Study of Factors Affecting Artificial Aging of 6061 Aluminum Alloy by Factorial Design

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ABSTRACT

The objective of this research was to study into the effects of the impact factors hardness of the Aluminum alloy 6061 from the process of artificial aging. This research uses 2^3 factorial design had implemented in which 3 independent factors were used time durations for solution treatment and for temperatures and time durations aging. Two fixed levels of each factor were chosen from a recommended practical range. factorial design was, therefore, implemented with the following levels of each factor: solution treatment temperatures (in ^{o}C) 500 and 595; aging times (in hour) 2 and 8; and, aging temperatures (in ^{o}C) 175 and 200.The results found that, solution time and aging time It has affecting hardness them are significant statistically and the all factors interaction, and a mathematical model for predicting hardness from the independent variables had been formulated. The model could give ± 6.73 BHN as 95% confidence limits.

Keywords: Aluminum alloy 6061, artificial aging, Design of experiment, Factorial Design.

1. INTRODUCTION

Nowadays, with the development of the industry continues, aluminum in industrial applications has continuously increased (Polmear, I.J., 2006). This is due to its lightweight, ability to resist corrosion in itself, and easy formation (Chandler, H., 1996). Aluminum alloy 6061 is used as a key component for industrial production of cars, boats, and is also used as raw materials in the production of other goods.

Aluminum alloy 6061 contains magnesium alloy 0.8-1.2% and silicon 0.4-0.8%. It is a type of material that hardness and strength can be increased by cold forming and heat treatment [3-8], a crystallization process to enhance its mechanical properties thus making it higher in mechanical properties. Generally, an age hardening of aluminum alloy grade 6061 has steps as follows: firstly, it is heat-treated to a solution treatment, the solution treatment temperature that allows phase to dissolve solids into a homogeneous content, secondly water quench it in order to make magnesium and silicon residue in solid solution in amounts greater than saturation at lower temperatures before artificially aging it to crystallize (precipitation). The crystals formed have a strong interface with the basic structure (coherent precipitates).

A number of present studies on the process of hardening by means of crystallization to optimize the hardening process have been conducted but only in a limit range. The purpose of this research is therefore to investigate into the part of information that has not yet been found by studying the influence of the structure after heat treatment by means of crystallizing aluminum alloy 6061. The factorial statistical experiment design has been used to study the influence of factors affecting the hardness values after an artificial aging to show the relationship between the hardness values and the factors that significantly influences the hardness values in the form of linear equations.

2. EXPERIMENTAL DESIGN

Prior to designing, a study of related research including the consideration of suggestions for practice of ASTM Standards (American Society for Testing and Material, 1998). to determine the optimal level of each factor for use in the trial was carried out. In the trial, the time for a constant solution aging was set at 2 hours according to the study of Remesh et al. (2009), Ozturk et al. (2010) and Rattanaporn (2011). The experimental factors, as shown in Table 1, showed the highest and lowest levels of each factor.

Table 1 Factor Levels in the 2^3 Factorial Experiments

Factors	Factor Levels		Symbols
	Low (-1)	High (1)	
Solution Temperature (h)	500	595	A
Aging Time (h)	2	8	B
Aging Temperature (°C)	175	200	C

The 2^3 factorial experiment design has eight experimental conditions (treatment combinations)[13-14], each was repeated four times (4 replicates) to increase the accuracy of observation values and to reduce the experimental errors. The order of 32 experimental operations were randomly made in order for the effects of noise variable to share with every value of the data and to make the data of each value independent to each other. The order of experiment is shown in Table 2.

Table 2 the 2^3 Factorial Experiment Design

Aging Time (h)	Aging Temp (^{0}C)	Solution Temp (^{0}C)							
		1		2		3		4	
		500	595	500	595	500	595	500	595
2	175	2	17	20	5	25	14	29	27
	200	8	24	28	7	4	16	12	13
8	175	11	18	15	19	22	10	31	3
	200	23	1	30	9	21	26	6	32

3. RESULTS AND DATA ANALYSIS

3.1 Results

After heat treatment under the given conditions, the specimens were immediately measured for Brinell hardness with a Brinell Hardness Tester (with a 10 mm indenter, 500 kgf load, and 30 seconds pressing). Each piece of specimens would be oppressively measured for 4 times before being measured again for the size of indentation with a stereo microscope. The diameter obtained from each point's average was compared for strength with the strength table (ASTM). The strength values obtained from the experiment are shown in Table 3.

Table 3 Results

Aging Time (B)	Aging Temp (C)	Solution Temp (A)							
		500	595	500	595	500	595	500	595
2	175	40.15	94.05	38.60	97.80	39.49	97.65	38.98	91.45
	200	44.18	111.25	41.25	109.75	44.09	104.42	39.76	106.82
8	175	76.08	110.25	76.50	112.00	43.01	106.38	73.92	107.28
	200	52.10	115.00	57.28	118.75	72.51	110.49	54.99	113.38

The analysis of variance with ANOVA at a significant level of the hypothesis testing 5% ($\alpha = 0.05$) with the 2^3 factorial experiment design gives the results both in a linear and a summary of the factors significantly influencing the hardness linear as follows.

Table 4 Analysis of Variance for the 2^3 Factorial Experiments

Source	DF	Sum of Squares	Mean Squares	F	P-Value
A	1	23862.8	23862.8	2240.13	0.000
B	1	2116.2	2116.2	198.66	0.000
C	1	1.4	1.4	0.13	0.725
A*B	1	309.6	309.6	29.06	0.005
A*C	1	727.6	727.6	68.30	0.000
B*C	1	555.1	555.1	52.11	0.000
A*B*C	1	171.6	171.6	16.11	0.001
Error	24	225.7	10.7		
Total	31	27999.9			

From Table 4 Analysis of the influence of factors can be summarized as follows:

1) Factor A significantly affects the hardness (P-Value<0.001)
2) Factor B significantly affects the hardness (P-Value<0.001)
3) Factor A does not significantly affect the hardness at the significant level 0.05
4) Cofactors A, B significantly affect the hardness (P-Value<0.001)
5) Cofactors A, C significantly affect the hardness (P-Value<0.001)
6) Cofactors B, C significantly affect the hardness (P-Value<0.001)
7) Cofactors A, B, C significantly affect the hardness (P-Value<0.01)

Figure 1 shows the influence of the three main factors. When considering the graph between the average hardness with level of each key factor, it shows the result of the influence of a soluble linear time and the result of the influence of solution temperature, aging time and aging temperature in a linear manner. And when considering the influence of the main factors which are solution temperature and aging time, it can be seen that the average hardness increases indicating that when the temperature and time factors increase, the average hardness increases accordingly. For the aging temperature, the average hardness values are similar when the temperature increases.

When considering the graph that shows the average hardness of the interaction between the solution temperature, aging time, and aging temperature in Figure 2, the results of the linear interaction are as follows:

1) Interaction between the solution temperature and aging time affects the hardness in a linear manner after heat treatment. Solution heat treatment with high temperature and aging for a long time provide higher hardness than with a lower temperature and less time aging.

2) Interaction between the solution temperature and aging temperature affects the hardness in a linear manner after heat treatment. Solution heat treatment with high temperature and high-temperature aging provides a higher hardness than with a lower temperature and low-temperature aging. However, solution heat treatment with a temperature at 500 °C and with the aging temperature at 175 °C provides higher values than aging with the temperature at 200 °C.

3) Interaction between aging time and temperature affects the hardness in a linear manner after heat treatment. Solution heat treatment with high temperature and aging for a long time provides a higher hardness than with low temperature and less time aging. However, using the aging time for 8 hours with a temperature at 175 °C provides a higher hardness than aging with the temperature at 200 °C.

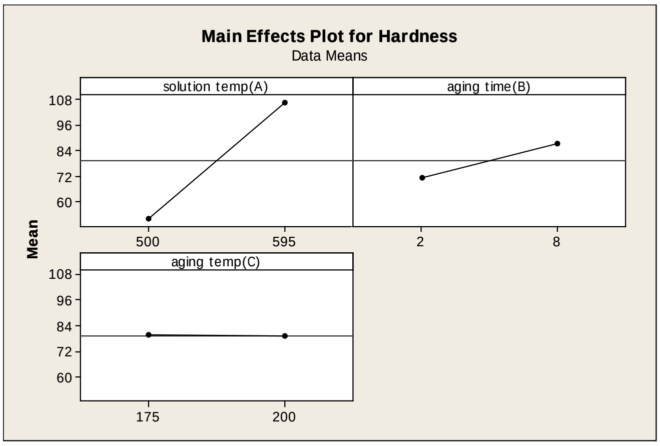


Figure 1 Main effects plot for hardness

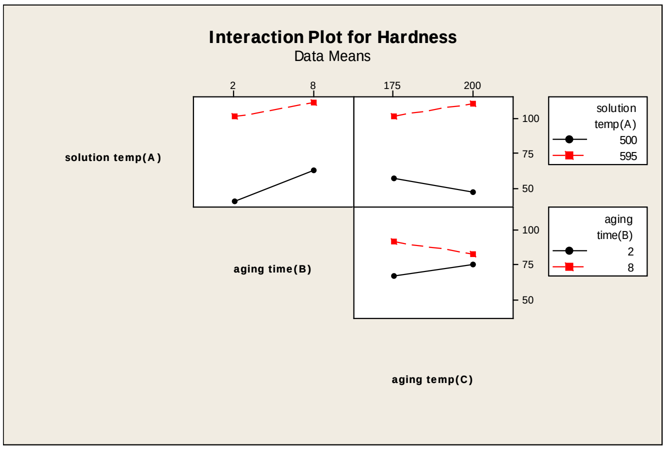


Figure 2 Interaction plot for hardness

3.2 The Regression Model

From the experiment, a linear regression model with linear equations to show the relationship between the hardness values with variables in a curve manner by considering only the main factors and cofactors that significantly influence/affect the hardness values, can be given as below.

$$\hat{Y} = \hat{\beta}_0 + \hat{\beta}_1 x_1 + \hat{\beta}_2 x_2 + \hat{\beta}_{12} x_1 x_2 + \hat{\beta}_{13} x_1 x_3 + \hat{\beta}_{23} x_2 x_3 + \hat{\beta}_{123} x_1 x_2 x_3 \qquad (1)$$

Where $\hat{y}$ is the fitted value

$\hat{\beta}_0$ is the average hardness of all data

$\hat{\beta}$ is regression coefficient

x_1 is the solution temperature (A)

x_2 is the aging time (B)

x_3 is the aging temperature (C)

From equation (1), an equation for estimating the hardness values of the main factors and cofactors that significantly influence the hardness values can be given as:

$$\hat{y} = 79.36+27.3A+8.13B-3.11AB+4.76AC-4.167BC+2.316ABC$$

3.3 Confidence Intervals

To estimate the confidence interval at 95% ($\alpha = 0.05$) of the hardness values obtained from estimating values in the regression model can be found from the following equation.

$$Y \pm t_{\alpha/2,N-a}\sqrt{MSE} \qquad (2)$$

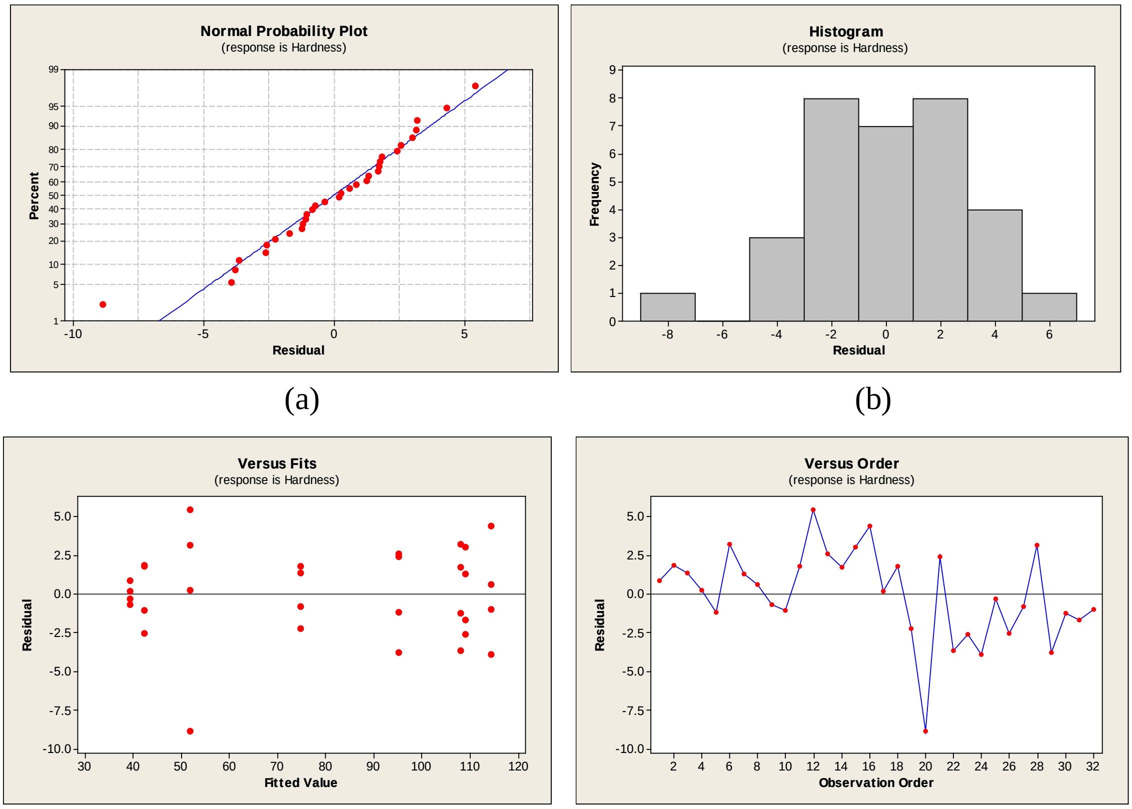
The confidence level at 95% (α=0.05), /α2=0.025 and the MSE values can be found from Sum of Squares of the non-significant factors plus Sum of Squares of Error divided by the degrees of freedom. By analyzing the variance of the simulation model, the MSE values can be given as:

$$Y \pm 6.73 \text{ BHN}$$

Therefore, the hardness values estimated from the model have a confidence interval of 95% or equivalent to ± 6.73 BHN of the estimated values.

3.4 Diagnostic Checking

After the analysis of variance and creation of a simulation model, the data has to be verified for accuracy prior to each use. Assumptions about the experimental design and errors or residuals of the model have to be normally distributed and are independent to each other with mean zero and constant variance.



(a) (b)

(c) (d)

Figure 3 Residual Plots for Hardness

1) Checking for a normal distribution, Figure 3(a) shows plots of errors. This is the checking for the normal distribution of residuals of the results obtained from the experiment conducted with a normal probability method. As can be seen, the plots are distributed along the straight line and so are data. Thus, it can be estimated that the residuals are normally distributed. Figure 3(b) shows the histogram of residuals in a bell-shaped curve. This also indicates the normal distribution of the data.

2) Checking for independence, Figure 3(c) is a scatter diagram showing the plots between errors or residuals of the data with the model's fitted values to confirm their independence. From the chart, the distribution of errors of the residuals compared with the fitted

values shows that the distribution of residuals is formed independently. It is randomly, consistently, and equally distributed in both positive and negative sides. The data also shows no difference of variance in each group.

3) Checking for residual variance of the data with a trial order by using the distribution chart of errors (Residuals). Figure 3(d) shows the distribution of errors with the trial order (Residual Plot Versus the Order). Errors of the data are in the form of random distribution and are not clear in patterns. This indicates that the hardness values do not depend on the order of trials.

4. CONCLUSION

The results showed after precipitation hardening that all main factors significantly influence the hardness in a linear manner. Almost all the factors which are solution temperature and aging time except aging temperature significantly influence the hardness. In addition, there are also interactions of two and three factors where each of them influences the hardness significantly.

The relationship between the hardness values and factors has thus involved variables as cofactors. The mathematical model derived from this experimental design can be used to estimate the hardness values with an error not over ± 6.73 BHN and with a reliability of 95%. Checking of errors or residuals has been found to conform to the hypothesis of the experimental design, that is, there is a normal distribution. In addition, there is a random, consistent, and equal distribution at each level of the main factors.

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