data in a controlled way, in order to obtain information about the behavior of a given process. The greatest advantage of this method is the saving of effort in conducting experiments; saving experimental time, reducing the cost and discovering significant factors quickly. The effect of many different parameters on the performance characteristic in a condensed set of experiments can be examined by using the orthogonal array experimental design proposed by Taguchi. Once the parameters affecting a process that can be controlled have been determined, the levels at which these parameters should be varied must be determined. Taguchi's robust design method is a powerful tool for the design of a high-quality system. In addition to the S/N ratio, a statistical analysis of variance (ANOVA) can be employed to indicate the impact of process parameters on mechanical properties of weld joints. The steps applied for Taguchi optimization in this study are as follows:

- ➢ Selecting process parameters and number of levels
- ➢ Selection of orthogonal array
- ➢ Conduct experiments
- ➢ Finding out responses
- ➢ Analyze results; (Signal-to-noise ratio)
- ➢ Predict optimum performance
- ➢ Confirmation experiment

IV. EXPERIMENTAL DESIGN

A standard Taguchi L9 orthogonal array is chosen for this investigation as it can operate up to four parameters, each at three levels. Three parameters, Pulse Current (P); Base Current (B) and Pulse Frequency (F) were chosen for this study, which affect the microhardness, ASTM grain size number of weld zone and HAZ Width. Sufficient details of the effect of different parameter values on experimental results can be obtained by choosing three levels for each parameter to investigate. The criteria used for choosing the three parameter levels were based on the literature survey and the limiting values were decided by no of trial experiments. A large number of trial runs were carried on 5mm-thick aluminium alloy 7039 samples to find out the feasible working limits of pulsed current GTAW parameters. After examining bead morphology of samples, the upper and lower limit of the peak current, base current and pulse frequency were decided. The bead contour, bead appearance and weld quality of the weld joint were inspected in order to identify the welding parameters. From the above analysis, following observations are made:

- ➢ If the peak / pulse current (P) < 150 A, incomplete penetration and lack of fusion were observed. At the same time, if the P > 210 A, under cut, spatters and overheating were observed.
- ➢ If background current (B) < 75 A, arc length was found to be very short. On the other hand, B > 135A, arc became unstable and arc length was increased.
- ➢ If the pulse frequency (F) < 50Hz t he bead cont our and bead appearance was not of good quality. However, if the F > 150 Hz, there was a harsh sound in welding machine.

So here we have selected the range of Peak Current (P) 150 to 210 A, Base Current (B) 75 to 135A and Pulse Frequency (F) 50 to 150 Hz.

V. EXPERIMENTAL PROCEDURE

A. Plan of Experiments:

Taguchi methods which combine the experiment design theory and the quality loss function concept have been used in developing robust designs of products and process [8]. The degrees of freedom for three parameters in each of three levels were calculated as follows [9]. Degree of Freedom (DOF) = number of levels -1. For each factor, DOF equal to:

For (P); DOF = 3 – 1 = 2
For (B); DOF = 3 – 1 = 2
For (F); DOF = 3 – 1 = 2

In this research nine experiments were conducted at different parameters. For this Taguchi L9 Orthogonal array was used, which has nine rows corresponding to the number of tests, with three columns at three levels. L9 OA has eight DOF, in which 6 were assigned to three factors (each one 2 DOF) and 2 DOF was assigned to the error. For this purpose of observing the degree of influence of the process parameters in

GTA Welding, three factors, each at three levels, are taken into account, as shown in tables 2. The microhardness values (H), ASTM grain size number (N) and HAZ width (W) values corresponding to each experiment were shown in table 3.

Table 2 Welding Parameters and Their Levels

Process Parameters	Level 1	Level 2	Level 3
Peak / Pulse Current (P)	150	180	210
Base Current (B)	75	105	135
Pulse Frequency(F)	50	100	150

Table 3 Experimental Results

Exp No.	P	B	F	N	H (VPN)	W (µm)
1.	150	75	50	21.40	85.0	928.8
2.	150	105	100	21.20	90.8	1028.9
3.	150	135	150	21.92	86.0	1248.5
4.	180	75	100	20.50	89.7	1269.0
5.	180	105	150	20.80	87.1	1299.0
6.	180	135	50	18.28	80.7	1325.0
7.	210	75	150	19.20	83.5	1472.0
8.	210	105	50	18.08	75.1	1618.0
9.	210	135	100	17.80	75.6	1743.0

B. Experimental Details:

As per DOE in table 3, nine samples were made by pulsed GTAW process (as discussed in section II, Welding of AA7039) the following welding conditions were maintained constant during the welding:

- *Electrode: Tungsten with 2% Zirconium*
- *Electrode size: 2.4 mm diameter*
- *Shielding gas: 30% helium + 70% argon*
- *Shielding gas flow rate: 8 Liter/min*
- *Filler diameter: 3.15 mm*
- *Welding speed: 4.16 mm/sec*
- *Electric voltage: 16.8 V*
- *AC Balance %: 0 (sinusoidal)*

Specimens were separated out from the transverse section of the weld joint and polished using a standard metallographic procedure, which consisted of molding, polishing and etching. Specimens were etched with Keller's reagent. The microstructures of the specimens were studied under optical microscope (GX51 N233U, Olympus). Image analysis of micrographs of the weld metal was carried out using an image analyzing software.

C. Measurement of Responses:

Microhardness testing at the centre of welds was carried out as per ASTM E-384, which gives an allowable range of loads for testing with a diamond indenters and the resulting indentation was measured and converted to a hardness value. In this study a Digital Vickers Microhardness Tester is used and average microhardness values of weld zone in VHN are presented in table 3. Also the ASTM grain size numbers and HAZ width were measured by optical microscope with image analyzing software and tabulated in the same table.

VI. RESULTS AND ANALYSIS OF EXPERIMENTS

A. Analysis of S/N Ratio:

Taguchi method stresses the importance of studying the response variation using the signal-to-noise (S/N) ratio, resulting in minimization of quality characteristic variation due to uncontrollable parameter. The microhardness and ASTM grain size number were considered as the quality characteristic with the concept of "the larger-the-better" and HAZ width with the concept of "the smaller the better". The S/N ratio used for this type response is given by [8]:

The S/N ratio for the larger-the-better is:

$$S/N = -10*\log\ (\text{mean square deviation})$$

$$S/N = -10 \log 1/n\ (\textstyle\sum 1/y^2) \qquad (1)$$

and for the smaller the better characteristics:

$$S/N = -10 \log 1/n\ (\textstyle\sum y^2) \qquad (2)$$

Where n is the number of measurements in a trial / row, in this case, n=1 and y is the measured value in a run / row. The S/N ratio values are calculated by taking into consideration eqn. 1 and 2. The response values measured from the experiments and their corresponding S/N ratio values are listed in table 4. The response table for the pulse current; base current and pulse frequency was created in the integrated manner and the results are given in table 5.

Table 4 Response values and S/N ratio values for experiments

Exp No	N	H (VHN)	W (µm)	S/N Ratio
1	21.40	85.0	928.90	30.8754
2	21.20	90.8	1028.9	30.8235
3	21.92	86.0	1248.5	30.9796
4	20.50	89.7	1269.00	30.5381
5	20.80	87.1	1299.00	30.6301
6	18.28	80.7	1325.00	29.5547
7	19.20	83.5	1472.00	29.9579
8	18.08	75.1	1618.00	29.3997
9	17.80	75.6	1743.00	29.3258

Table 5 Response Table for Signal to Noise Ratios

Level	Peak Current	Base Current	Pulse Frequency
1	**30.89**	**30.46**	29.94
2	30.24	30.28	30.23
3	29.56	29.95	**30.52**
Delta	1.33	0.51	0.58
Rank	**1**	**3**	**2**

Regardless of the category of the performance characteristics, a greater S/N value corresponds to a better performance. Therefore, the optimal level of the pulse welding parameters is the level with the greatest S/N value. Based on the analysis of the S/N ratio, the optimal welding performance was obtained at 150A pulse current (level 1), 75A Base Current (level 1) and 150 Hz Pulse Frequency (level 3). Fig. 1 shows the main effects of the process parameters on the microhardness, grain size and HAZ width. The microhardness, ASTM grain size number and HAZ width are proportional to increasing in Pulse frequency but inversely proportional to pulse and base current. This can be explained with the help of heat input equation of arc welding. As heat input increases the grains became coarser. Heat input during welding is calculated as $H= [60EI]/1000S$, where H is heat input (kJ/mm), E is arc voltage (V), I is current (A) and S is travel speed of weld (mm/min) [8]. Optimum heat input produces fine grains, higher microhardness and lesser HAZ width, which can be possible only by optimized process parameters

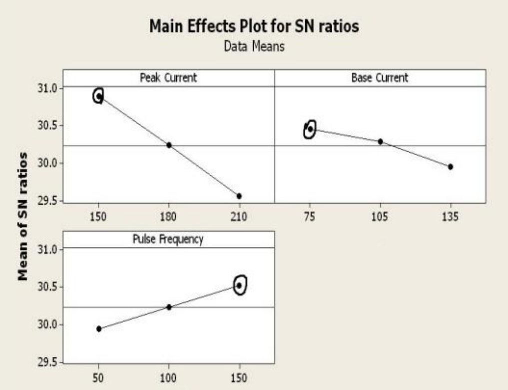

Fig 1 Main Effects Plot for SN ratios

B. *Analysis of Variance (ANOVA):*

ANOVA is a statistically based, objective decision-making tool for detecting any differences in the average performance of groups of items tested. ANOVA helps in formally testing the significance of all main factors and their interactions by comparing the mean square against an estimate of the experimental errors at specific confidence levels. The ANOVA results are illustrated in table 6.

Table 6: Analysis of Variance for Means

Para--meter	DOF	Sum of Square	Mean Square	F	Contributed %
P	2	80.271	40.13	18.1	61.58
B	2	28.616	14.30	6.45	21.95
F	2	17.039	8.520	3.84	13.07
Error	2	4.436	2.218		3.40
Total	8	130.361			

Statistically, there is a tool called as F test, named after Fisher [10], to see which design parameters have a significant effect on the quality characteristic. In the analysis, the F-ratio is traditionally used to determine the significance of a factor. From Fig 2, 3 and 4 the effect of pulse / peak current, base current and pulse frequency on the microhardness, grain size and HAZ width are clearly identified. A confirmation of the experimental design was necessary in order to verify the optimum welding conditions.

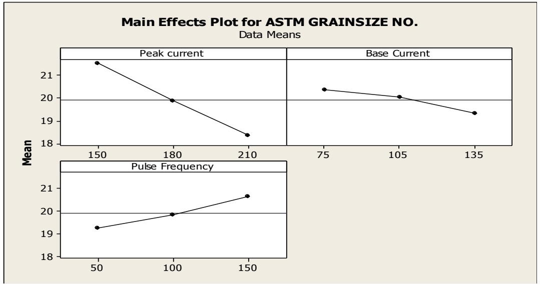

Fig 2 Effect of Process Parameters on Grain Size

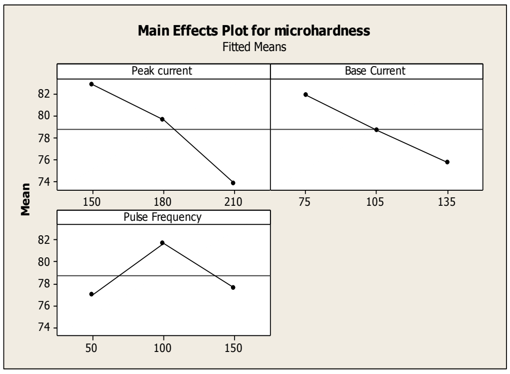

Fig 3 Effect of Process Parameters on Microhardness

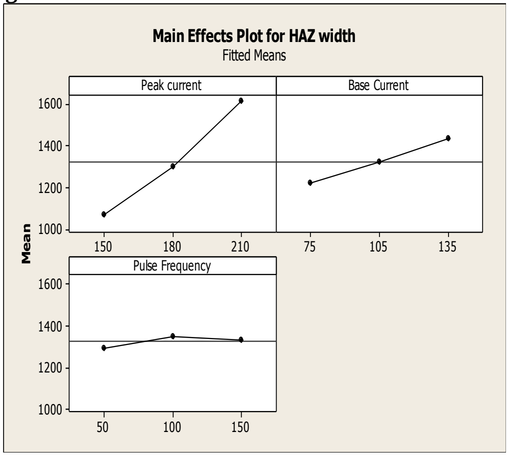

Fig 4 Effect of Process Parameters on HAZ Width (μm)

C. *Confirmation Test:*

The experimental confirmation test is the final step in verifying the results drawn based on Taguchi's design approach. The confirmation experiment is a crucial step and is highly recommended by Taguchi to verify the experimental results [11]. In this study, a confirmation experiment was conducted by utilizing the levels of the optimal process parameters (P1B1F3) for better microhardness of 98.9 VHN in weld zone, grain size 23.4 (ASTM grain size number) and HAZ width 913 (μm).

VII. CONCLUSION

This study has discussed an application of the Taguchi method for investigating the effects of process parameters on the weld microhardness; grain size and HAZ width in the GTA Welded Aluminium Alloy 7039. From the analysis of the results using the signal-to-noise (S/N) ratio approach, analysis of variance and Taguchi's optimization method, the following can be concluded:

- Peak current of 150A, base current of 75A and pulse frequency of 150 Hz are the optimized welding parameters for getting highest microhardness, smallest eqiuxed weld grains and minimum HAZ width.
- Out of three selected parameters, peak current has the highest contribution i.e. 61.58%.

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