The Hardness Behaviour of TIG Welded Al6061 Alloy Using Statistical Tool

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Received: December 2017 Accepted: March 2018

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DOI: 10.22068/ijmse.15.2.88

Abstract: *Correlation between weldability and improvement in properties is a key issue in materials science research. The objective of this work is to optimize the process parameters viz., aging temperature, aging time, solutionizing time, to enhance the hardness of Al6061 alloy. Hence, the present paper deals with hardness study of Tungsten Inert Gas welded 6061 aluminium alloy after age hardening under three different aging temperatures, aging time and solutionizing time using Taguchi's L_9 Orthogonal array. Finally, a second order model has been generated for hardness using Response Surface Methodology with 20 runs for full design. The predicted and experimental results are in good agreement.*

Keywords: *6061 Aluminium Alloy, Tungsten Inert Gas Welding, Taguchi's Design of Experiments, Hardness, Response Surface Methodology.*

1. INTRODUCTION

Aluminum- magnesium-silicon alloys (Al-Mg-Si; also denoted as 6xxx series), are medium strength, heat treatable alloys with good formability and corrosion resistance. The 6061aluminium alloy has been studied extensively because of their technological importance and further increase in strength obtained by precipitation hardening. Precipitation hardening method is used to improve mechanical properties of material which includes alloys of aluminium, magnesium, nickel copper, titanium, and some stainless steels[1,2]. From decades 6061 Aluminium alloy has been extensively used in automobile and aerospace applications due to its high strength, excellent weldability and resistance to corrosion. Due to reduction in strength at heat affected zone (HAZ) they do not exhibit clear endurance limit [3]. Square-butt joints were fabricated in a single-pass welding without filler. The microstructures of the as-welded joints showed appreciable changes in the grain size of the aged joints. When the temperature was changed greatly, as in the welding process, the precipitation kinetics modified significantly and this had a great impact on the mechanical behavior of the welded joints. The hardness values of fusion zone (FZ) and heat affected zone was higher in the artificially aged welded joints than those of the as-welded joints because of the creation of hardened precipitates during aging treatment. The artificial aging was found to be valuable to augment the tensile strength of the TIG welded joints. Uniform distribution of precipitates resulted by the aging treatment, enhances the resistance to depression during the action of tensile loading. The fracture surfaces of the base metal and TIG welded joints reveals the type failure and the UTS values of artificially aged joints was found to be higher when compared with the values of as-welded joints [4]. Joints were fabricated by variable polarity tungsten inert gas (VPTIG) welding process on AA2219 aluminium alloy and the effects of post welded heat treatment (PWHT) on the tensile properties, microstructure and fatigue behavior of the welded joints was investigated. The VPTIG welding was carried out using the filler ER2325. The welded samples were divided into as-weld and post weld heat treatment. For AW joints the tensile and fatigue tests were performed immediately after welding process and for PWHT joints, heat treatment was conducted before the latter tests [5]. Taguchi method was found to have a systematic application of design and analysis of experiments which has become a powerful tool for aiding in

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[DOI: 10.22068/ijmse.15.2.88]

production of high quality products at low cost [6]. Mathematical modelling of processes with the principle of design of experiments has evidenced to be an efficient procedure for carrying out minimum number of experiments leading to saving time and cost [7,8].

Present work focusses with hardness study of TIG welded 6061 aluminium alloy after age hardening under three different aging temperatures, aging time and solutionizing time using Taguchi's L_9 Orthogonal array. Finally, a second order model has been generated for hardness using Response Surface Methodology with 20 runs for full design. The objective of this paper is to highlight the correlation between weldability and improvement in properties and optimization of the process in order to understand their relationship using statistical tool. The study reveals that the predicted and experimental results obtained for the improvement in hardness by age hardening of TIG welded 6061 Aluminium alloy are in good agreement.

2. EXPERIMENTAL PROCEDURE

The TIG welded 6061 aluminium alloy specimen of 6mm thickness and 300mm X 75mm area on a V-groove of angle 65° (Fig. 1) having hardness of 84 BHN on weldment has been used in this experimentation. The weld shows excellent fusion at the joints without cracks or burrs. Fig. 2 shows the SEM image of 6061 Aluminium alloy. The image shows equi-axial fine grains without porosity or micro cracks. Table 1 shows the chemical composition of 6061 Al alloy. The weldment is then age hardened for three different aging temperatures aging time and solutionizing time using levels selected by Taguchi's L9 orthogonal array (Table 2). Finally, a second order model has been generated using levels selected by response surface methodology which is an experimental design [7, 8] based on the factors and their levels (Table 3).

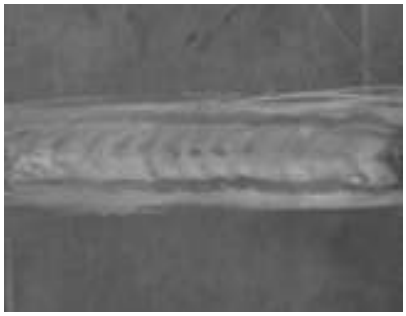

Fig. 1. Pictorial View of TIG Welded Specimen

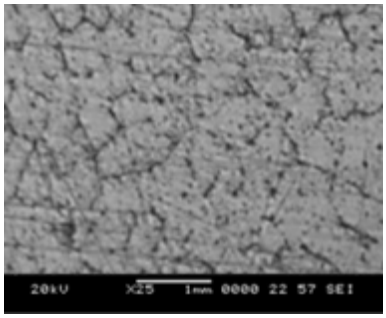

Fig. 2. SEM image of 6061 Aluminium alloy

Table 1. Nominal Chemical Composition of 6061Al alloy

Element	Cu	Mg	Si	Cr	Al
Wt.%	0.25	1.0	0.6	0.25	Balance

Table 2. Levels and Factors (Taguchi's Methodology)

Levels	Aging temperature (^{o}C)	Aging time (h)	Solutionizing time (h)
1	100	5	1
2	150	8	2
3	200	11	3

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Table 3. Levels and Factors (Response Surface Methodology)

Levels	Aging temperature (°C)	Aging time(h)	Solutionizing time(h)
1	100	5	1
2	200	11	3

3. DESIGN OF EXPERIMENTS

In order to carry out the optimization design of experiments (DOE) is used widely in a variety of situations. Some variations are made to one or other process variables in the experiment in order to observe the consequence of those changes have on the response variables. It is an effective method for planning experiments so that the data achieved can be considered to produce valid and objective conclusions. DOE allows manipulation of multiple input factors determining their effect on a desired response. The analysis is made using the design of experiment applications with MINITAB software. The possible interactions between the control factors is considered prior to attempting to use the model as a predictor for the measure of performance. To know the influence of several factors, their interactions, relative significance and to determine the experimental deviation, it is desirable to develop analysis of variance (ANOVA) or analysis of means (ANOM) table.

3. 1. Taguchi's Method

Taguchi techniques is being used extensively in manufacturing design [9]. Taguchi techniques uses parameter design, an engineering technique for product or process design which emphases on determining the parameter settings generating the best levels of performance characteristic with a minimum variation. It provides a dominant method for process design that operate steadily and optimally over a variety of circumstances. Determination of the optimum design results in the use of strategically planned research which discovers the process to numerous stages of design parameters [10].

3. 2. Response Surface Methodology

The Response Surface Methodology (RSM) is a technique used with an aim of calculating and optimizing the output variables that are influenced by several factors.In the present paper, the Central Composite Design (CCD) of RSM is used for creating the experimental association amongst the input hardness factors and the output variables of 6061 aluminium alloy.

4. RESULTS AND DISCUSSION

Presently, many investigations are on to determine the usage of 6061 aluminium alloy. It has become a potential material for aerospace and automotive applications. However, welding of 6061 aluminium alloy poses some challenges. Hence results and discussion deal with weldment study such as hardness for three different aging temperatures aging time and solutionizing time with Taguchi's L_9 Orthogonal array (as shown in Table 4). Response Surface Methodology is generated using a second order model (as shown in Table 7).

Table 4. Experimental design matrix L9 Orthogonal array

Aging temperature (°C)	Aging time (h)	Solutionizing time (h)	Hardness (BHN)
100	5	1	97.34
100	8	2	101.62
100	11	3	104.55
150	5	2	94.66
150	8	3	97.33
150	11	1	94.83
200	5	3	94.34
200	8	1	93.29
200	11	2	89.54

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4. 1. Taguchi's Design of Experiments

Hardness behaviour of TIG welded 6061 aluminium alloy under different aging conditions has been identified for different aging temperature, aging time and solutionizing time using L_9 orthogonal array to obtain optimum condition for hardness (as shown in Table 4).

The graph (as shown in Fig. 3) clearly shows that the optimum solutionizing time is 3h. Aging time is more significant thus more desirable. Solutionizing at 1h and 2h, hardness is less during aging at different temperatures which may be due to partial phase change of the two phase room structure into single high temperature phase [11-13]. Fig. 4(a) and (b) show the Optical images of 6061 aluminium alloy welded (as weld) and age hardened at 100°C aging temperature, 8h aging time and 3h solutionizing time (optimized). Confirmation test is carried out to check the hardness and the result was positive showing increase in hardness than all the other combinations shown in table 4. The optical image showed very fine grains without voids or cracks. Aging at high temperatures shows decrease in the peak hardness values. But peak hardness values are attained in shorter duration compared to lower aging temperature [8]. The main effects plot (ANOVA and ANOM) Figs. 5 and 6 for hardness indicates the selection of aging temperature of 100°C, aging time of 8 h and solutionizing time of 3 h result in best combination to get more hardness value for TIG welded 6061 aluminium alloy. Age hardening at different temperature leads to change in the hardness values[

The table for analysis of variance is developed to analyse the order of significant factors as well as of interactions for a significance level of $\alpha = 0.05$, i.e. for a confidence level of 95%. The level of significance for each cause is shown in table 5 with the actual P values. The measure of performance is considered to have a statistically

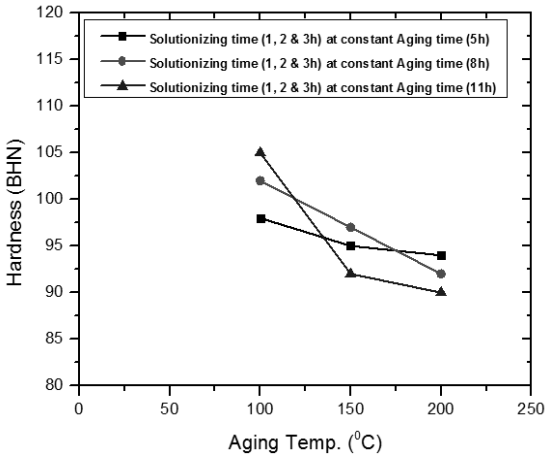
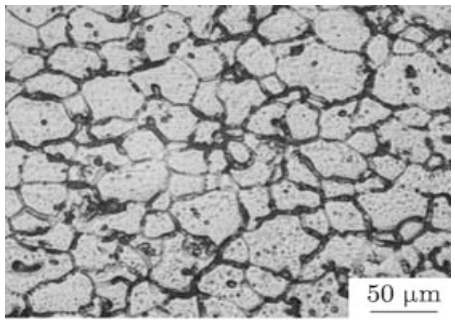
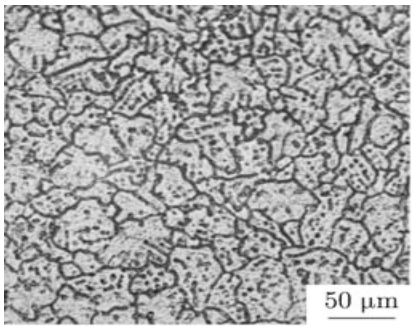


Fig. 3. Variation of Hardness with gaining temperature for different aging time and solutionizing time.



(a) As-weld (before optimizing)



(b) Age hardened at 100° C, 8h aging time and 3h solutionizing time(optimized).

Fig. 4. Optical image of 6061 Aluminium alloy

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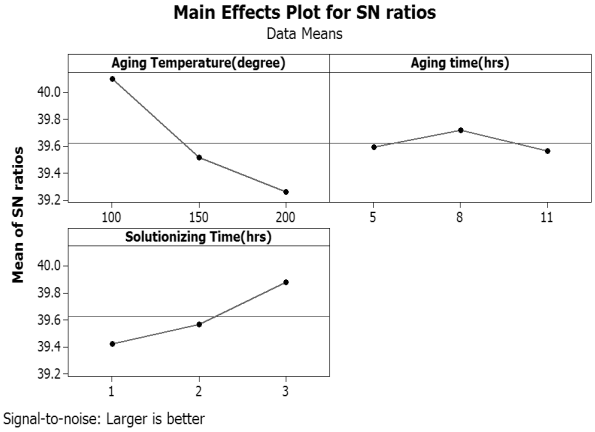

Fig. 5. Mean S/N graph for Hardness (BHN)

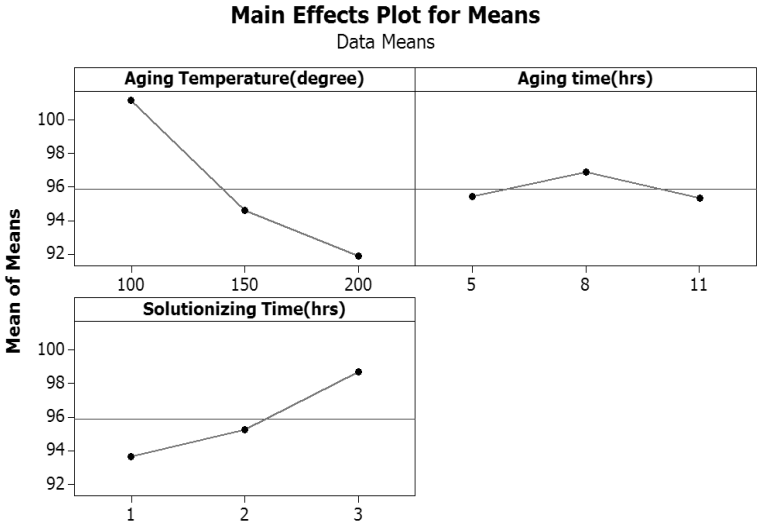

Fig. 6. Mean of means for Hardness (BHN)

substantial impact for a cause with a P-value less than 0.05. The percent influence of each source to the total deviance representing the amount of influence on the outcome is also shown in the table 5.

It is observed that the percentage contribution

Table 5. Analysis of variance for S/N ratio

Source	DF	Seq SS	Adj SS	Adj MS	F	P	P (%)
Aging Temperature (°C)	2	1.104	1.104	0.5523	19.35	0.049	77.7
Aging Time(h)	2	0.039	0.039	0.0199	0.70	0.589	2.30
Solutionizing Time (h)	2	0.329	0.329	0.1646	5.77	0.148	20.0
Residual Error	2	0.057	0.057	0.0285			
Total	8	1.530					

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Table 6. Response table for Signal to Noise ratios: Larger is better

Level	Aging temperature (°C)	Aging time (h)	Solutionizing time (h)
1	40.10	39.59	39.42
2	39.52	39.72	39.57
3	39.26	39.56	39.88
Delta	0.83	0.15	0.46
Rank	1	3	2

Table 7. Response table for Means: Larger is better

Level	Aging temperature (°C)	Aging time (h)	Solutionizing time (h)
1	101.17	95.45	93.62
2	94.61	96.88	95.27
3	91.85	95.31	98.74
Delta	9.32	1.57	5.12
Rank	1	3	2

(P %) of Aging Temperature has the maximum influence of about 77.70% in the enhancement of hardness. It can be seen that Aging Time (P=2.30%), and solutionizing time (P=20%) present a statistical significance, and percentage of physical significance of influence to the hardness. Table 6 and Table 7 show the Response table for Signal to Noise ratios and means using 2-way ANOVA model.

4. 2. Second Order Model for Hardness Behavior of Age Hardened 6061 Aluminium Alloy Response Surface Methodology

In response surface methodology, 20 arrays of experiments are dealt with using the standard ordering and are carried out according to experimental design matrix as shown in Table 8. A second-order model has been established for hardness using response surface methodology. The second order response surface representing the hardness parameters such as (A-degree), (B-h), and (C-h). The relationship between the output variable 'y' and the hardness parameters (A, B, and C) is expressed in the form of a second degree linear polynomial regression equation [12].

$$y = \beta_o + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 A^2 + \beta_5 B^2 + \beta_6 C^2 + \beta_7 AB + \beta_8 AC + \beta_9 BC + \varepsilon \quad (1)$$

where, β_0, β_1, β_2, β_9 are the regressor coefficients and ε is the random error [15]. The relationship between the hardness and age hardening parameters obtained has been expressed as follows:

Hardness (BHN) = 79.4809 - 0.0223321A +7.78075B – 5.54818C + 0.00030181818A2 - 0.294495B2 + 1.38455C2 -0.0200167AB - 1.40800x10-17 BC -2.7059x10-16AC----- (2)

Table 9 shows the result of ANOVA for measured hardness. The study is carried out for a level of significance of 5%. Since the calculated F value is greater than the F-table value ($F_{0.05}$, 9, 10=3.02), the developed second order response function is agreeable.

Fig. 7 shows the Contour and Surface Plot for Hardness (BHN) V/s Aging Temperature (degree) and Aging Time (h).

In brief, lower temperature of aging and longer duration results in higher peak hardness value.

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Table 8. Experimental design matrix

Aging temperature (°C)	Aging time (h)	Solutionizing time (h)	Hardness (BHN)
100	5	1	97.34
200	5	1	94.34
100	11	1	104.55
200	11	1	89.54
100	5	3	97.34
200	5	3	94.34
100	11	3	104.55
200	11	3	89.54
100	8	2	101.62
200	8	2	93.24
150	5	2	94.66
150	11	2	94.83
150	8	1	97.33
150	8	3	97.23
150	8	2	97.33
150	8	2	97.33
150	8	3	97.23
150	8	2	97.33
150	8	2	97.33
150	8	2	97.33

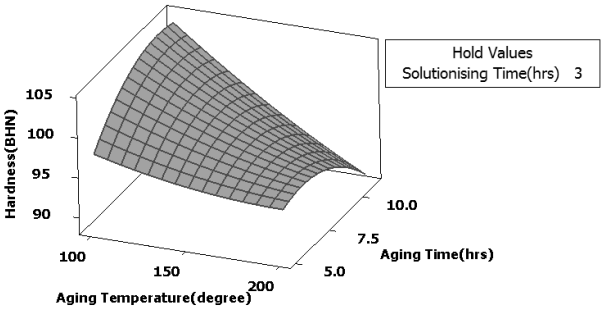

Fig. 7. Contour and Surface Plot Hardness (BHN) V/s Aging Temperature (degree), Aging Time (h)

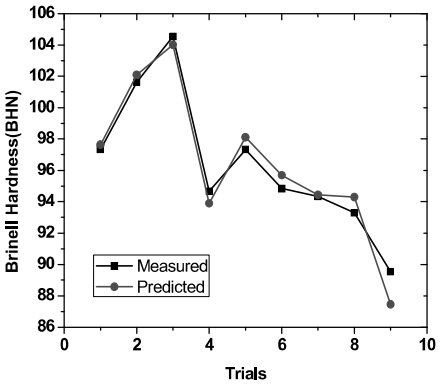

Fig. 8. Comparison plots of the measured and predicted hardness of 6061 Aluminium alloy

Table 9. Analysis of variance for Hardness (BHN)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	303.556	303.556	33.7285	25.07	0.000
Linear	3	211.629	211.629	70.5431	52.43	0.000
Square	3	19.807	19.807	6.6023	4.91	0.024
Interaction	3	72.120	72.120	24.0400	17.87	0.000
Residual Error	10	13.455	13.455	1.3455		
Pure Error	5	0.016	0.016	0.0033		
Total	19	317.011				

5. VALIDATION OF EXPERIMENTAL RESULTS

The validation tests are carried out to confirm the adequacy of the Taguchi experimental results for hardness after age hardening under three different aging temperatures, aging time and solutionizing time by means of Taguchi's L_9 Orthogonal array. The Taguchi L_9 experimental results of hardness and the anticipated results of hardness as per RSM are used for drawing the comparison plots. Fig. 8, shows that the

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experimental outcomes of hardness are in decent agreement with the predicted outcomes of hardness.

6. CONCLUSIONS

Results of the present research work concludes as follows

1. The main effects plot (ANOVA and ANOM) for hardness indicates the selection of aging temperature (100°C), Aging time (8h) and solutionizing time of (3h) result the best combination to get more hardness value for TIG welded 6061 aluminium alloy.
2. Percentage influence (P %) of the different factors for hardness shows that aging temperature has the highest contribution of about 77.70%. Hence aging temperature is one essential factor to be considered. It is noticed that aging time (P=2.30%), and solutionizing time (P=20%) has a statistical significance, and the percentage of physical significance of influence to the hardness.
3. A second-order response surface model for the hardness was established from the experimental data. The anticipated and measured values found to be fairly close by, which specifies that the developed model can be effectively used to estimate the hardness of TIG welded 6061 aluminium alloy with 95% confidence levels. Remarkable savings in cost and time can be obtained making use of such model.
4. Validation tests prove that the results of hardness obtained through RSM are adequate with more than 95% confidence level.
5. The result achieved shows that by means of an appropriate selection of age hardening parameters, it is possible to achieve a better understanding of TIG welded 6061aluminium alloy.

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