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Optimizing Tensile Properties of Age Hardened A356 Aluminium Alloy via Taguchi Method

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Research Article

Abstract

This paper presents the effectiveness of optimising single-thermal ageing characteristics of A356 aluminium alloy using Taguchi methodology. In this research work, Taguchi's L9 (3^4) orthogonal array was successfully used forexperimental design to study the influence of artificial ageing treatment (T6) parameters on the tensile properties of A356 aluminium alloy. Ageing parameters such as solutionizing temperature, solutionizing time, ageing temperature and ageing time were employed in this study. The tensile test and microstructural analysis were conducted using a universal testing machine and optical metallurgical microscope respectively. Also, the experimental data were analysed with the aid of Minitab 18 statistical software based on the larger the better criterion. The results showed that the optimum value obtained for tensile strength based on Taguchi prediction was 136.23 N/mm2 and 11.23% for percent elongation. Thus, the level of the improvement attained for both tensile strength and percent elongation at the optimized condition was 50 % higher than that of the as-cast sample properties. The results further revealed that ageing temperature and solutionizing time were the prominent factors influencing the tensile properties of T6-treated A356 alloy. The microstructural analysis confirmed that the improvement of the tensile properties of T6-treated A356 aluminium alloy could be directly related to the spheroidization of eutectic Silicon (Al-Si) and the presence of Mg_2Si inter-metallicprecipitates in the structure.

Keywords
Aluminium Alloy; Artificial Ageing; Optimization; Taguchi method; Tensile Properties

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1. Introduction

The demand for aluminium-base alloys as lighter and stronger materials in the automotive and aircraft industries is gaining popularity (Dwivedi *et al.*, 2014 &Esmaeili*et al.*, 2003). The heat treatable Al-Mg-Si alloys such as A356 cast aluminium alloy are widely developed to substitute heavier metals by virtue of their excellent fluidity and castability, relative high strength-to-weight ratio and good corrosion resistance. These unique attributes lead to less vehicle and aircraft weight, reduction of fuel consumption and less carbon dioxide emission to the atmosphere (Esmaeili *et al.*, 2003 & Popoola *et al.*, 2011). As compared to pure aluminium metal, cast aluminium A356 alloys have been developed with significant ductility, strength, elongation, hardness and toughness at room temperature.

It is well known that the mechanical properties of A356 aluminium alloys are highly dependent, not only on the casting process, but on the responsiveness to heat treatment via age or precipitation hardening (T6) treatment. Precipitation hardening or T6 treatment provides the most widely applied mechanism for the strengthening of Al-Mg-Si alloys by the formation of uniformly dispersed second-phase precipitates within the Al α-phase matrix (Ochieze *et al.*, 2018 & Peng *et al.*, 2011). Ceschini *et al* (2017) stated that the response of this class of alloys to T6 heat treatment is strongly related to the factors controlling each treatment phase viz; solutionizing, quenching and aging processes. Hence, the performance of the alloys depends heavily on the parametric design of the thermo processing route.

Although numerous investigations on the microstructural and mechanical characterization of A356 alloys have been conducted, little systematic study on the process optimization of age hardening treatment process has been reported. Further improvement of the mechanical properties of A356 is therefore possible with the optimization of ageing parameters such as solutionizing time, solutionizing temperature, ageing temperature and ageing time. In the last three decades, Taguchi optimization method has been successfully adopted to robustly design experimental processes with a desired goal of maximizing a single quality characteristic such as tensile strength (Radhika *et al.*, 2011 & Maleque *et al.*, 2018). Attempt has, therefore, been made in this study to investigate the influence of age hardening parameters on the microstructural evolution and the tensile properties of A356 aluminium alloy under artificial ageing (T6) treatment conditions using Taguchi's optimization technique.

2. Experimental Methods

The A356 aluminium alloy used in this study was produced through the conventional sand casting method. The composition of the as-cast sample is given in Table 1. The as-cast rods with dimension of 350 mm length and 15mm diameter were machined to standard dimension required for the Hounsfield tensile test samples (ASTM E-8) using lathe machine. Taguchi method was used for the experimental planning of the precipitation hardening treatment schedules and parametric optimization. The four factors considered for the precipitation hardening treatment includes; solutionizing temperature, solutionizing time, ageing temperature and ageing time. A tabular layout of these selected factor levels used is given in Table 2. The tensile strength and percentage elongation were considered as the responses for this investigation. The experimental design was based on Taguchi's L9 (3^4) orthogonal array consisting primarily of nine experimental trial rows and four factors at three levels, as shown in coded form in Table 3.

Table 1: Composition of the produced Al-Si-Mg (A356) aluminium alloy

Element	**Al**	**Si**	**Mg**
% weight	92.7	7.0	0.3

Table 2**:** Selected Experimental Factors and their Levels

Control Factors	**Denotation**	**Levels**		
		1	**2**	**3**
Solutionizing Temperature (ºC)	A	510	540	570
Solutionizing Time (h)	B	2	4	6
Ageing Temperature (ºC)	C	150	180	210
Ageing Time (h)	D	4	6	8

Table 3**:** Taguchi's L9 Experimental Orthogonal Array

Exp. No	**Control Factors**			
	A	**B**	**C**	**D**
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

A total of eighteen (18) tensile test samples were subjected to precipitation hardening treatment using the experimental design layout and designated levels shown in Table 4, with each experimental trial having two samples. The samples were heated in the muffle furnace to solutionizing temperatures of 510, 540 and 570ºC and holding temperatures of 2, 4 and 6 hours. The solutionized samples were rapidly quenched in a bath of warm water maintained at a temperature of 65ºC. The as-quenched samples were then artificially aged in an electric oven maintained at varying ageing temperatures of 150, 180 and 210ºC and ageing time of 4, 6 and 8 hours. Finally, the age-hardened samples were left to cool in air prior to tensile testing.

Tensile test was carried out on the as-cast and precipitation hardened (T6-treated) samples to determine the tensile strength and the percentage elongation data obtained from Hounsfield tensometer experiment. The operation involved mounting each end of the tensile sample to the tensile casing. The casings were then coupled and the samples subjected to tension in a horizontal direction by manually turning the wheel attached to the machine. The tensile force was recorded as a function of the increase in gauge length and calculated by dividing the load at break by the original minimum cross-sectional area. Thus, the ultimate tensile strength (UTS) and percentage elongation were also calculated accordingly.

The experimental data obtained for the two responses (tensile strength and Percentage elongation) were subjected to Taguchi analysis for optimization purpose using Minitab 18 software. In this study, the larger the better characteristics approach was selected as the goal is to maximize the two responses. In Table 5, a layout is given in an account of the signal to noise ratio (S/N) of the responses using the larger the better approach, which is represented mathematically by the equation. 1;

$$\left(\frac{S}{N}\right)_L = -10LOG\left(\frac{1}{n}\sum\left(\frac{1}{{y_i}^2}\right)\right) \quad (1)$$

Where 'n' is the sample size or number of trials and y_i is the response or result of the experiment (ultimate tensile strength and percentage elongation) of the ith experiment for each of the trials. Once all of the S/N ratios have been computed on the MINITAB 18 for each run of an experiment, a graphical approach was used to analyze the data. In the graphical approach, the S/N ratios and average responses are plotted for each factor against each of its levels. From the graphs, higher the better the values were selected and the confirmation tests were conducted. Confirmation experiment was carried out to validate the best heat treatment conditions obtained during the optimization as well as to verify the model predictabilities. For microstructural analysis, the as-cast and some selected age-hardened samples were prepared using standard metallographic procedure. The samples were ground, polished and lightly etched with freshly prepared Keller's reagent. The prepared samples were then observed with an optical microscope (OPM) in order to reveal their microstructural details.

3. Results and Discussion

3.1 Tensile Properties

Table 4 shows the variations of the selected control factors over a total of nine experimental trials using Taguchi's L9 (3^4) orthogonal array. It also shows the results obtained for the average tensile strength and percentage elongation. As can be seen, two samples were selected for each of the experimental trial and the averages were calculated as presented in columns 8 and 11 respectively (Table 4).

Table 4: Experimental Results Using L9 (3^4) Orthogonal Arrays

Exp. No	Control Factors				Response					
	Sol. Tempt, A (ºC)	Sol Time, B (h)	Ageing Tempt, C (ºC)	Ageing Time, D (h)	Tensile Strength (N/mm^2)			% Elongation		
					1	2	Mean	1	2	Mean
1	510	2	150	4	82.54	100.74	91.64	9.16	8.96	9.06
2	510	4	180	6	82.01	77.12	79.57	8.23	7.41	7.82
3	510	6	210	8	121.19	114.81	118.00	11.67	10.03	10.85
4	540	2	180	8	107.75	104.26	106.01	9.47	9.24	9.36
5	540	4	210	4	102.16	102.16	102.16	8.82	8.82	8.82
6	540	6	150	6	103.39	109.53	106.46	11.36	11.38	11.37
7	570	2	210	6	131.23	131.23	131.23	12.36	12.36	12.36
8	570	4	150	8	80.86	83.10	81.98	8.72	8.61	8.67
9	570	6	180	4	83.51	87.51	85.51	9.09	10.00	9.56

Table 5 shows the result of the signal to noise ratio for the tensile strength characteristic of T6-treated A356 alloy based on the larger-the-better criterion. It is observed from the table that experiment number 7 had the highest value S/N ratio of 42.3607dB corresponding to the value of 131.23 N/mm^2. The combination of factors for this experiment is as follows; 570^0C solutionizing temperature (A3), 2hrs solutionizing time (B1), 210ºC ageing temperature (C3) and 6hrs ageing time (D2). Table 6 shows the response values for tensile strength and the interaction of the control factors as well as the degree of the contribution that each of these factors in maximizing the tensile strength of the heat treated alloy.

The delta values obtained in Table 6 were calculated by the difference between the maximum and minimum mean values. Based on these delta values, the rank for each of the factors is usually determined with their rankings. As shown from the table rank '1' indicates that the Aging temperature (C) has the highest influence on the tensile strength of the age hardened alloy and that solutionizing temperature (A) which was ranked '4' is the least contributor.

Figure 1 shows the main effects plot for S/N ratios; the inclination of the plot is used to determine the significance of each parameter and the value that corresponds with the highest point of these parameters is the optimum value for that factor. From this plot, it is seen that the optimum levels obtained occurs at A2B1C3D2; which are: 540ºC solutionizing temperature, 2 hours solutionizing time, 210ºC aging temperature and 6 hours aging time. Table 7 represents a summary of the factors and the optimum levels as obtained from the main effects plot for signal to noise ratio.

Table 5: Signal to Noise Ratio for the Tensile Strength of T6-Treated A356 alloy

Experiment Number	Control Factors				Tensile Strength (N/mm^2)	S/N (dB)
	A (ºC)	B (h)	C (ºC)	D (h)		
1	510	2	150	4	91.64	39.2417
2	510	4	180	6	79.57	38.0150
3	510	6	210	8	118.00	41.4376
4	540	2	180	8	106.01	40.5069
5	540	4	210	4	102.16	40.1856
6	540	6	150	6	106.46	40.5437
7	570	2	210	6	131.23	42.3607
8	570	4	150	8	81.98	38.2742
9	570	6	180	4	85.51	38.6403

Table 6: Response Table for the Tensile Strength T6-treated A356 alloy

Level	A	B	C	D
1	39.56	40.70	39.35	39.36
2	40.41	38.82	39.05	40.31
3	39.76	40.21	41.33	40.07
Delta	0.85	1.88	2.27	0.95
Rank	4	2	1	3

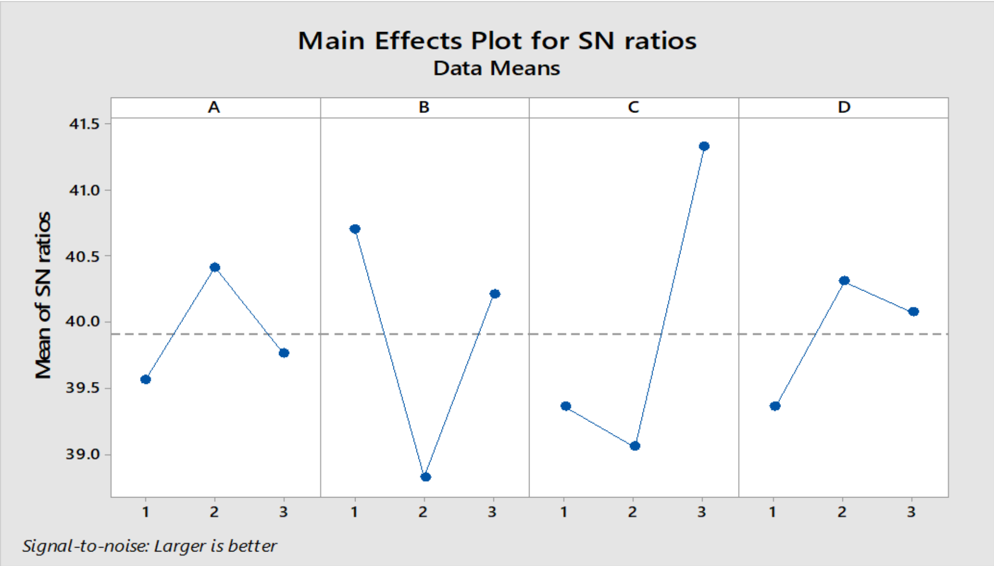


Figure 1: Main Effects Plot for the Tensile strength of T6-Treated A356 alloy

Table 7**:** Optimum values of factors and their levels

Parameters	**Designation**	**Optimum Value**
		Tensile strength
Solutionizing Temperature (ºC)	A2	540
Solutionizing Time **(h)**	B1	2
Ageing Temperature (ºC)	C3	210
Ageing Time **(h)**	D2	6

The amount of elongation undergone by T6-treated A356 alloy specimen during testing provides a value for the ductility of the metal as shown in Table 8. In general, percent elongation is directly proportional to the ductility of an alloy. From the experimental result (Table 8), similar trend was observed as it was in the tensile strength result, where experiment number 7 showed the highest value for percentage elongation of 12.36%. The response table for percent elongation is shown in Table 9. It is seen in Table 9 that contrary to tensile strength results, the solutionizing time (B) is ranked 1st and has the most influence on the percentage elongation of the alloy; ageing temperature is ranked 2nd and ageing time 3rd. The result further reiterates the fact that solutionizing temperature is the least significant of the control factors. Moreover, Figure 2 displays a graphical plot of data for the main effects, it is clear that the optimum combination of factors and their levels with respect to the signal to noise ratio are given as A3B3C3D2 which represents 570ºC solutionizing temperature, 6 hours solutionizing time, 210ºC aging temperature and 6 hours aging time.

Table 8: Signal to Noise Ratio for Percent Elongation

Experiment Number	**Control Factors**				**% Elongation**	**S/N (dB)**
	A (ºC)	**B (h)**	**C (ºC)**	**D (h)**		
1	510	2	150	4	9.06	19.1426
2	510	4	180	6	7.82	17.8641
3	510	6	210	8	10.85	20.7086
4	540	2	180	8	9.36	19.4255
5	540	4	210	4	8.82	18.9094
6	540	6	150	6	11.37	21.1152
7	570	2	210	6	12.36	21.8404
8	570	4	150	8	8.67	18.7604
9	570	6	180	4	9.56	19.6092

Table 9: Response Table for Percent Elongation

Level	**A**	**B**	**C**	**D**
1	19.24	20.14	19.67	19.22
2	19.82	18.51	18.97	20.27
3	20.07	20.48	20.49	19.63
Delta	0.83	1.97	1.52	1.05
Rank	4	1	2	3

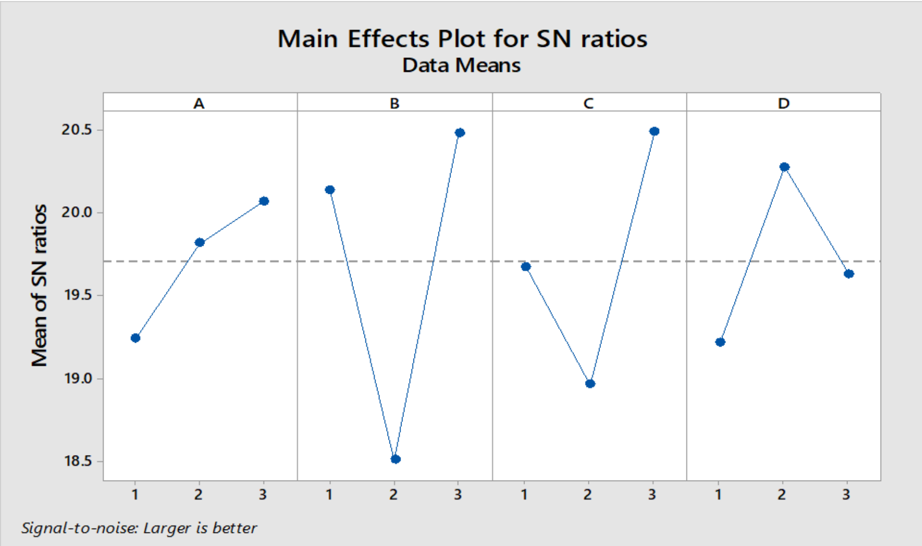


Figure 2: Main Effects Plot for Percent Elongation (S/N ratio)

Table 10: Optimum values of factors and their levels

Parameters	**Designation**	**Optimum Value**
		Percent Elongation
Solutionizing Temperature (ºC)	A3	570
Solutionizing Time (h)	B3	6
Ageing Temperature (ºC)	C3	210
Ageing Time (h)	D2	6

For both tensile strength and percent elongation, the experimental runs were made at the optimum levels of A2B1C3D2 for tensile strength and A3B3C3D2 for percent elongation (Tables 7 and 10 respectively). The responses selected at optimal values of the input variables are termed as the predicted responses while the experimental observations are the actual responses obtained through the T6 heat treatment carried out at the predicted parameter conditions. The actual experimental observations are compared with the predicted ones and the residuals are computed in Table 11. Furthermore, the percentage improvement in the tensile properties of the A356-T6 alloy was subsequently calculated using the predicted optimal response value of 136.51N/mm^{2}and 11.72% for tensile strength and percent elongation respectively. The percentage improvement was done by comparing these values with the as-cast response values of 90.8N/mm^2 for tensile strength and 7.78% for percent elongation. Therefore, the percentage improvement for tensile strength is given as;

$$\%\, Improvement = \frac{136.23-90.8}{90.8} \times 100\% = 50.03\%$$

While for Percent Elongation is given as;

$$\%\, Improvement = \frac{11.72-7.78}{7.78} \times 100\% = 50.64\%$$

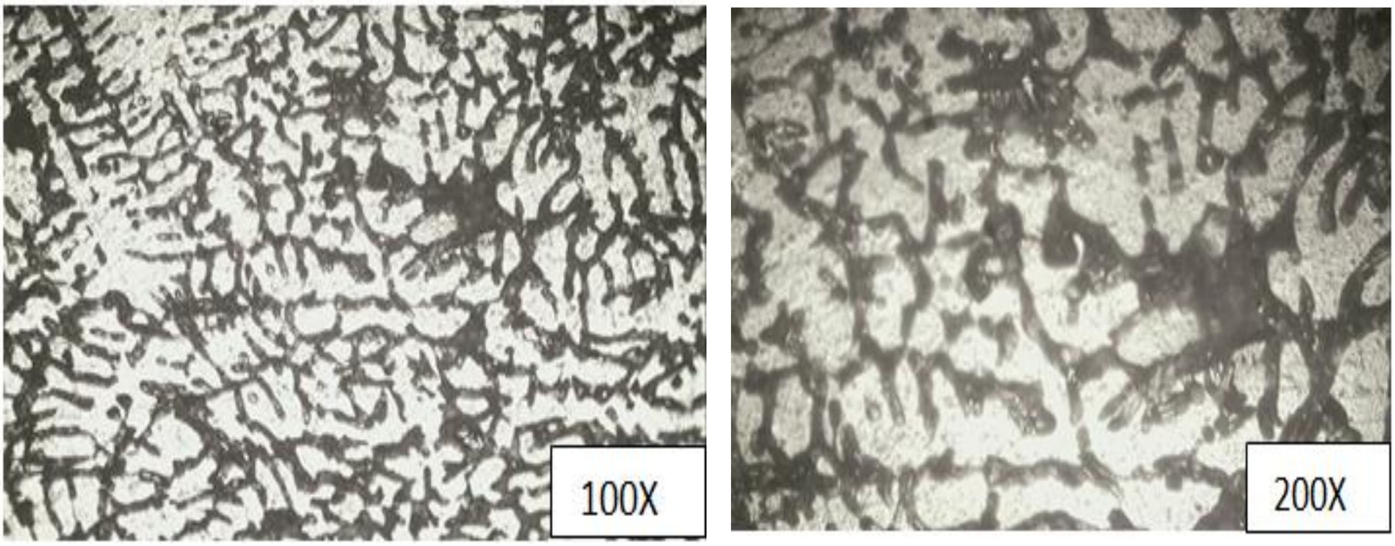
From the above calculations, it is seen that for both responses considered in this work, the percentage improvement recorded from Taguchi optimization is almost 50% when compared with that of the as-cast sample. Also, the percentage errors obtained in the validation of Taguchi prediction is about 1.67% and 7.75% for tensile strength and percent elongation respectively. This therefore confirmed the adequacy of the Taguchi optimization technique for predicting tensile properties of A356-T6 treated alloy.

Table 11: Analysis of Confirmation Test for T6-Treated A356 Alloy

		Tensile Strength	Percent Elongation
1	Predicted	136.23 (N/mm^2)	11.72
2	Experiment	134.51 (N/mm^2)	12.64
3	% Error	1.3	7.24
4	% Improvement	50.03	50.64

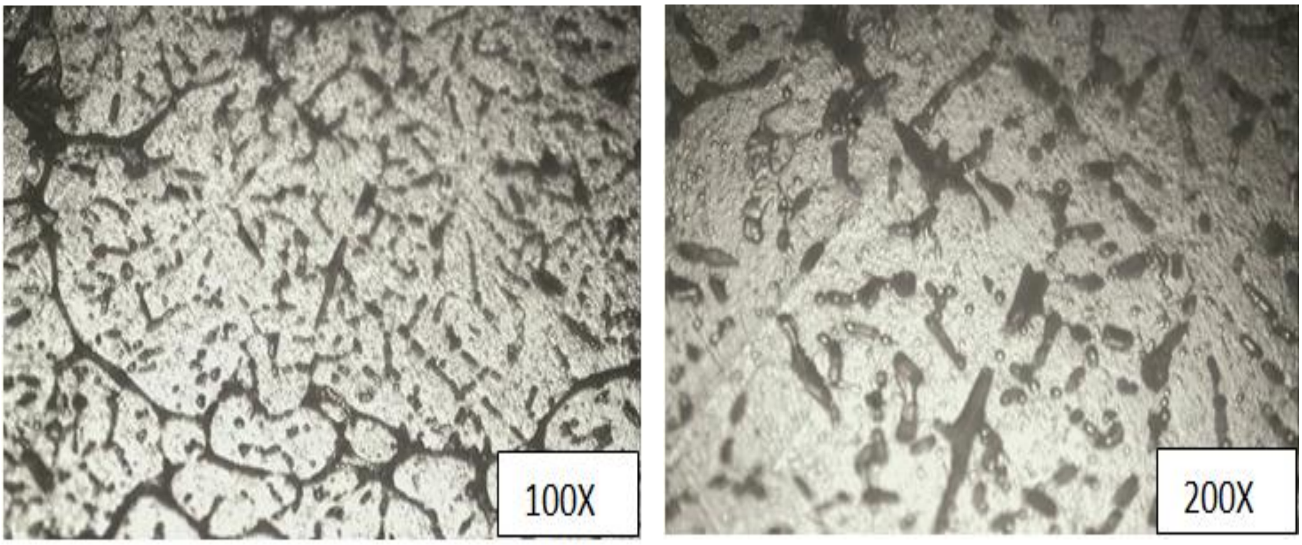
3.1 Microstructural Evaluation

It is a known fact that the variables affecting the microstructure of an alloy mainly include composition, solidification conditions, and heat treatment (Popoola *et al.*,2011). Figure 3 shows the as-cast sample of the A356 aluminum alloy. As can be seen, the structure of the monolithic A356 Al alloy consists of primary α phase (white regions) and Al-Si eutectic structure (darker regions) with intermetallic Mg_2Si particulates. The morphology of the eutectic Si has a great impact on the mechanical properties of the alloy. As observed, it is seen that the microstructure largely exhibits a continuous inter-dendritic structure for the eutectic silicon and few spheroids which is dispersed across the microstructure. The dendritic α-Al matrix phase was formed due to the rate of solidification of the A356 as-cast sample.



(a) (b)

Figure 3: Optical Micrograph of As-cast A356 alloy: Magnification (a) 100x (b) 200x

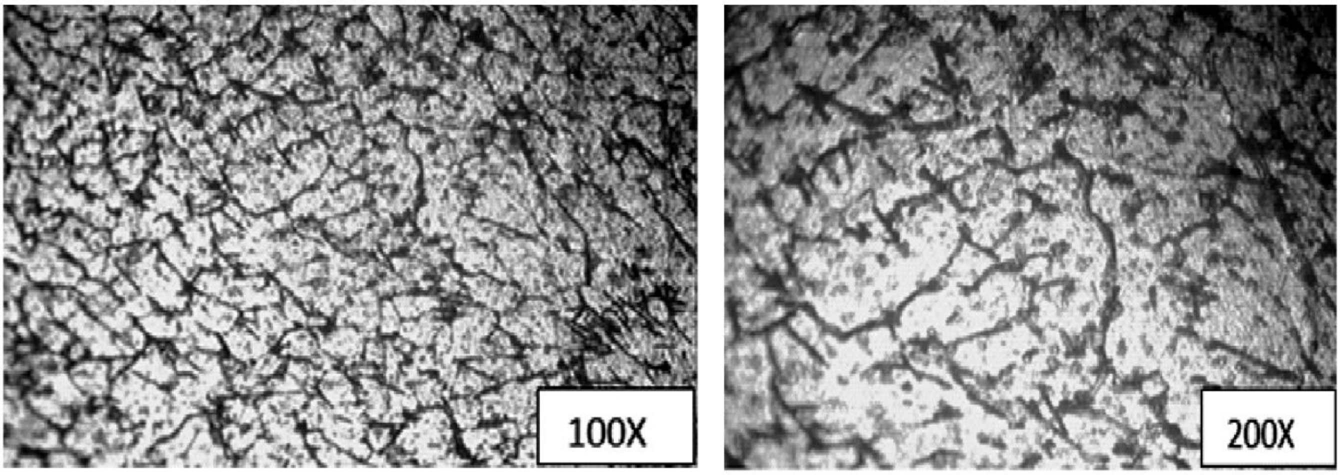


(a) (b)

Figure 4: Optical Micrograph sample 7: Magnification (a) 100x. (b) High magnification, 200x

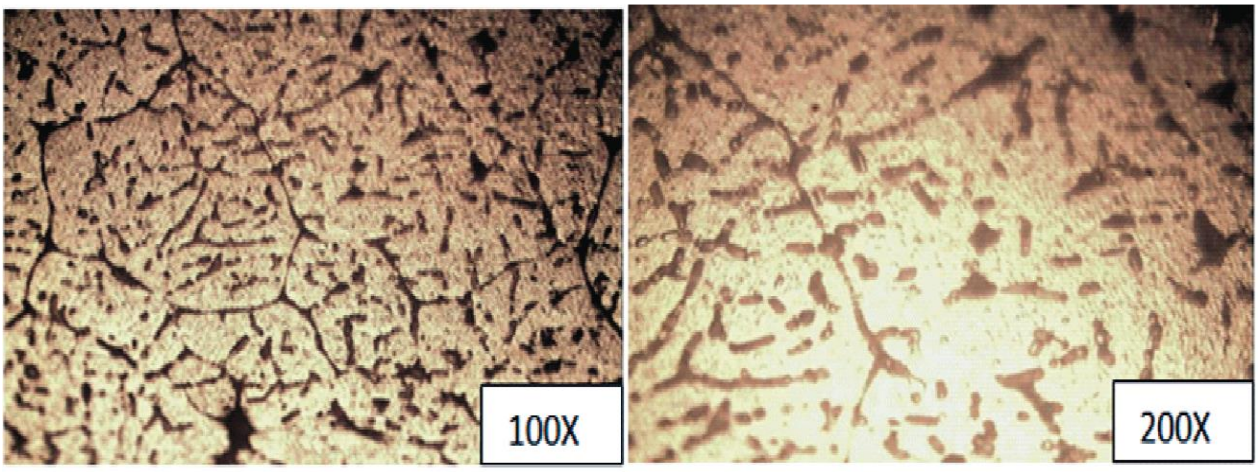
The microstructures of T6-treated A356 alloys (sample 7) conducted under the experiment 7 condition (Table 4) are presented in Figure 4. As previously identified, the microstructure shown in the micrograph represents the sample with the best response for both tensile strength and percent elongation. In Figure 4(b), it can be seen clearly that the continuous branch-like eutectic silicon separated into segments, consequentially the average particle size is decreased notably creating a discontinuous morphology for the eutectic silicon. Also, it is observed that ageing heat treatment under this condition causes the spheroidization of eutectic silicon thus resulting to a decrease in the spacing of the secondary dendritic arm. This could therefore be responsible for the simultaneous high tensile strength and ductility obtained in this sample.

Figure 5 shows the micrograph of sample treated under experimental trial 2 condition, which is the least response characteristics for both the percent elongation and tensile strength. This sample was heat treated at 510ºC solutionizing temperature, 4 hours solutionizing time, 180ºC ageing temperature and 6 hours ageing time. It is seen that there is a significant decrease in the spheriodized inter-dendritic eutectic silicon as observed in Figure 4. The eutectic silicon then forms a strained inter-dendritic morphology. This increases the tendency for crack propagation from the Mg_2Si inter-metallic precipitates which are more susceptible to fracture thus resulting to a decrease in the ductility and the tensile strength of the alloy. Figure 6 reveals the microstructure of the experimental sample conducted at the optimized condition. As can be seen, the structure consists of spheriodized eutectic silicon in α-Al matrix as comparable to the sample observed in Figure 4 (sample 7).



(a) (b)

Figure 5: Optical Micrograph of sample treated under experimental trial 2 condition. Magnification. (a) 100x (b) 200x



(a) (b)

Figure 6: Optical Micrograph for Confirmation Samples

4. Conclusions

An experimental study has been carried out to determine the influence of artificial aging treatment parameters on the tensile properties of artificially aged A356 aluminum alloy using Taguchi's optimization technique. Based on the experimental observations, it can be concluded that;

i. The A356 Aluminum alloy has been successfully produced and artificially aged using sand casting method and precipitation hardening (T6) treatment respectively.
ii. The Taguchi technique was successfully applied to optimize the tensile properties of the age hardened A356-T6 alloy. The tensile strength and percent elongation of T6-treated A356 alloy were significantly controlled by ageing temperature and solutionizing time while the solutionizing temperature revealed the least effect.
iii. The microstructural analysis confirms that T6 heat treatment is effective in the spheroidization of the silicon precipitates and that the improvement of the tensile properties of T6 treated A356 aluminum alloy could be directly related to the spheroidization of eutectic Silicon (Al-Si) during ageing.
iv. Significant levels of the improvement of about 50% were attained at the optimized parameter condition for

the tensile properties of T6-treated A356 alloy when compared to the property of the as-cast sample.

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