**TIG WELDING PROCESS PARAMETER OPTIMIZATION FOR ALUMINIUM ALLOY 6061 USING GREY RELATIONAL ANALYSIS AND REGRESSION EQUATIONS**

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**Abstract**

The present research enumerates the process parameter optimization of TIG welding process with Aluminium alloy 6061 (AA6061). The input parameters such as Weld Current, shielding gas flow rate and Double V Groove angle have been considered in view of optimizing the output parameters such as Tensile strength and hardness of the TIG welded specimens. The experiments are conducted based on L9 orthogonal array. Grey Relational Analysis (GRA) has been employed to get the common optimal combination of considered input factors which yields better results for both the output responses. Optimal regression equations have been generated with the help of Design Expert software. The influence of the input parameters on the output results have been analysed using ANOVA using minitab software. 3D surface plots have been plotted to show the relationship between combinations of input factors with the output responses.

**Keywords:** TIG welding, Aluminium alloy 6061, Regression analysis, Grey Relational Analysis and Double V Groove angle.

1. Introduction

Different types of welding processes are carried out in joining of metals at various manufacturing environments each one has its own process parameters. Various parameters of welding determine the quality of weldments in turn the quality of the components. Tungsten Inert Gas (TIG) welding is one of the commonly used metal joining process owing to its advantage of quality weldments as it is carried out in inert gas environment. Aluminum alloys are difficult weld materials and TIG welding process is commonly employed for such alloys as the concerned parameters are controllable in this process. The various parameters such as Weld Current (WC), Shielding Gas Flow Rate (SGFR) and Double ‘V’ Groove Angle (DVGA) are some of the important process parameters that influence the quality of the weld greatly.

Aluminium Alloy 6061 (AA6061) sets the standard for a medium-to-high strength, lightweight and economical material. The properties of AA6061 include its structural strength and toughness, its machinability, and its ability to be easily welded and joined. AA6061 is used extensively as a construction material and most commonly in manufacturing of automotive components. The commonly used aluminium alloy of grade AA6061 has been chosen in this work for joining using TIG welding process in view of optimizing the various process parameters mentioned above. In order to study and analyze the process parameters and to optimize the same, the AA6061 material specimens have been welded using TIG welding process. The trial of experiments has been planned as per Taguchi L9 orthogonal array by considering the input parameters of WC, SGFR and DVGA at three different levels. The output parameters such as Tensile strength and Hardness at the weld zones have been considered. The results have been analyzed using Grey Relational Analysis (GRA) and formulating regression equations. The best optimized input parameter combination of TIG welding process for AA6061 material in terms of the considered output responses have been suggested. Further, the effect of influence of each input parameters have been predicted with respect to the output responses by carrying out Analysis of Variance (ANOVA) with MINITAB software of version 18.0.

In view of understand the progress made in this area, the published literatures have been collected and thoroughly analysed. Some of them have been presented with their highlights. G.Magudeeswaran et al. had performed on the activated TIG (ATIG) welding process by focusing the depth of penetration of weldment [1]. K.S.Pujari et al. optimized the gas tungsten arc welding process parameters of Aluminium Alloy 7075-T6 welded joints. Further, ANOVA analysis was employed by the authors to reveal the influence of individual parameters in obtaining the optimal results [2].M.Balasubramanian et al. used lexicographic method to optimize the gas tungsten arc welding process parameters for titanium alloy material and the authors suggested the optimal factor combination in order to obtain the strong weld pool geometry [3]. Arun Kumar Srirangan et al. had an attempt on optimizing the TIG welding process parameters with the Inconel alloy 800HT by considering current, welding speed and voltage as the influencing parameters [4]. A.Kumar et al. had an attempt to analyze the tungsten inert gas welding process parameters on Al-Mg-Si alloy welded joints in order to improve their mechanical parameters and their results revealed that the impact strength and notch tensile strength were inversely proportional to each other [5]. G. Rambabu et al. had developed mathematical model for the corrosion resistance of aluminium alloy 2219 friction stir welded joints by setting profile of tool pin, axial force, rotational and welding speeds as the input parameters for the work [6]. S.C Juang., et al. had analyzed the optimal selection of input parameters to set the geometry of the weld pool on the TIG welded stainless steel specimens [7]. A. Kumar et al. had published another work with 5456 Aluminum alloy weldments and improved mechanical properties through pulsed TIG welding process. Taguchi method was employed by them for optimizing the influencing factors of pulsed TIG welded on AA5456 joints [8]. Joby Joseph et al. focused in their published work on optimizing the activated TIG welding controllable factors for achieving better strength with AISI 4135 PM steel TIG welded specimens by means of Genetic Algorithm (GA). Further, they reported that voltage and current had maximum influence on obtaining maximum tensile strength in A-TIG-welded joint [9]. RaviShanker Vidyarthy et al. investigated the TIG welding process parameters on 9 to 12 % Chromium Ferritic Stainless steel using Central Composite Design; and reported that welding speed, welding current and flux coating density had the direct influence on the weld strength [10]. A.Balaram Naik et al. had an optimization work on TIG welding process parameters with 2205 stainless steel material. The authors used Neural network technique and ANOVA for setting out the optimal input combinations [11].

It is inferred from the literatures that the optimization of process parameters with respect to TIG welding process with various materials have been considered by various authors. The AA6061 material is one of material used for non corrosive environment has got the scope for further study with TIG welding process. The input parameters such as WC, SGFR and DVG have a scope for further analysis with respect to Output responses of Tensile strength and hardness. The oxidizing nature of aluminum alloys limits the weldability of AA6061 and TIG welding is one of convenient process to overcome the same. The study of optimizing the process parameters would help the manufacturers involved in use of such alloys.

1. Experimental Work

The proposed material AA6061 of size 150 X 75mm with the thickness of 6mm has been chosen as master piece and V groove of various angles was formed at the edges after cleaning the surface. The welding was performed using TIG welding process along the length of 150mm. The test specimens were prepared using Wire Cut Electrical Discharge (WEDM) machining process from the master piece as per ASTM standard E-8M for performing tensile test. The Vickers hardness test was performed over the welded zone. The chemical composition and the mechanical properties of Al6061 alloy are presented in the tables 1 and 2.

Table 1. Chemical composition of Al 6061

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Element** | Cr | Cu | Fe | Si | Ti | Zn | Mg | Mn | Al |
| **Wt. %** | 0.15 | 0.21 | 0.60 | 0.38 | 0.03 | 0.01 | 1.03 | 0.06 | Bal. |

Table 2. Base Material Properties

|  |  |
| --- | --- |
| **Properties** | **Values** |
| Ultimate tensile strength (MPa) | 310 |
| Yield strength (MPa) | 270 |
| Modulus of elasticity (GPa) | 70 – 80 |

* 1. Design of Experiments (DOE)

In view of optimizing the strength and hardness of the weldment, the input parameters of TIG welding such as Weld current (WC), Shielding Gas Flow Rate (SGFR) and Double ‘V’ Groove Angle (DVGA) were considered for the analysis at three different levels which are presented in table 3. The experiments to be performed were decided based on Taguchi’s L9 orthogonal array table. The combinations of the selected parameters for performing experimentation on samples with the input parameters and their levels are presented in table 4.

Table 3. Selection of levels and parameters

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **S.No.** | **Parameters** | **Units** | **Level 1** | **Level 2** | **Level 3** |
| 1 | WC | Amps | 150 | 170 | 190 |
| 2 | SGFR | Lpm | 6 | 8 | 10 |
| 3 | DVGA | Degrees | 30 | 40 | 45 |

* 1. Specimen Preparation

In each category of samples three specimens were prepared and tested. Hence for nine set of parameters, as presented in Table 4, totally 27 samples were prepared using TIG welding process. The test samples were prepared from the master sample for tensile and hardness tests using Wire-cut Electrical Discharge Machine (WEDM) following ASTM Standards. The welded zone was grinded so as to make smooth surface by removing the burrs.

Table 4. The Taguchi’s L9 Orthogonal Array

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **S.No.** | **Sample No.** | **Input Parameters** | | |
| **WC** | **SGFR** | **DVGA** |
| 1 | SA01 | 150 | 6 | 45 |
| 2 | SA02 | 150 | 8 | 40 |
| 3 | SA03 | 150 | 10 | 30 |
| 4 | SA04 | 170 | 6 | 40 |
| 5 | SA05 | 170 | 8 | 30 |
| 6 | SA06 | 170 | 10 | 45 |
| 7 | SA07 | 190 | 6 | 30 |
| 8 | SA08 | 190 | 8 | 45 |
| 9 | SA09 | 190 | 10 | 40 |

* 1. Tensile Test

Tensile tests on the samples were performed with computer interfaced universal testing machine of 60 tones capacity. It had the provision to extract the test data to a computer interfaced with the digital data logger. The tensile test specimens before and after the testing are shown in figure 1 and 2.

|  |  |
| --- | --- |
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| **Fig 1.** Specimens for the tensile testing | **Fig 2.** Tensile tested specimens |

* 1. Hardness Test

Hardness test was conducted on Vickers Hardness Testing machine. The hardness test was made on all the test specimens at the welded portion.

* 1. Optimization Techniques

Grey Relational Analysis (GRA) is one of the multi objective optimization techniques since it provides the optimized combination of input parameters for obtaining desirable results for all the output parameters. With the grey relational grade values obtained from the analysis, Taguchi’s approach was used to confirm the results.

Regression analysis provides the relationship between the input parameters with each output parameter in the form of statistical equations. By conducting more number of experiments, we can frame the regression equation with better accuracy.

1. Results and Discussion

The results of tensile strength test and hardness test are presented in table 5.

**Table 5.** Tensile Test Results

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **S.No.** | **Sample No.** | **Ultimate Strength (MPa)** | | | | **Vickers Hardness Number (VHN)** | | | |
| **T1** | **T2** | **T3** | **Tavg** | **T1** | **T2** | **T3** | **Tavg** |
| 1 | SA01 | 123.50 | 122.70 | 123.10 | 123.10 | 87.60 | 86.60 | 87.10 | 87.10 |
| 2 | SA02 | 99.80 | 98.80 | 99.30 | 99.30 | 86.20 | 87.00 | 86.60 | 86.60 |
| 3 | SA03 | 132.60 | 133.40 | 133.00 | 133.00 | 86.10 | 85.30 | 85.70 | 85.70 |
| 4 | SA04 | 103.90 | 105.50 | 104.70 | 104.70 | 84.50 | 80.40 | 82.45 | 82.45 |
| 5 | SA05 | 110.80 | 111.20 | 111.00 | 111.00 | 82.90 | 84.30 | 83.60 | 83.60 |
| 6 | SA06 | 121.00 | 120.80 | 120.90 | 120.90 | 87.40 | 82.20 | 84.80 | 84.80 |
| 7 | SA07 | 106.20 | 105.00 | 105.60 | 105.60 | 86.50 | 82.20 | 84.35 | 84.35 |
| 8 | SA08 | 127.50 | 125.10 | 126.30 | 126.30 | 84.20 | 81.80 | 83.00 | 83.00 |
| 9 | SA09 | 138.40 | 136.50 | 137.45 | 137.45 | 84.20 | 83.10 | 83.65 | 83.65 |

* 1. Grey Relational Analysis (GRA)

With the avialable test results, the technique of GRA has been employed for predicting the best set of parameters that yields best tensile and hardness value.

The output parameters of tensile and hardness properties will have different units. In order to consider them together, the normalization of the parameters are inevitable. The normalization of the above parameters were carried out as the first step of GRA. Followed by, the deviation sequences for the considered outpt responses were predicted. Table 6 represents the normalized values and deviation sequences of each output responses.

**Table 6.** Normalized values and Deviation sequensces of responses

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **S.No.** | **Sample No.** | **Normalized values** | | **Deviation Sequences** | |
|  | **VHN** |  | **VHN** |
| 1 | SA01 | 0.624 | 1.000 | 0.376 | 0.000 |
| 2 | SA02 | 0.000 | 0.892 | 1.000 | 0.108 |
| 3 | SA03 | 0.883 | 0.699 | 0.117 | 0.301 |
| 4 | SA04 | 0.142 | 0.000 | 0.858 | 1.000 |
| 5 | SA05 | 0.307 | 0.247 | 0.693 | 0.753 |
| 6 | SA06 | 0.566 | 0.505 | 0.434 | 0.495 |
| 7 | SA07 | 0.165 | 0.409 | 0.835 | 0.591 |
| 8 | SA08 | 0.708 | 0.118 | 0.292 | 0.882 |
| 9 | SA09 | 1.000 | 0.258 | 0.000 | 0.742 |

The Grey Rlational Coefficient values and Grade Relational Grade values were computed with the help of regular formulae, which are tabulated and presented in table 7.

**Table 7.** Grey Relational Coefficient and Grey Relational Grade values of output responses

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Sample No.** | **Grey Relational Coefficient** | | **Grey Relational grade** | **Rank** |
|  | **VHN** |
| SA01 | 0.571 | 1.000 | 0.785 | 1 |
| SA02 | 0.333 | 0.823 | 0.578 | 4 |
| SA03 | 0.811 | 0.624 | 0.718 | 2 |
| SA04 | 0.368 | 0.333 | 0.351 | 9 |
| SA05 | 0.419 | 0.399 | 0.409 | 8 |
| SA06 | 0.535 | 0.503 | 0.519 | 5 |
| SA07 | 0.375 | 0.458 | 0.416 | 7 |
| SA08 | 0.631 | 0.362 | 0.496 | 6 |
| SA09 | 1.000 | 0.403 | 0.701 | 3 |

Taguchi analysis was then made to finalize the optimal combination of input responses from the Grey Relational Grade values with the help of minitab software 18.0. The main effect plot for the S/N ratio values of the Grey Relational Grades obtained from the Taguchi analsyis is shown in the figure 4.

As observed from figure 4, the optimal parameter combination for the TIG welding process on Alloy 61s regarding Tensile strength and Hardness were noted as: Current (150 A), Gas flow rate (10 lpm) and Double V Groove angle (45 degree). The confirmation test was conducted with the arrived optimal combination of input parameters and the results were arrived for the Tensile strength value as 136.4 MPa and Hardness value as 87 VHN. Analysis of Variance was prformed for the Grey Relational Grades corresponding to the levels of input parameters. The ANOVA table obtained for the proposed case is as shown in the table 8. From the results of ANOVA table, it was palpable that Weld current inflenced more in getting optimal output results; and the least inflencing factor was identified as Double ‘V’ Groove angle.

|  |
| --- |
|  |
| **Fig.4.** Main effects plot for S/N ratio values of Grey Relational Grade values |

**Table 8.** ANOVA Results for the considered process parameters

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Main Control Factors** | **Degree of**  **freedom**  **(DF)** | **Sum of squares**  **(SS)** | **Mean of squares**  **(MS)** | **P - Value** | **Contribution,**  **C (%)** |
| **WC (A)** | 2 | 0.10820 | 0.054099 | 0.209 | 57.46 |
| **SGFR (lpm)** | 2 | 0.04009 | 0.020043 | 0.417 | 21.29 |
| **DVGA (Degree)** | 2 | 0.01139 | 0.005695 | 0.715 | 6.05 |
| **Error** | 2 | 0.02861 | 0.014307 | - | 15.20 |
| **Total** | 8 | 0.18829 | - | - | 100.00 |

* 1. Regression Analysis

The tensile and hardness test results were fed into the Design Expert software with their corresponding combination of input parameters. The optimized statistical relationship between the input parameters and tensile strength as well as with hardness values were arrived as represented in equations 1 and 2 with the R-squared values of 0.9694 and 0.8768.

(Equation 1)

(Equation 2)

|  |  |
| --- | --- |
| C:\Users\MARCEL\Desktop\TS.bmp | C:\Users\MARCEL\Desktop\VHN.bmp |
| **Fig 5.** 3D surface plot of TS vs. WC & SGFR | **Fig 6.** 3D surface plot of VHN vs. SGFR & DVGA |

The 3D response plots were drawn and analyzed the effects of varying the levels input factors on the responses, which are shown in figures 5 and 6. The 3D plots revealed that increasing the value of Weld Current, it can be achieved the TIG welded specimens with more tensile strength. Tensile strength also increased with the increase in gas flow rate. In case of achieving better hardness results, Double ‘V’ Groove angle had less siginificant effect and the increase in the gas flow rate and increase in VHN were of directly proportional.

1. Conclusion

* In this work, optimization of TIG welding process parameters was performed using Taguchi based Grey Relational analysis and Regression analysis. Three parameters with three levels were considered for the analysis. Experiments have been conducted as per the parameter combination of L9 Orthogonal Array.
* From the Grey Relational analysis, the optimal parameter combination for the TIG welding process on AA6061 are: Current (150 A), Gas flow rate (10 lpm) and Double V Groove angle (45 degree).
* The optimal results for the tensile strength and hardness values were noted for the TIG welded Aluminium Alloy 6061 joints were noted as 136.4 MPa and 87 VHN respectively.
* ANOVA results revealed that the most influencing process parameter for achieving the optimal results was Weld current (57.46%), followed by Shielding Gas Flow Rate (21.29%) and Double ‘V’ Groove angle (6.05%).
* The statistical relationships were arrived for the input parameters with each output responses with the help of Regression analysis with the R-Squared values of 0.9694 and 0.8768.
* The 3D relationship plots were drawn and analyzed. The results showed that tensile strength will be higher while increasing the values of weld current and gas flow rate. By increasing the gas flow rate, the hardness value of the welded specimens got increased.

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