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Influence of Time and Temperature Variables on the Heat Treatment of an AL-MG SI Alloy

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Abstract

This study investigates the effect of time and temperature on the heat treatment of 6082 Al-Mg-Si alloy. Solubilization, quenching, and artificial aging were performed under parameter combinations defined using the Taguchi method. Mechanical testing supported the development of a multiple linear regression model, which identified aging temperature as the most significant factor influencing ultimate tensile strength and yield strength. High aging temperatures promoted coarse precipitate formation and reduced strength, while lower temperatures minimized this effect and maintained or improved mechanical performance. The results demonstrate the potential of combining statistical design with predictive modeling to optimize heat treatment parameters and enhance alloy performance for industrial applications.

Keywords: Al Mg Si alloy; heat treatment; Taguchi optimization; regression model.

1. Introducion

Alloy 6082 has moderate mechanical strengths, high corrosion resistance, and excellent weldability which makes it particularly attractive for engineering applications. It is widely employed in sectors such as automotive, electrical, railway, and precision parts that use this aluminum alloy (Aginagalde et al., 2009). Their high specific strength and good fatigue resistance make them ideal for use in lightweight and structural components (Barbosa et al., 2023).

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To address the growing demands of diverse engineering applications, efforts to enhance the mechanical properties of aluminum alloys have increasingly focused on heat treatments, particularly solubilization and aging (Ribeiro et al., 2009; 2011). These treatments rely on controlled heating and cooling cycles, exploiting phase transformations to modify the alloy's microstructure and, consequently, its mechanical performance (Ram et al., 2023).

Recent studies (Gairola & Jayaganthan, 2023; Ogunsanya et al., 2023; Varga & Szlancsik, 2023) have examined the complex mechanisms underlying heat treatments in aluminum alloys. Previous studies (Monica et al., 2019; Mrówka-Nowotnik et al., 2006; Tash & Alkahtani, 2013) demonstrated that variations in treatment parameters exert a significant influence on the resulting mechanical properties. Comprehending these variables is crucial for the optimization of heat treatment processes, facilitating a more accurate and application-oriented adjustment of alloy properties.

Heat treatments applied to 6082 aluminum alloys enhance their mechanical performance primarily through precipitation hardening. During solubilization, magnesium (Mg) and silicon (Si), the main alloying elements, are dissolved in a supersaturated solid solution. Subsequent aging promotes the controlled precipitation of Mg_2Si particles, which act as effective strengthening phases by hindering dislocation motion and thereby improving strength and fatigue resistance (Krishna Pal Singh Chauhan, 2017).

The solubility of Mg_2Si (β phase) in the aluminum matrix (α phase) increases with temperature, enabling the dissolution of the β phase during solubilization. Upon subsequent artificial aging, the supersaturated solid solution undergoes a precipitation sequence that typically progresses from Guinier–Preston (GP) zones to coherent β'' precipitates, then to semi-coherent β', and finally to the equilibrium β phase. Among these, the fine and uniformly dispersed β'' precipitates are the most effective in impeding dislocation motion, thereby providing the greatest contribution to strengthening. This controlled precipitation process is fundamental to achieving improved mechanical performance in 6xxx series aluminum alloys (Myhr, 2001).

This study investigates the influence of heat treatments on the mechanical properties of 6082-T651 aluminum alloy. Specimens will be subjected to controlled treatment cycles, and the resulting changes in mechanical behavior will be evaluated. A multiple linear regression model will be applied to identify and predict the effects of treatment parameters.

2. Experimental Procedure

The 6082-T651 aluminum alloy was selected as the material for this study due to its favorable characteristics. This alloy combines good machinability (Ribeiro et al., 2017), weldability (Costa et al., 2021; Richter-Trummer et al., 2011) and corrosion resistance (Ravnikar et al., 2023), while also exhibiting superior mechanical strength compared to conventional alloys of the same series, such as 6061.

In this study, the selected material was subjected to a T651 heat treatment following manufacturing. The parameters for the T6 heat treatment, summarized in Table 1, were defined based on literature data and the successful results reported in previous studies, as outlined in the introduction.

Table 1. Heat treatment variables.

Levels	Variable 1	Variable 2	Variable 3	Variable 4	Variable 5
	Solubilization temperature (ºC)	Solubilization time (hours)	Waiting time (hours)	Ageing temperature (ºC)	Ageing time (hours)
1	540	4	48	260	24
2	520	2	24	220	16
3	500	1	12	180	8
4	480	0,5	0	140	2

Two key factors in this study are the time and temperature applied during the solubilization and aging stages. In addition, the effect of waiting time was considered, since in industrial practice the availability of equipment and materials can introduce delays in the treatment process. To address these variables, the Taguchi method was employed, a robust statistical approach for process optimization, which enhances quality and performance by minimizing variability and reducing the influence of external factors. Systematic experimental designs are employed, in which factors are varied to quantify their effects on the system response. In this work, an L_{16} orthogonal array was adopted, as reported in the literature (Agboola et al., 2020), defined by four levels and five factors, as presented in Table 1. This design required 16 distinct experimental combinations to evaluate the variables under consideration.

Table 2 shows the final combination of factors for carrying out the heat treatments studied in this work.

Table 2. Combination of heat treatment variables.

Treatments	Solubilization temperature (ºC)	Solubilization time (hours)	Waiting time (hours)	Ageing temperature (ºC)	Ageing time (hours)
A	540	4	48	260	24
B	540	2	24	220	16
C	540	1	12	180	8
D	540	0.5	0	140	2
E	520	4	24	180	2
F	520	2	48	140	8
G	520	1	0	260	16
H	520	0.5	12	220	24
I	500	4	12	140	16
J	500	2	0	180	24
L	500	1	48	220	2
M	500	0.5	24	260	8
N	480	4	0	220	8
O	480	2	12	260	2
P	480	1	24	140	24
Q	480	0.5	48	180	16

The specimens were prepared from material arranged in a square section with dimensions of 30 × 30 × 15 cm. The tensile specimens were prepared in the longitudinal direction. After machining, the specimens were subjected to heat treatment conditions defined by the Taguchi array. Each experimental cycle consisted of two furnace stages: solubilization and aging.

Tensile tests were conducted in accordance with NP EN 10002-1 using an Instron 4485 universal testing machine with a 15-ton load cell. Specimen preparation and testing conditions, including room temperature and a crosshead rate of 2 mm/min, followed the standard specifications.

Prediction models are fundamental tools for identifying the most influential variables within a system. In this study, a multiple linear regression model was developed to evaluate the effects of time and temperature on the heat treatment response of the alloy under investigation.

Multiple linear regression is a statistical method used to examine the relationship between a dependent variable and multiple independent variables. Its purpose is to establish a mathematical model that describes the linear dependence of the response variable on the predictors (Jobson, 1991a, 1991b). The general form of this model is expressed in Equation 1, where:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n + \varepsilon \tag{1}$$

Y = dependent variable to be predicted;

x_1, x_2,...,xn = independent variables;

β0,β1,β2 ,...,βn = coefficients that represent how the independent variables influence Y.

ε = random error.

The coefficient of multiple determination, denoted as R^2, measures how effectively the model explains the variability of the dependent variable based on the independent variables considered. A higher R^2 value, approaching

1, indicates that the model accounts for most of the total variation, reflecting a good fit. Thus, the coefficient of determination is widely used as an indicator of model quality (Jobson, 1991a), where:

$$R^2 = \frac{\sum_{i=1}^{n}(\hat{Y}-\bar{Y})^2}{\sum_{i=1}^{n}(Y-\bar{Y})^2} \tag{2}$$

$\hat{Y}_i$ = values estimated by the regression equation;
$\bar{Y}$ = average of the observed values;
Y_i = observed values;

Multiple linear regression checks whether the coefficients (β) of the variables are zero or not and whether they affect the dependent variable. Thus, there are two hypotheses (Jobson, 1991a):

H_0: $\beta_0 = \beta_1 = \cdots = \beta k = 0$ or
H_1: $\beta_1 \neq 0, \beta_2 \neq 0, \ldots, \beta n \neq 0$.

To evaluate the influence of the independent variables, it is necessary to test and potentially reject the null hypothesis (H_0), which assumes that the regression coefficients of the independent variables are equal to zero and, therefore, have no effect on the prediction of the dependent variable. Rejecting H_0 allows the assessment of the contribution of each independent variable to the estimation of the dependent variable. This evaluation is performed through analysis of variance (ANOVA), which examines the overall significance of the model using the F-test. A p-value for the F statistic below the established significance threshold of 0.05 suggests that the model is statistically significant, demonstrating a meaningful relationship between the predictor variables and the response variable.

3. Results and discussion

Table 3 summarizes the results obtained from the mechanical tests performed on the alloy.

Table 3. The results of the mechanical properties of the alloy obtained in the tensile test.

Specimen	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation (%)
A	155.82	75.41	20.5%
B	195.06	112.75	15.5%
C	250.45	200.9	14.6%
D	355.55	320.61	16.0%
E	330.53	316.65	12.8%
F	317.11	298.8	13.2%
G	161.13	83.31	19.5%
H	214.34	150.57	16.5%
I	317.26	302.46	12.1%
J	230.93	175.22	14.2%
L	204.20	144.23	13.6%
M	188.4	118.05	15.6%
N	179.98	121.04	15.4%
O	165.59	99.57	17.1%
P	301.24	248.62	18.0%
Q	229.71	181.63	15.1%
Standard*	331.30	304.24	15.8%

The standard specimen was not subjected to the heat treatment cycles applied to the other samples.

The relationship between ultimate tensile strength, yield strength, and elongation is evident for different time and temperature parameters, as illustrated in Figure 1.

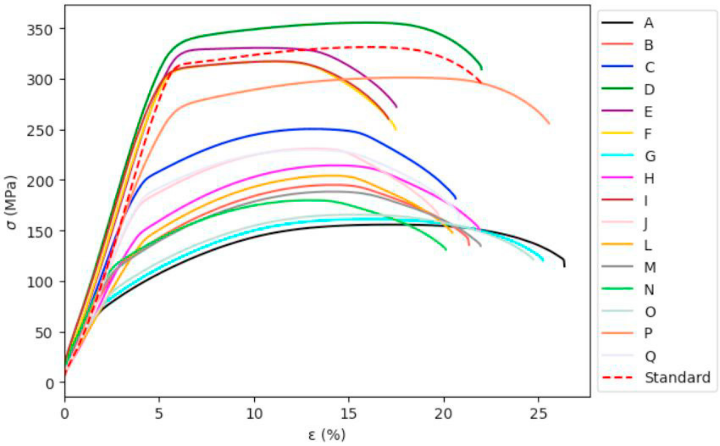

Fig. 1. - Stress versus strain graph of the specimens tested.

Table 4 presents the regression equations derived from the model, which quantitatively describe the relationship between the independent variables considered in the heat treatment process and the corresponding response of the alloy's mechanical properties.

Table 4 - Multiple linear regression equations.

Mechanical properties	Equation
Ultimate tensile strength	$Y = 229.8 - 0.06x_1 - 2.86x_2 - 0.10x_3 - 0.40x_4 - 0.36x_5$
Yield strength	$Y = 0.03 + 0.00x_1 - 0.00x_2 - 7.40\ x_3 + 0.00\ x_4 + 0.00\ x_5$
Elongation	$Y = 313.96 + 0.40x_1 + 1.49x_2 - 0.09x_3 - 1.32x_4 - 1.60x_5$

The regression model for the ultimate tensile strength (Table 5) exhibited a coefficient of determination (R^2) of 0.90, indicating that 90% of the variability in the response is explained by the independent variables considered. Furthermore, the analysis of variance yielded a global significance value of F = 0.000, leading to the rejection of the null hypothesis of no regression and confirming that the model is statistically highly significant.

Table 5 - Regression statistics for the ultimate tensile strength.

Mechanical properties	R^2	Global significance F-value
Ultimate tensile strength	0.900	0.000

The regression analysis identified aging temperature as the most significant factor in predicting ultimate tensile strength, with a negative coefficient indicating that higher aging temperatures lead to a reduction in strength. This trend is consistent with the over-aging phenomenon in aluminum alloys, where excessive thermal exposure promotes precipitate coarsening and reduces the material's strengthening effect. Aging time also presented a negative coefficient, suggesting a potential detrimental effect; however, its p-value (0.067) is slightly above the conventional 0.05 threshold, implying a possible but less statistically robust relationship. In contrast, the remaining variables, like solutionizing temperature, solutionizing time, and waiting time between cycles, did not exhibit a statistically significant effect on ultimate tensile strength, as summarized in Table 6.

The regression model for predicting the material's yield strength demonstrated a good fit, as presented in Table 7. The coefficient of determination (R^2=0.899) indicates that approximately 90% of the observed variability is explained by the independent variables considered. Moreover, the analysis of variance yielded a global significance value of F = 0.000, confirming the statistical significance of the model at the 5% level and highlighting its reliability for predicting the alloy's yield strength.

Table 6 - Influence of variables on the ultimate tensile strength.

Variable	Coefficients	P-value
Solubilization temperature (ºC)	0.40425	0.191
Solubilization time (hours)	1.48948	0.763
Waiting time (hours)	-0.09479	0.799
Ageing temperature (ºC)	-1.31794	0.000
Ageing time (hours)	-1.60046	0.067

Table 7 - Regression statistics for the yield strength.

Mechanical properties	R²	Global significance F-value
Yield strength	0.899	0.000

Concerning the variables, temperature and aging time demonstrated a statistically significant influence on the response, with negative coefficients, as shown in Table 8. These negative coefficients suggest that an increase in temperature and aging time is associated with a significant decrease in the yield strength of the alloy.

Table 8 - Influence of variables on the yield strength.

Variable	Coefficients	P-value
Solubilization temperature (ºC)	0.35725	0.366
Solubilization time (hours)	5.79122	0.379
Waiting time (hours)	-0.03873	0.937
Ageing temperature (ºC)	-1.70516	0.000
Ageing time (hours)	-2.47475	0.035

On the other hand, the remaining variables (solutionizing temperature, solutionizing time, and waiting time) did not show a statistically significant relationship with the response, highlighting the statistical importance of temperature and aging time compared to the other variables considered in the model.

The model for the elongation variable yielded an R² of 0.52, indicating that approximately 52% of the observed variability in elongation can be explained by the variables included in the regression model. Although this value suggests a moderate amount of variation in the mechanical property, the global significance F-value is 0.14, as shown in Table 9, suggesting that the model may not be statistically significant at a 95% confidence level.

Table 9 - Regression statistics for the elongation.

Mechanical properties	R²	Global significance F-value
Elongation	0.52	0.14

The influences of temperature and time variables in solutionizing and aging heat treatments were analyzed, and mechanical properties were evaluated through multiple linear regression modeling. Parameters were generated for each scenario to validate the model. Table 10 presents newly defined parameters deemed optimal according to prior results.

Table 11 shows the predicted values of ultimate tensile strength and yield strength from the multiple linear regression equations using the study's proposed model.

Table 10 - Definition of optimal conditions.

Treatments	Solubilization temperature (ºC)	Solubilization time (hours)	Waiting time (hours)	Ageing temperature (ºC)	Ageing time (hours)
Validation test specimen	510	2	0	140	5

Table 11 - Predicted values for the optimum condition.

Validation test specimen	Ultimate tensile strength (MPa)	Yield strength (MPa)
#	330.59	306.77

Figure 2 displays the stress-strain graph of the validation specimen compared to the standard specimen.

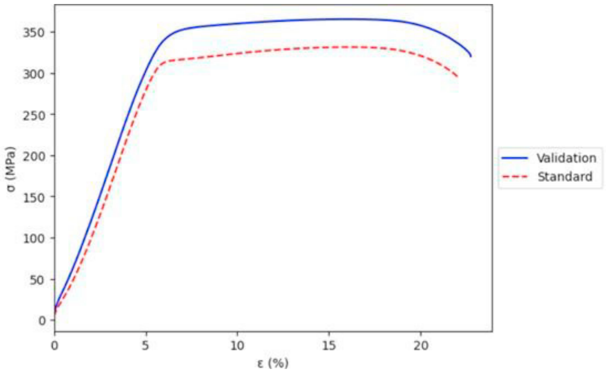

Fig. 2. - Stress versus strain graph of validation and standard specimens.

For comparative purposes, the following is considered in Table 12:

Table 12 - Comparison between predicted and observed values.

Variable	Predicted value	Observed value	Model accuracy (%)
Ultimate tensile strength (MPa)	330.59	365.16	90.53
Yield strength (MPa)	306.77	329.15	93.20

As shown in Table 12, the model's accuracy for these predictions was higher than the R² established in each equation.

4. Conclusion

This study demonstrated that heat treatment parameters significantly influence the mechanical behavior of 6082-T651 aluminum alloy. High aging temperatures and longer exposure times promoted coarse precipitate formation associated with over-aging, thereby reducing strength, while shorter treatments mitigated these effects. The regression model developed proved highly effective in predicting ultimate tensile strength and yield strength, though predictions of elongation were less reliable due to the variability of this property in a limited sample set. Among the variables considered, aging temperature emerged as the most significant factor, with aging time also exerting a negative but less statistically robust effect. Other factors showed no significant influence on mechanical properties. The integration of regression modeling with microstructural analysis enabled the identification of optimal conditions, validated by specimens that exhibited improvements of approximately 9% in ultimate tensile strength and 8% in yield strength.

Overall, the methodology highlights potential for broader application in process optimization, offering gains in both quality and energy efficiency. Future work should extend this approach to larger sample sets and different aluminum alloys to further validate its predictive capacity and industrial relevance.

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