Process Parameter Selection for Optimization of Hardness Properties of A356 Aluminium Alloy Using Taguchi Method

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***Abstract:*-The selection of process parameter for obtaining an optimal hardness properties in the heat treatment of A356 aluminium alloy has been done in this study. The samples were produced via chill casting method and machined into standard hardness test samples. The hardness was evaluated by an FIE Vickers hardness tester of MV1-PC model in accordance with ASTM E384 and ASTM E92 standards. The heat treatment condition were solution heat treatment temperature, solution heat treatment time, ageing temperature and ageing time. The effect of each condition on the hardness of this alloy was considered using Taguchi L9 method which was followed by determining the process parameter with the optimal heat treatment condition. The results obtained have been articulated in this report.**

***Keywords*: Heat treatment, Vickers hardness tester, Chill casting, Micro-hardness**

I. INTRODUCTION

Aluminum is a very light metal with a better strength to weight ratio than other materials. The densities of aluminium alloy lies between 2500 and 2900 Kg/m^3 while its young modulus value is about $75Gpa$. Comparing this value to steel with about 8000 Kg/m^3 as density and young's modulus of about $200Gpa$. The Al-Si-Mg (A356) alloy has many advantages in the braking system because of its high strength and excellent casting ability. [1]Have reported that Magnesium has a high solubility in aluminium, impacting strength with an improvement inwork-hardening properties of aluminium, while decreasing its ductility. Generally, the presence of magnesium in aluminium improves its corrosion resistance and weldability [1-2].

One of the most important car safety systems is the brake foundation because it is considered to play an important role in the movement of the brake discs and pads by converting the vehicle's kinetic energy into heat energy [2]. To optimize the design, the development of disc brakes requires several steps, and several aspects of the brake system must be considered to ensure compliance with legal and customer standards. The disc brake is very important in a vehicle as it slows rotation of the wheel using the friction caused by pushing the brake pads against a brake disc with a set of calipers [3]. This brakes as compared with drum brakes provide a better stopping performance, including its resistance to brake fade caused by overheating the brake. Most road vehicles use cast iron or steel to create a rotating brake disc due to friction, thermal properties and high melting point of iron. The main disadvantages of conventional cast iron or steel is that it increases weight, fuel consumption and vehicle emissions. This encourages automotive and relevant researchers to find ways to reduce vehicle weight using lightweight materials.

However, in recent time processed and conditioned monolithic aluminium alloys have regained attention in automobile engineering applications due to some excellent properties displayed. As a guide, isothermal treatment has been claimed as a tool to enhance better electromechanical properties [4]. Although one of the major problems encountered in the use of aluminium alloy is the overheating and softening of the material due to its low melting point. [4] Studied the design and thermal analysis of disc brake rotor using aluminium alloy 2014 and generalized experimental analysis for temperature distribution. The area of study was concentrated on temperature variation as a function of time only. The result showed a maximum temperature at the surface which can affect the tribological properties such as damage and failure at the surface of the disc as compared with mild steel.

Since heat treatment still remains the major way of improving the properties of aluminium alloy, the use of Taguchi approach in optimizing the hardness properties of this alloy was proposed in this study.

II. TAGUCHI METHOD FOR OPTIMIZATION OF PROCESS PARAMETERS

The primary goal of every robust design is to find a factor that can be set, in order to minimize response variation, while adjusting/keeping the process on target. When these factors affecting the variation are known, they can be used as setting for controlling the factors that will either reduce the variation and/or make the product insensitive to changes in an uncontrolled situation like the noise factor. Designing the product with this goal will result in a more consistent performance, not regarding the environment in which it is used [5].

2.1 Fundamental Terms Used in Taguchi Design

Some of the terms used in Taguchi are orthogonal arrays, signal to noise (S/N ratios), mean square deviation (MSD) analysis and analysis of variance (ANOVA).

2.2 Orthogonal Arrays

In order for large number of variables to be studied with a smaller number of experiment, Taguchi utilizes an orthogonal array from the design of experiment theory. The conclusions drawn from these small scaled experiment become valid over the entire region of the experiment conducted by setting the control factors.

Orthogonal array is not new in design of experiment, but Taguchi have simplified the use of orthogonal array and there corresponding linear graphs to fit specific conditions of the analysis. Example of standard orthogonal; arrays are L4, L8, L12, L16, L32 and L64 all of these at 2 levels, and L9, L18 and L27, all at 3 and 2 levels. L16 and L32 are modified at 4 levels, while L25 is used at 5 levels. A standard notation for orthogonal arrays is L16 (3 2). In the above case, 16 represent the number of experiments, 3 is used for the number of levels, while 5 represent the number of factors used [6].

The total degrees of freedom has to be computed in order to select an orthogonal array to be used in the experiment. The degrees of freedom can be defined as the number of comparisms between these process parameters that will determine the better level and specifically how much better it is. After determining the degree of freedom, an appropriate orthogonal array is then selected to fit the specific task.

2.3 S/N Ratios and MSD Analysis

One difference between Taguchi and other optimal process is the use of a signal to noise ratio. The idea here is that apart from maximizing the mean (signal), it is also important to minimize the process variations (noise) which are both achievable using the S/N ratio. Determining the effect of each factor on the responses will involve calculating the S/N ratio of each factor. The signals indicated that the sensitivity of the experiment output to the noise factors were measured from its effect on the average responses and the noise. Selecting the required S/N ratio depends on the mean square deviation (MSD) for analyzing repeated results. The MSD which is consistent with Taguchi quality objective combines variation around the given target [7]. The relationships existing among the observed results, MSD and S/N ratio are summarized below

$$MSD = \frac{\left(\left(Y_1 - \overline{Y}\right)^2 + \left(Y_2 - \overline{Y}\right)^2 + \ldots\ldots\ldots \left(Y_n - \overline{Y}\right)^2\right)}{n}$$

………………. For nominal is better (1)

$$MSD = \frac{\left(Y_1{}^2 + Y_2{}^2 + \ldots\ldots\ldots + Y_n{}^2\right)}{n}$$

……………... For smaller is better (2)

$$MSD = \frac{\left(\frac{1}{Y_1{}^2} + \frac{1}{Y_2{}^2} + \ldots\ldots\ldots + \frac{1}{Y_n{}^2}\right)}{n}$$

…………….. For bigger is better (3)

$$S/N = -10\log(MSD)$$

……… For all characteristics (4)

Where:

$Y =$ Observed data

$\overline{Y}$ = Average of the observed data

n = Number of observations

2.4 Analysis of Variance, ANOVA

ANOVA is generally used in studying the relationships existing amongst the sampled data. It makes it possible to analyze the difference between two or more sample means. The ANOVA is achieved by subdividing the total sum of squares. One way ANOVA is the simplest case. Generally, ANOVA is similar to regression as it is used in investigating and modelling the relationship existing between a response variable and the independent variables [8].

2.5 Prediction for Optimized Value

From the S/N analysis and mean response characteristics, the optimum levels of the control factors can be calculated. Hence, the predicted mean of quality characteristics can be calculated using the relationship below.

$$S_{opt} = \overline{Y} + \left(\overline{A_2} - \overline{Y}\right) + \left(\overline{B}_1 - \overline{Y}\right) + \left(\overline{C}_1 - \overline{Y}\right) \quad (5)$$

Where

$\overline{Y} =$ Total average of performance characteristics (in this case, corresponding to all the 27 (9x3) readings

$\overline{A}_2$, $\overline{B}_1$ and $\overline{C}_1$ are the average values of the materials wear, friction and hardness

$S_{opt} =$ Predicted mean of the Al-Si-Mg alloys wear, friction and hardness at optimum conditions

The optimization allows the industrial user to easily repeat with negligible error the optimal condition and process parameters in achieving the desired properties. It searches for a combination of factor levels that can satisfy the conditions of the individual factors and responses.

2.6 Running Confirmation Experiment

The final step involves predicting and verifying the improvement in terms of responses, using the optimal conditions of the process parameters.

III. HEAT TREATMENT PROCESS OF CAST A356 ALUMINIUM ALLOY

Heat treatment is one of the major factors used to enhance the properties of heat-treatable Al-Si-Mg alloys, through an optimization of both solution and ageing treatments given to these alloys. The solution treatment homogenizes the cast structure and minimizes segregation of alloying elements in the casting. Typical heat treatment process for cast Al-Si-Mg alloy is T6-temper condition, which consist of a solution heat treatment, quenching and ageing at an elevated temperature [9].

Basically it is a two steps procedure; first a single phase supersaturated solid solution is produced by heating the material at a temperature where the phase diagram exhibits a maximum solubility, generally at a eutectic temperature, followed by rapid quenching at room temperature. This step is then followed by an ageing procedure consisting in maintaining the sample at a room temperature (natural ageing or T4) or a higher temperature generally around 200^{o}C (artificial ageing or T6) where a hardness peak is observed.

This process produces precipitates evolving from the Guinier-Preston (GP) zones to coarse incoherent precipitates (β) when the equilibrium is reached. Usually, the improved properties of the material is due to the presence of fine intermediate (coherent/semi-coherent) precipitates (β^{1}/β^{11}) which harden the matrix upon a subsequent deformation process [10].

3.1 Heat treatment of the A356 aluminium alloy

Following the method described in [10], the high purity aluminium wire with charge calculation shown in Table 1 was melted in a muffle resistance furnace that was allowed to heat to 750^{o}C. The crucible was then removed from the furnace, and the alloying elements added before returning to the furnace for further 30 minutes, during which the furnace temperature will have raised to 800^{o}C for superheat to occur. Elemental sodium (0.01% Na) was then added and stirred thoroughly before pouring into the produced mold.

Table 1: Charge calculation (wt. %) of the chill cast A356 aluminium alloy

Element	Al	Si	Mg
Wt.%	92.05	7.50	0.45

Source: [10]

IV. TAGUCHI EXPERIMENTAL DESIGN OF THE HEAT TREATMENT PROCESS

L9-Taguchi design was employed to optimize the chosen key factors namely: solution heat treatment (SHT) temperature and time, and ageing temperature and time, in relation to the response which are hardness and wear rate. Table 2 shows the levels of the factors used in the experiment

Table 2: Levels of the Factors used in the Experiment

Control factor	level			
	1	2	3	Units
A: SHT temperature	500	540	580	^{o}C
B: SHT time	30	60	90	Mins
C: AGEING temperature	160	180	200	^{o}C
D: AGEING time	60	120	180	mins

Nine experiments were performed as illustrated in Table 3 according to the Taguchi design of experiment with 4 factors and 3 levels of each factor. In each case, three experimental runs was conducted in order to obtain an average value.

Table 3: L9 Taguchi Matrix of the Heat Treatment Process

Expt. No.	Factors			
	SHT tempt (^{o}C)	SHT time (min)	Ageing tempt (^{o}C)	Ageing Time (min)
1	500	30	160	60
2	500	60	180	120
3	500	90	200	180
4	540	30	180	180
5	540	60	200	60
6	540	90	160	120
7	580	30	200	120
8	580	60	160	180
9	580	90	180	60

4.1 Heat Treatment of the A356 aluminium alloy

The produced chill cast Al-7.5%Si-0.45%Mg alloy was subjected to solution heat treatment temperatures (500, 540 and 580^{o}C) at solution heat treatment time of (30, 60 and 90 mins), quenched in warm water (60^{o}C) and ageing at temperatures of (160, 180 and 200^{o}C)for ageing times of (60, 120 and 180 mins) as illustrated in Table 3.

4.2 Micro-hardness Measurement of the Heat Treated A356 Aluminium Alloy

The Microhardness characteristic of the treated Al-7.5%Si-0.45%Mg alloy was evaluated by an FIE Vickers hardness tester of MV1-PC model in accordance with ASTM E384 and ASTM E92 standards. The measurements were carried out under a load of $0.3kgf$ .Four three- level parameters (control factors) were positioned in an L9 orthogonal array design. A total of 9 runs were conducted using the various combination of levels for each control factor and presented in Table 4. Each run was repeated at least three times and the average mean value was recorded. The signal-to-noise (S/N) ratios were also calculated using the condition been larger is the better.

Table 4: Taguchi L9 orthogonal array, experimentally measured values for average hardness and their S/N ratios for A356 aluminium alloy

Run	Control factor levels				Mean hardness value	
	A	B	C	D	Value (Hv)	S/N ratio (dB)
1.	500	30	160	60	34.40	30.7312
2.	500	60	180	120	43.53	32.7758
3.	500	90	200	180	54.43	34.7168
4.	540	30	180	180	63.63	36.0732
5.	540	60	200	60	83.57	38.4410
6.	540	90	160	120	41.70	32.4027
7.	580	30	200	120	55.53	34.8906
8.	580	60	160	180	56.00	34.9638
9.	580	90	180	60	74.73	37.4699

The S/N analysis was used to evaluate the experimental results. In S/N analysis, the greater the S/N value, the better the experimental results. This suggest that from Table 4, at 540^{o}C for 1 hour soaking time, with 200^{o}C/1 hour ageing procedure the highest value of S/N (38.4410) was obtained corresponding to a higher hardness profile. This can be deduced based on this experimental process that the S/N ratio and the hardness profile of this alloy under the ageing condition are directly proportional. However, it is also expected that at higher ageing temperature, a lower ageing time is expected to precipitate the solute atoms. This however is in line with other works elsewhere [11].The S/N ratio was used to maximize the robustness of the process and to calculate the "main effect" of each parameter. It have advantages of measuring the relative quality and is independent of the mean value. Also, it reflects the variability in the response of a system caused by noise factors and does not introduce unnecessary complications [12].

Since Taguchi experimental design is orthogonal, separating the effect of each control factor at different levels by averaging the responses or their S/N ratios at each level was possible [13]. For example, the mean S/N ratio for hardness in ACRH at levels 1-3 of control factor A (solution heat treatment temperature) can be calculated by averaging the S/N ratios for the runs 1-3, 4-6 and 7-9 respectively. Table 5 gives the summarized S/N ratio mean results for hardness in ACRH and the calculated main effect i.e. difference between the maximum and minimum value

Table 5: S/N Ratio Response (dB) Table for Hardness in ACRH

Level	SHT temp(^{o}C)	SHT time (mins)	AGEING temp(^{o}C)	AGEING time (mins)
1.	32.74	33.90	32.70	35.55
2.	35.64	35.39	35.44	33.36
3.	35.77	34.86	36.02	35.25
Main effect	3.03	1.50	3.32	2.19

The calculated result of hardness presented in Table 4 and the S/N analysis of Table 5 show that ageing temperature has the largest effect on the hardness properties of the A356 aluminium alloy. On the other hand, solution heat treatment time has the lowest effect. This may be because at the ageing temperature, precipitation of solute atoms are formed which serve as obstacle to the movement of dislocation, hence higher hardness value obtained. An increase in hardness of the alloy will depend on the amount of obstacles that is available to hamper the dislocation movement. The other selected factors have almost the same effects on the hardness properties of this alloy. Thus, it can be concluded that the ageing temperature has the largest effect on the maximum hardness properties of the A356 disc brake in the ACRH using the factors in the optimization process. The results obtained from the current analysis agree with other reports [14].

Figure 1 and 2 shows the effect of control factors on the heat treatment properties. It can be seen that the influence of ageing temperature is very high, while that of SHT time is less important. A fact which can also be concluded from the main effect values presented in Table 6.

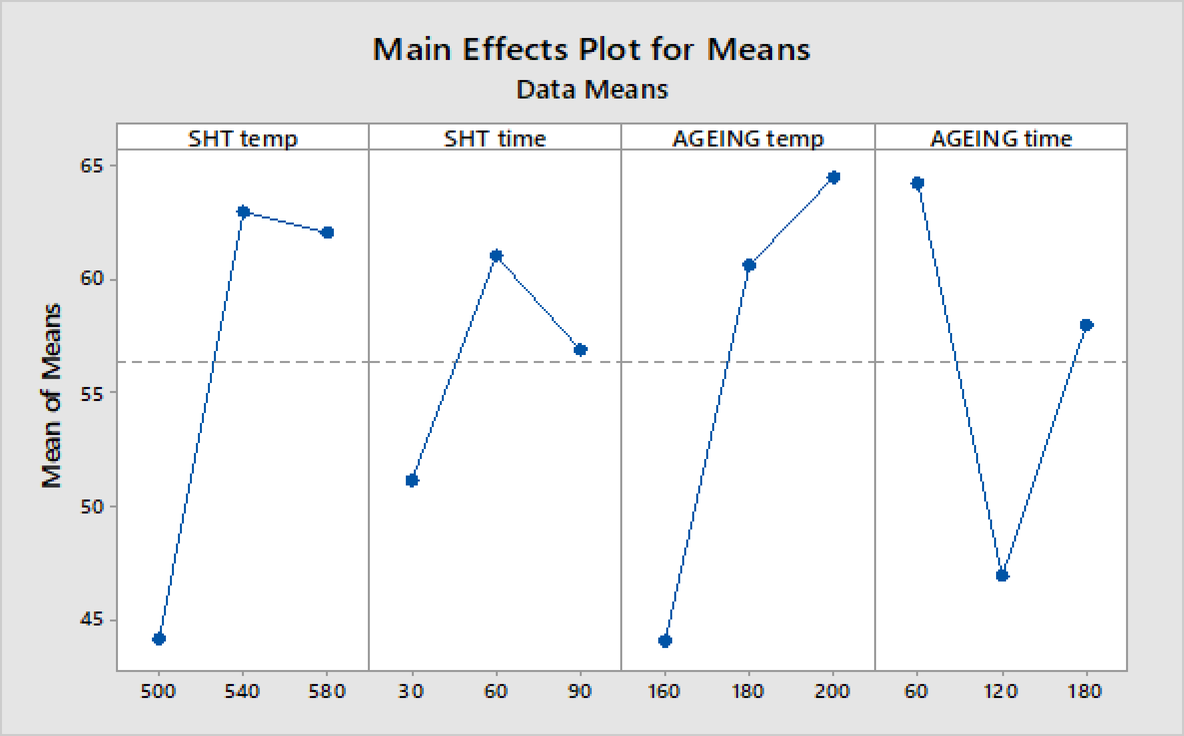

Fig 1: Effect of process parameters on mean response characteristics of Al-7.5%Si-0.45%Mg alloy (hardness in the absence of carbonized rice husk)

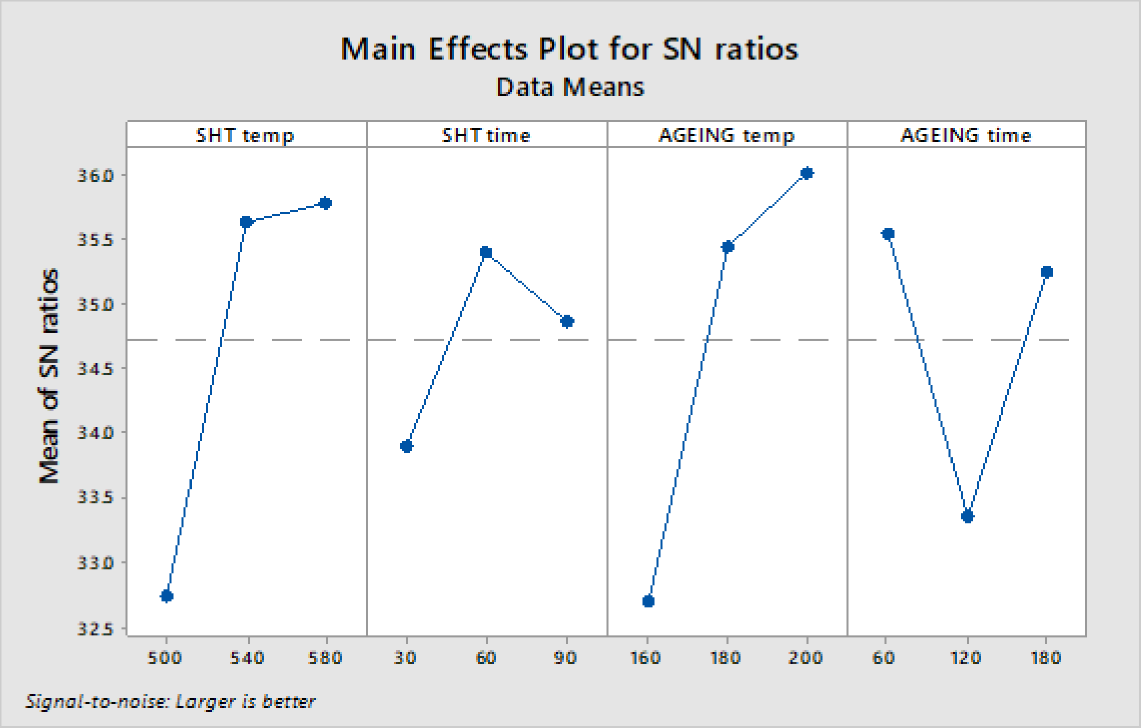

Fig 2: Effect of process parameters on average S/N ratio of Al-7.5%Si-0.45%Mg alloy (hardness in the absence of carbonized rice husk)

At this stage, it is possible to predict the appropriate heat treatment conditions based on the mean and the S/N ratio values of A356 aluminium alloy shown in Figure 1.

4.3 Prediction for Optimized Hardness Value of A356 Aluminium Alloy

It is now possible to predict the appropriate heat treatment conditions based on the mean of mean values of hardness shown in Figures 1 and 2. Analyzing the result shows that a high hardness values were obtained at levels of A_3 (SHT tempt at 540^{o}C), B_2 (SHT time of 60 mins), C_3 (Ageing tempt of 200^{o}C) and D_1 (Ageing time of 60 mins). To evaluate the validity of this result, a statistical analysis based on the developed model and a set of analysis were conducted.

4.4 Developing Model for Predicting the Optimal Hardness of A356 Aluminium Alloy

Let

H_{mh} = Predicted mean hardness

$H_{S/Nh}$ = Predicted S/N ratios

h_{mh} = Total average of hardness performance characteristics [i.e. corresponding to all the 36 (9x4) readings in Table 4]

$h_{S/Nh}$ =Total average of S/N ratio performance characteristics [i.e. corresponding to all the 36 (9x4) readings in Table 4]

$\bar{A}_2, \bar{B}_2, \bar{C}_3$ and $\bar{D}_1$ = The average values of hardness with process parameters at their respective optimal levels.

Therefore,

$$H_{mh} = \bar{h}_{mh} + \left(\bar{A}_2 - \bar{h}_{mh}\right) + \left(\bar{B}_2 - \bar{h}_{mh}\right) + \left(\bar{C}_3 - \bar{h}_{mh}\right) + \left(\bar{D}_1 - \bar{h}_{mh}\right) \quad 1$$

$$H_{S/Nh} = \bar{h}_{S/Nh} + \left(\bar{A}_2 - \bar{h}_{S/Nh}\right) + \left(\bar{B}_2 - \bar{h}_{S/Nh}\right) + \left(\bar{C}_3 - \bar{h}_{S/Nh}\right) + \left(\bar{D}_1 - \bar{h}_{S/Nh}\right) \quad \text{…. …2}$$

Equations 1 and 2 can be used to predict the optimal mean and S/N values for hardness. It is however be noted that in this study assumptions are made on the basis that there is no interaction between any of the factors A, B, C and D.

4.4 Confirmation of the Predicted Hardness Value of A356 Aluminium Alloy

To evaluate the validity of the analysis, a statistical analysis based on the predicted S/N ratio and a set of experiments were conducted. Table 6 shows the comparisms between the predicted hardness values and experimental results.

Table 6: Comparisms between the predicted hardness values and experimental results obtained

Response(Hv)	Level	Predictive values		Experimental values		Percentage error		Improvement	
		Mean (Hv)	S/N (dB)	Mean (Hv)	S/N (dB)	Mean	S/N	Value	%age
Hardness	$A_2B_2C_3D_1$	83.57	38.4410	89.73	39.0588	6.87	1.58	6.16	10.92

The percentage error in mean hardness is 6.87 which is however less than the maximum recommended 10% error reported in literature [15- 16]. The percentage improvement in hardness of 10.92 showed that the hardness of the A356 aluminium alloy can be further increased by the use of Taguchi design of experiment.

V. CONCLUSIONS

Inthis work, the selection of process parameter for A356 alloywith the optimal hardness properties have been reported. The optimal hardness was calculated using the larger the better quality characteristics. Experimental results have shown that the use of Taguchi design of experiment for optimization have greatly improved the hardness properties of the alloy under investigation.

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