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Optimization of Heat Treatment Parameters for the A2024 aluminum Alloy Using Taguchi's Orthogonal Array Approach

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Abstract: Aluminum based alloys have significant applications in automobile and aerospace industries because of their high fatigue resistance, high strength to weight ratio and wear resistance. In specific, A2024 aluminum alloys are best suited for aircraft structural components such as fuselages, wings and automotive parts. It is necessary to improve the hardness and tensile strength of this alloy with the objective of increasing the arena of its applications. This paper deals with the optimization of process parameters of this aluminum alloy considering four significant factors affecting the hardness and tensile strength. For the purpose of experimentation, Taguchi's L9 orthogonal array has been chosen; nine experiments have been conducted and analysis is carried out using Signal-to-noise ratio.

Keywords: Al2024, ageing, hardness, UTS, Taguchi, orthogonal array

1. INTRODUCTION

Aluminium alloys are alloys in which aluminium (Al) is the predominant metal. The typical alloying elements are copper, magnesium, manganese, silicon and zinc. The two major alloying elements of aluminium castings are copper (Cu) and silicon (Si), but there are many more elements which are added in very small quantities to improve flow during pouring, to give good casting definition, to reduce porosity etc. Both silicon and copper modify the crystal structure to increase hardness and tensile strength [1] [5]. All the above alloys are considerably stronger than pure aluminium when sand cast, but their strength can further be improved by a heat treatment called as ' Solution treatment ', followed by quenching and then age hardening. Solution heat treatment is the process of heating an alloy to a suitable temperature and holding at temperature long enough to cause one or more hardening constituents to enter into solid solution. Solution treating is typically performed in the 450 to 575°C (842 to 1067°F) range in air, followed by rapid quenching into cold water, hot water, boiling water (-T61 temper), water-polymer (glycol) solution, water spray or forced air. Subsequent heat treatment at tower temperatures i.e. ageing or natural ageing at room temperature allows for a controlled precipitation of the constituents thereby achieving increased hardness and strength. Aluminium alloys are widely used in engineering structures and components where light weight or corrosion resistance is required. Alloys composed mostly of aluminium have been very important in aerospace manufacturing and automobile industry. Aluminium alloy surfaces will formulate a white, protective layer of corrosion aluminium oxide if left unprotected by anodizing and/or correct painting procedures.

1.1 Taguchi method:

The Taguchi method is a powerful tool for designing high quality systems based on orthogonal array experiments that provide much-reduced variance for experiments with an optimum setting of process control parameters. The method has also been widely used in engineering analysis to optimize performance characteristics through design parameter settings. The Taguchi method is based on orthogonal arrays to minimize the number of experiments and to effectively improve product quality. Some of its many advantages include:

- Designs Orthogonal arrays (OA) to balance process parameters and minimize test runs.
- Employs signal-to-noise (S/N) ratio to analyze experiment data, and conclude more information. Taguchi recommends using the S/N ratio for determining quality characteristics implemented in engineering design problems.
- Estimates individual parameter contributions.

Since the purpose of this study is to maximize hardness and tensile strength within optimal levels of process parameters, the higher the better quality characteristic is selected. Each parameter has three levels. The current study considered hardness and tensile strength as optimization criteria and also analyzed the influence of each heat treatment parameter on the quality of the research object. The project also obtains contributions of individual process parameters and optimal parameters for hardness, and tensile strength in the heat treatment process of aluminum 2024, respectively. In this way, the optimal levels of process parameters can be estimated.

2. EXPERIMENTATION

2.1 Selection of Orthogonal Array

To select an appropriate orthogonal array for experiments, the total degrees of freedom need to be computed. The degrees of freedom are defined as the number of comparisons between process parameters that need to be made to determine which level is better and specifically how much better it is. For example, three-level process parameter counts for two degrees of freedom. The degrees of freedom associated with interaction between two process parameters are given by the product of the degrees of freedom for the two process parameters. In the present study, there is no interaction between the heat treatment parameters. Therefore, there are eight degrees of freedom owing to the four heat treatment parameters.

TABLE 1.1: Control Factors and their Levels

Symbols	Control factors	Levels			Units
		1	2	3	
A	Solution Temperature	460	475	490	°C

B	Solutionizing time	30	60	90	Minutes
C	Age hardening Temperature	140	160	180	°C
D	Age Hardening Time	2	4	6	Hours

There are three levels and four factors. Factor A has three levels, its degree of freedom will be LEVEL – 1, i.e. two. Similarly the other factors will also have two degrees of freedom each. Therefore, there are eight degrees of freedom owing to the four heat treatment parameters. So, the minimum numbers of experiments to be conducted are 8+1 = 9.

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Once the degrees of freedom required are known, the next step is to select an appropriate orthogonal array to fit the specific task. Basically, the degrees of freedom for the orthogonal array should be greater than or at least equal to those for the process parameters. In this study, an L9 orthogonal array is used. This array has thirty five degrees of freedom and it can handle three-level process parameters. Each heat treatment parameter is assigned to a column and thirty six heat treatment combinations are available. A minimum of nine experimental runs must be conducted, using the combination of levels for each control factor (A–D) as indicated in the table below

TABLE 1.2: Physical Layout

Experiment number	Solution Temperature	Solutionizing time	Age hardening Temperature	Age Hardening Time	Hardness RHB			Tensile strength Mpa		
	A	B	C	D						
1	460	30	140	2						
2	460	60	160	4						
3	460	90	180	6						
4	475	30	160	6						
5	475	60	180	2						
6	475	90	140	4						
7	490	30	180	4						
8	490	60	140	6						
9	490	90	160	2						

2.2. Casting of aluminium 2024

In the present work aluminium 2024 alloy is taken without any reinforcement. The aluminum alloy was melted in an electrical furnace. Aluminium 2024 ingots weighing about 4kgs were placed in an electrical furnace at 850^0C for 20-30 minutes. The stirrer was introduced to perform mixing process when the molten temperature reached 850^0C. The manual stirring was carried out occasionally. Once the ingots were in the molten state, it was degassed by purging hexachloro ethane tablets. Then the melt was casted in cylindrical die. The internal surface of the die was applied with a water based die coat before each casting which acts as a lubricant between the molten metal and die, and also prevents the adhesion between the die cast metal and die. The pouring temperature of molten mixture was 850^0C and molten metal was poured into the die. Then the casting was ejected from the die at a temperature of 150^0C and it is allowed to cool in air.

2.3. Machining aluminium 2024 cast as per ASTM standard

The aluminium 2024 casts were machined to obtain tensile test specimen of length 51mm, diameter 12.5mm & gauge length of 26mm & diameter 6.25mm according to ASTM standard E8. Hardness specimens were machined to the following dimensions: diameter 20mm, height 15mm.

2.4. Heat treatment of Aluminium 2024

Firstly, the specimens were heat treated according to the physical experimentation layout. After solutionizing, the specimens were quenched in water at room temperature. Further the specimens were subjected to artificial ageing and left to cool at room temperature.

2.5.MechanicalTests

The castings were machined to the required dimensions as per ASTM E8 norms, heat treated and were tested at room temperature in a compact bench tensometer (KIPL-PC 2000) interfaced with computer. The tests were conducted at a speed of 0.2 mm per minute with length increment of 0.1 mm. The specimen have been fixed in the clamps of the machine and tightened. The data of the specimen was entered in the software and the loaded till fracture took place. The ultimate tensile strength, was obtained from the data acquisition system of the machine.

Inthepresentstudy,hardnessofthespecimenswasmeasuredbyusingastandardBrinellhardnesstesting machine.ThehardnesstestwasconductedinaccordancewithASTME10standards.Threereadingsweretakenforeachspecimenatdifferentlocationstocircumventthepossibleeffectofanyalloyingelementsegregationandtheaveragevaluewasconsidered.

2.6. Taguchi Method

TheTaguchimethodputsemphasisonS/Nratioasopposedtosimpleaverageofoutput.Itissobecauseinordertoachieverobustness,wemustconsiderstandarddeviationinsteadofbasingourdecisionsmerelyonaverages.Forhigherisbetterqualitycharacteristic,theS/NratiousedforthistyperesponseiscalculatedaccordingtoEq.(1)

Signaltonoiseratio(S/Nindb) = -10 log

$$\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right)(1)$$

Where:dBtheunitofS/N (decibel), Averagevaluestandarddeviationofexperimentalvalueoftheithqualitycharacteristic.Thestandardexperimentlayout3levelOAL9(3^4)forfactorsislistedforthiscaseandshowninTable1and3.

2.7. Experimentation and data collection

TABLE1.3ExperimentalResultsUsingL9(34)OrthogonalArrays

Experiment number	Solution Temperature	Solutionizing time	Age hardening Temperature	Age Hardening Time	Hardness RHB			Signal to Noise Ratio
	A	B	C	D				
1	460	30	140	2	71	70	71	36.9837
2	460	60	160	4	72	72	74	37.2245
3	460	90	180	6	73	74	76	37.4200
4	475	30	160	6	76	78	75	37.6508
5	475	60	180	2	73	72	75	37.3023
6	475	90	140	4	77	76	74	37.5745

7	490	30	180	4	81	81	80	38.0975
8	490	60	140	6	78	80	79	37.9511
9	490	90	160	2	76	77	77	37.6916

TABLE 1.4.ExperimentalLayoutUsingL9(34)OrthogonalArraysForUTS

Experiment number	Solution Temperature	Solutionizing time	Age hardening Temperature	Age Hardening Time	Tensile strength Mpa			Signal to Noise Ratio S/N Ratio
	A	B	C	D				
1	460	30	140	2	263.2	276.8	269.4	48.6153
2	460	60	160	4	318.4	304.6	312.6	49.8751
3	460	90	180	6	314.7	309.4	336.2	50.0891
4	475	30	160	6	322.6	334.16	319.71	49.2324
5	475	60	180	2	282.4	297.3	289.32	50.2460
6	475	90	140	4	312.19	318.8	309.01	49.9179
7	490	30	180	4	330.71	331.3	321.7	50.3125
8	490	60	140	6	349.2	335.7	348.1	50.7354
9	490	90	160	2	326.8	322.19	316.4	50.1493

3. ANALYSIS OF THE DATA

Table 1.3 above shows the hardness for various trial runs at three levels of solution temperature, solutionizing time, aging temperature, and aging time, respectively. Based on this information, the S/N values can be calculated and are also shown in the table 1.3. The tables 1.4 and 1.5 below show the mean hardness responses and mean S/N ratios responses for each level and corresponding heat treatment parameters. From response tables for mean and S/N ratio it was found that the solution treatment temperature is the most influential followed by ageing time, ageing temperature and solutionizing time. The optimal conditions are those that obtain high hardness from the main effects plot for means (Figure 1.1) and main effects plot for S/N ratio (Figure 1.2). They show that A3B1C3D3 are the best results for hardness. The optimal conditions are the following: solution temperature 490˚C, solutionizing time 30 min, aging temperature 180˚C, and aging time 6 hours respectively.

TABLE 1.5. Response Table for mean (hardness)

LEVEL	A	B	C	D
1	72.56	75.89	75.11	73.56
2	75.11	75	75.22	76.33
3	78.78	75.56	76.11	76.56
Delta	6.22	0.89	1.00	3.00
Rank	1	4	3	2

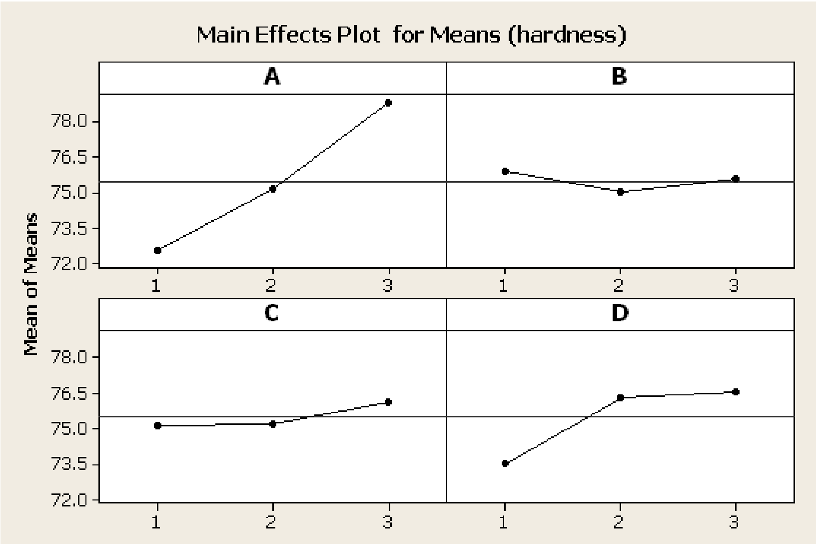

FIGURE 1.1. Main Effects Plot for mean (hardness)

TABLE1.6. Response Table for Signal to Noise Ratios, Larger is better

LEVEL	A	B	C	D
1	37.21	37.58	37.50	37.33
2	37.51	37.49	37.52	37.63
3	37.91	37.56	37.61	37.67
Delta	0.70	0.08	0.10	0.35
Rank	1	4	3	2

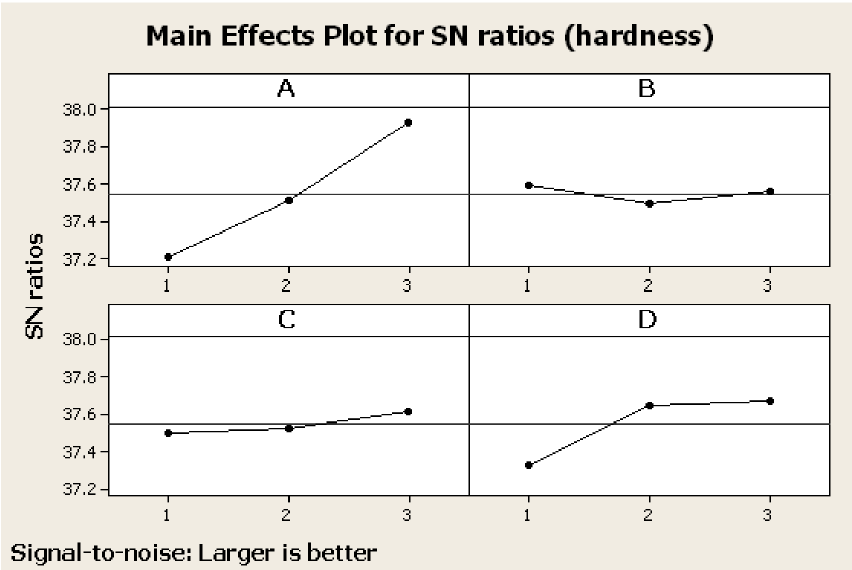

FIGURE 1.2. Main Effects Plot for S/N Ratios (hardness)

Table 1.4 above shows the tensile strength for various trial runs at three levels of solution temperature, solutionizing time, aging temperature, and aging time, respectively. Based on this information, the S/N values can be calculated and are also shown in table 1.4. The table below shows the mean tensile strength responses (Table 1.7) and mean S/N ratios for each level (Table 1.8) and corresponding heat treatment parameters. From response tables for mean and S/N ratio it was found that the ageing time is the most influential followed by solution treatment temperature, solutionizing time and ageing temperature. The optimal conditions are those that are obtained high tensile strength from the main effects plot for means (Figure 1.3) and main effects plot for S/N ratio (Figure 1.4). They show that A3B3C2D3 are the best results for tensile strength. The optimal conditions are the following: solution temperature 490˚C, solutionizing time 90 min, aging temperature 160˚C, and aging time 6 hours respectively.

TABLE 1.7. Response Table for mean (UTS)

LEVEL	A	B	C	D
1	300.6	307.7	309.2	293.8
2	309.5	315.3	319.7	317.6
3	331.3	318.4	312.5	330.0
Delta	30.7	10.7	10.6	36.2
Rank	2	3	4	1

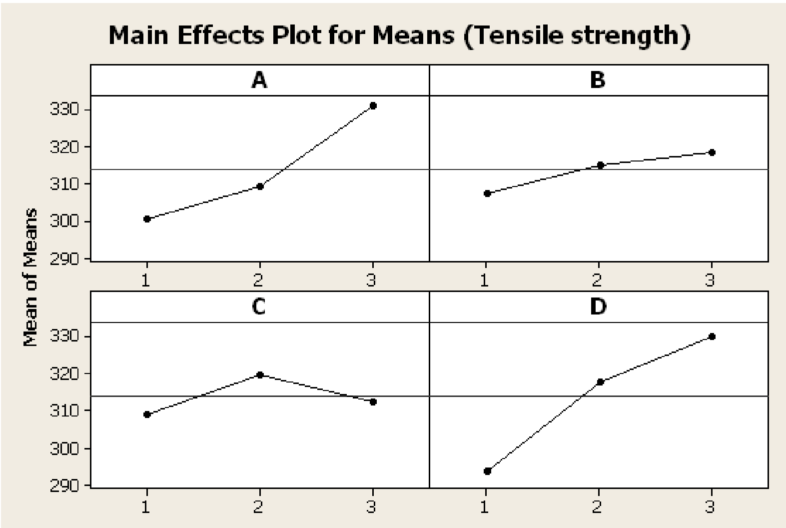

FIGURE 1.3. Main Effects Plot for Means (UTS)

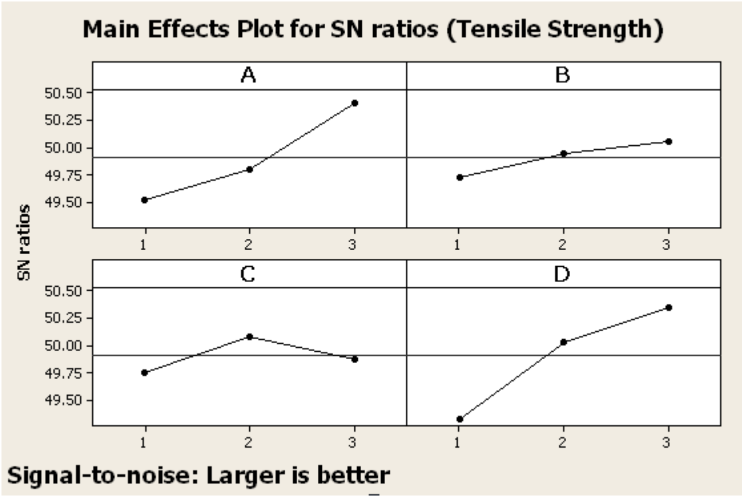

TABLE 1.8. Response Table for S/N Ratios (UTS)

LEVEL	A	B	C	D
1	49.53	49.72	49.76	49.33
2	49.80	49.95	50.09	50.03
3	50.40	50.05	49.88	50.36
Delta	0.87	0.33	0.33	1.02
Rank	2	4	3	1

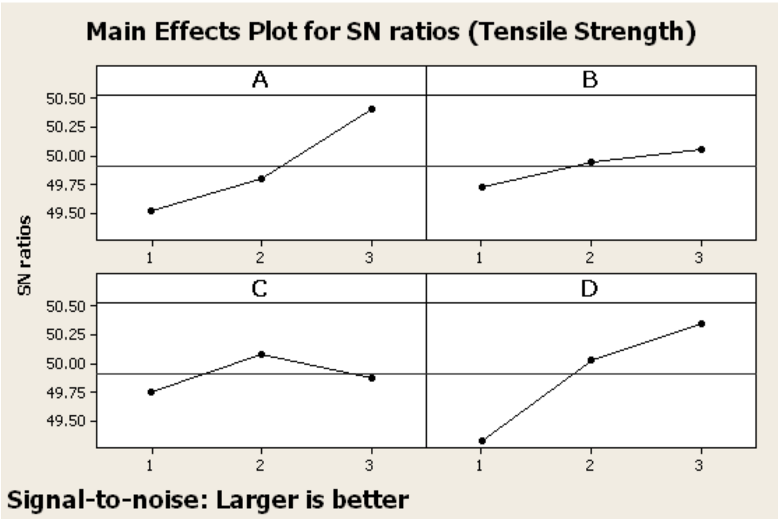

FIGURE 1.4. Main Effects Plot for Means (UTS)

4.0 CONCLUSIONS

We applied Taguchi's robust design method to determine the optimal heat treatment conditions for the Al 2024 alloy. The following conclusions were drawn from the experimental results:

- By using Taguchi's design the numbers of experiments were reduced from eighty one to nine.
- The optimal heat treatment conditions for maximizing the hardness of the Al 2024 alloy are a solution temperature of 490°C, solution time of 30 min, aging temperature of 180 °C, and aging time of 6 hours. With heat treatment under these optimal

conditions, the predicted hardness value of the Al 2024 would be 80.89 RHB.

- The optimal heat treatment conditions for maximizing the UTS of the Al 2024 alloy are a solution temperature of 490 °C, solution time of 90 min, aging temperature of 160 °C, and aging time of6 hours. With heat treatment under these optimal conditions, the predicted tensile strength value of the Al 2024 would be 358.014 MPa.
- The decreasing order of influential factors affecting hardness of Al 2024 alloys are as follows: solution temperature, aging time, aging temperature, and solutionizing time.
- In a decreasing order of influential factors affecting tensile strength of Al 2024 alloys are as follows: aging time, solution temperature, solutionizing time and aging temperature.

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