International Conference on Mechanical Engineering Research (ICMER2013), 1-3 July 2013
Bukit Gambang Resort City, Kuantan, Pahang, Malaysia
Organized by Faculty of Mechanical Engineering, Universiti Malaysia Pahang
Paper ID: P320

EFFECT OF SOLUTION TREATMENT TEMPERATURE ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF A356 ALLOY

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ABSTRACT

Over the years, aluminum content in a vehicle part is increasing due to the needs to reduce weight as well as increase fuel efficiency. Most of the cast product in a vehicle part is mostly cast from A356 alloy. It is used because A356 alloy posses'excellent characteristics over other type of alloy such as cast ability, high weight-to-strength ratio, good corrosion resistance and good weld-ability. Most of the cast component in vehicle such as cylinder head favors hardness over tensile strength. Most of the solution treatmentsstudied was done on sample having α-Al with dendritic structure.The objective of this research is to investigate the effect of solution treatment temperature on microstructure and mechanical properties of A356 (Al7Si0.3Mg) aluminum alloy. Heat treatment was done to harness the full potential of cast A356 alloy and T6 heat treatment is the commonly used treatment for this alloy. In the present study, the specimen was cast using low pouring temperature method which produces equiaxedα-Al structure. The specimen undergone solution treatment for two (2) hours at three different temperatures (530 °C, 540 °C, and 550 °C), quenched in water at room temperature, followed artificial aged for six (6) hours at 170 °C. Mechanical properties of A356 aluminum alloy were investigated by tensile test and hardness test. The relation between size, shape, and distribution of Si particle and the alloy's mechanical properties were investigated. Si particle size, shape, and dispersion affect the mechanical properties of cast A356 alloy. Higher solution treatment temperature produce smaller and more globular Si particle before completing T6 heat treatment. Elongations decrease while ultimate tensile strength (UTS) increase as solution temperature increased from 530 °C to 550 °C. A356 aluminum alloy specimen solution treated at 530 °C have comparable hardness compared with specimen solution treatment at 540 °C before and after artificial ageing - complete T6 heat treatment - with higher elongation and lower energy usage as added benefit.

Keywords: solution treatment temperature, equiaxed α-Al, hardness, A356 aluminum alloy

INTRODUCTION

Over the years, aluminum content in a vehicle part is increasing due to the needs to reduce weight as well as increase fuel efficiency. Most of the cast product in a vehicle part is mostly cast from A356 alloy(Campbell, 2003). It is used because A356 alloy posses' excellent characteristics over other type of alloy such as cast ability, high weight-to-strength ratio, good corrosion resistance and good weld-ability.

Dendritic α-Al structure is produced by casting A356 alloy using normal pouring (NP) method, which is pouring melted alloy at high temperature. The low pouring temperature (LPT) method, which is pouring melted alloy at a low temperature near its liquidus temperature produce α-Al with equiaxed or globular structure. Equiaxed structure reduces forming resistance, thus, more complicated component can be cast. In case of permanent mold and die casting, LPT method prolonged the mold service life.

Heat treatment is done to harness the full potential of cast A356 alloy. The distribution, morphology, volume fraction, degree of Si particle modification, composition of phases of the as-cast microstructure, along with the solution treatment parameters (temperature, time) chosen determine the successfulness of solution treatment.Solution treatment is done at a high temperature, close to the eutectic temperature of the alloy; its purpose is to(Sjölander & Seifeddine, 2010):

- Dissolve soluble phases containing Cu and Mg formed during solidification;
- Homogenize the alloying elements;
- Spheroidize the eutectic Si particles.

Study by (Möller, Govender, & Stumpf, 2008) shows long solution treatment time provide low hardness and short solution treatment provide high hardness.The time required for solution treatment depends on a few factors such as the composition, structure, size and distribution of the phases present after solidification, and solution treatment temperature (Sjölander & Seifeddine, 2010; Smith, Russell, & Bhatia, 2009).Most solution treatment is carried out between 4 to 6 hours at 540 ^{o}C and is said to be the most optimum condition (Cavaliere, Cerri, & Leo, 2004; Shabestari & Shahri, 2004; Tensi & Hogerl, 1996). Solution treatment of cast Al-Si-Mg alloys in the 400-560 ^{o}C range dissolves the hardening agents (Mg_2Si particles) into the α-Al matrix, reduces the micro-segregation of magnesium, copper, manganese, and other addition elements in aluminum dendrites, and spheroidize the eutectic silicon particles to improve the ductility (Davidson, Griffiths, & Machin, 2002).According to (Sjölander & Seifeddine, 2010), homogeneous solid solution is formed when atoms leave the coarse particles formed during solidification and propagate into the Al-Si matrix and reduces the concentration gradient. The time required to homogenize the castingdepends on the morphology of the diffusing atoms and the solution treatment temperature (diffusion rate) as well as by coarseness of the microstructure (Sjölander & Seifeddine, 2010). The time needed for spheroidize the eutectic Si particle is strongly depends on the solution treatment temperature, shape and structure, and size of the eutectic Si particles in the as-cast (AC) condition. The desired solution time and temperature, to a great extent, depend on the casting method, the extent of modification, and desired level of spheroidization and coarsening of silicon particles (Ma, 2006).The solution treatment time can be reduced if the AC microstructure is finer (Sjölander & Seifeddine, 2010).The maximum temperature for solution treatment of a metal must not exceed, when possible, its solidus temperature (Smith et al., 2009). (Möller et al., 2008)investigated the effects of variations from T6 standard treatment on the hardness, ductility, and UTS of A356 alloy cast in a permanent mould with and without strontium modification. The main variables considered in the experiments were solution treatment time and temperature. The as-cast samples were solution treated for various times (t=2, 4, 8, 16 and 32 hours) at 520 ^{o}C/540 ^{o}C and aged at 160 ^{o}C for 6.5. The highest hardness was obtained at a short solution treatment time (2 hours) for both unmodified and modified

A356, while the highest ductility was not achieved until the samples undergone 8 hours of solution treatment at the same temperature.

Most of solution treatment studied was based on dendritic α-Al structure like what was done by a number of researchers such as (Caceres, Davidson, Griffiths, & Wang, 1999; Möller et al., 2008; Sjölander & Seifeddine, 2008). The low pouring temperature method produced equiaxedα-Al structure, in which the alloying element is spread throughout the aluminum in a much higher degree compared to normal pouring which produces dendritic α-Al structure. This means that low pouring temperature helps in homogenizing the alloying element to some extent. Solution treatment will further homogenize the alloying element; therefore its priority now is to spheroidize the eutectic Si particle. Unsuitable solution treatment regime will waste the effort of producing equiaxed/globular α-Al structure of sand cast A356 alloy. If lower solution treatment temperature is used, the alloying elements will not have complete dissolution and become unavailable for precipitation hardening and highersolution treatment temperature increase the cost due to high energy usage than is necessary.Therefore, in this paper, the effect of solution treatment temperature on microstructure and mechanical properties of sand cast A356 aluminum alloy having α-al equiaxed structure is studied.

EXPERIMENTAL PROCEDURE

A356 aluminum alloy was used in the present study.Table 1 shows the chemical composition of A356 alloy.A356 ingots were melted in a diesel furnace and the molten metal was poured at a temperature of 620 °C.The cast product was then machine to cylindrical tensile test specimen with dimension as shown in figure 1.

Table 1. Chemical composition of A356 alloy (%)

Al	**Si**	**Mg**	**Cu**	**Fe**	**Mn**	**Ti**	**Zn**	**Other, each**	**Other, total**
Remain.	6.50 - 7.50	0.30 - 0.45	≤20	≤0.15	≤0.10	≤0.20	≤0.10	≤0.050	≤0.15

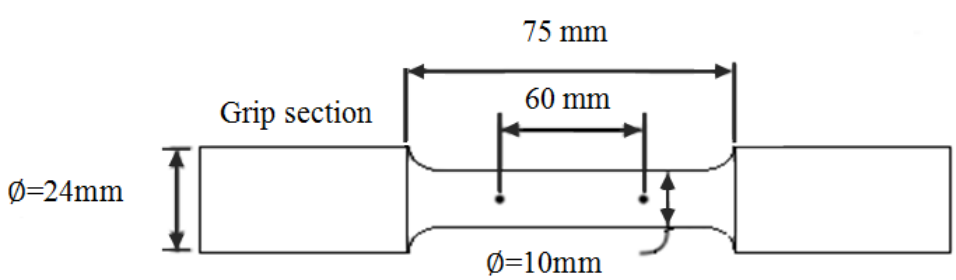

Figure 1. Dimension for tensile test specimen

The ST was done for two (2) hours at three (3) different temperatures as listed in Table 2. Notice that the only manipulated parameter made by the researcher in this study was the solution treatment temperature while the other parameters were kept constant. Two (2) tensile specimens for each temperature variation was solution treated in an induction furnace. All the specimens were rapidly quenched in water at room temperature after completing the solution treatment. After quenching, a sample for microstructure observation and hardness test was taken from tensile test specimen of each temperature variation before proceeds with artificial ageing. The specimens undergo solution treatment and quenching in water. After that, the sample was artificial aged at 170 °C for 6 hours. Again, a sample for microstructure observation and hardness test was taken from tensile test specimen of each temperature variation after completing T6 heat treatment.

Table 2: Heat treatment parameter

T6 heat treatment parameter			
ST Temperature	530 °C	540 °C	550 °C
ST Time	2	2	2
Quench	Water at room temperature		
AA Time	6 hours	6 hours	6 hours
AA Temperature	170 °C	170 °C	170 °C
No. of specimen	2	2	2

The microstructure was observed using optical microscope under magnification of 5× and 50×. Three (3) different field-of-views was observed and captured under the 5× magnifications.The size of Si particle and distribution statistic was analyzed using image analysis software for every field-of-view with magnification of 50×.

Vickers hardness test was used for hardness testing in this study. ASTM E384 was used as the standard for this test. The same specimens were used for microstructure observation.

Tensile test was done on sample T6 heat treated with strain rate of 1 mm/min using UTM machine.

RESULTS AND DISCUSSION

Microstructure Observation

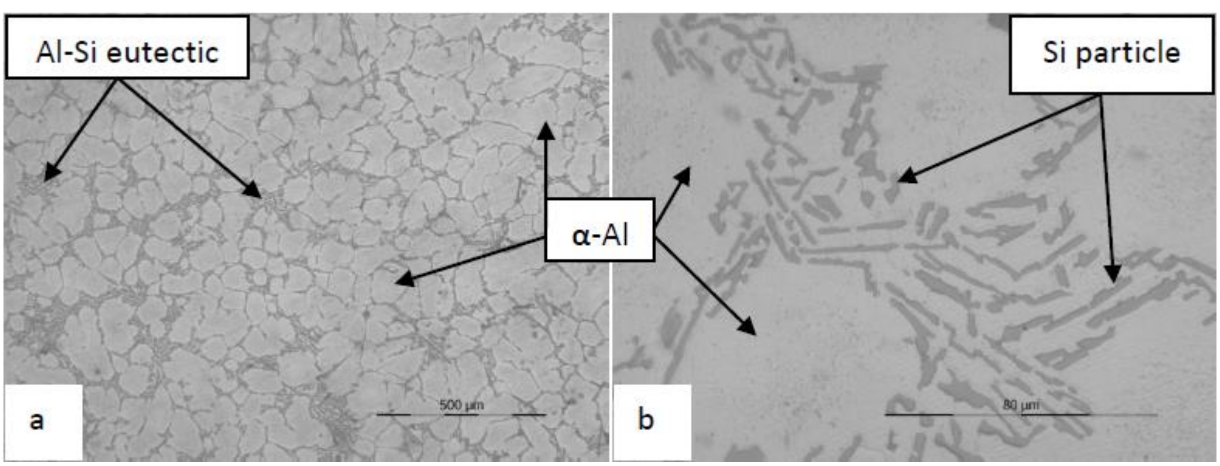

Figure 2.AC microstructure. (a) Magnification 5× and (b) Magnification 50×

The α-Al shape does not differ much between the three solution treatment temperatures even after completing the T6 heat treatment, which all exhibiting equiaxed shape (Figure 3). The major different observed is with the number of eutectic Si particle and its size produced by the different solution treatment temperature which became the interest of the present study (Figure 4).

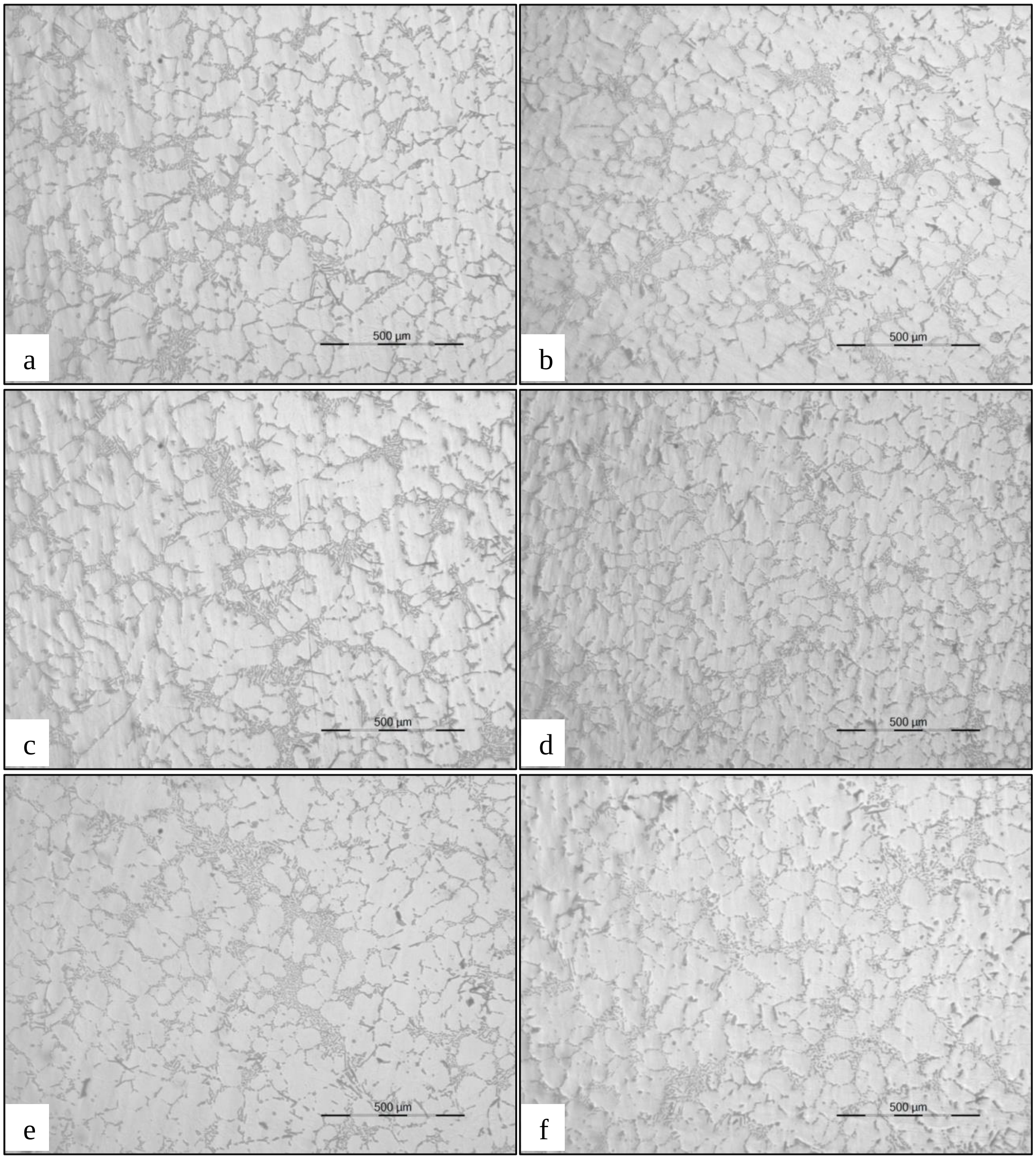

Figure 3.(a) 530 ST, (b) 530 T6, (c) 540 ST, (d) 540 T6, (e) 550 ST, and (f) 550 T6, withmagnification of 5×.

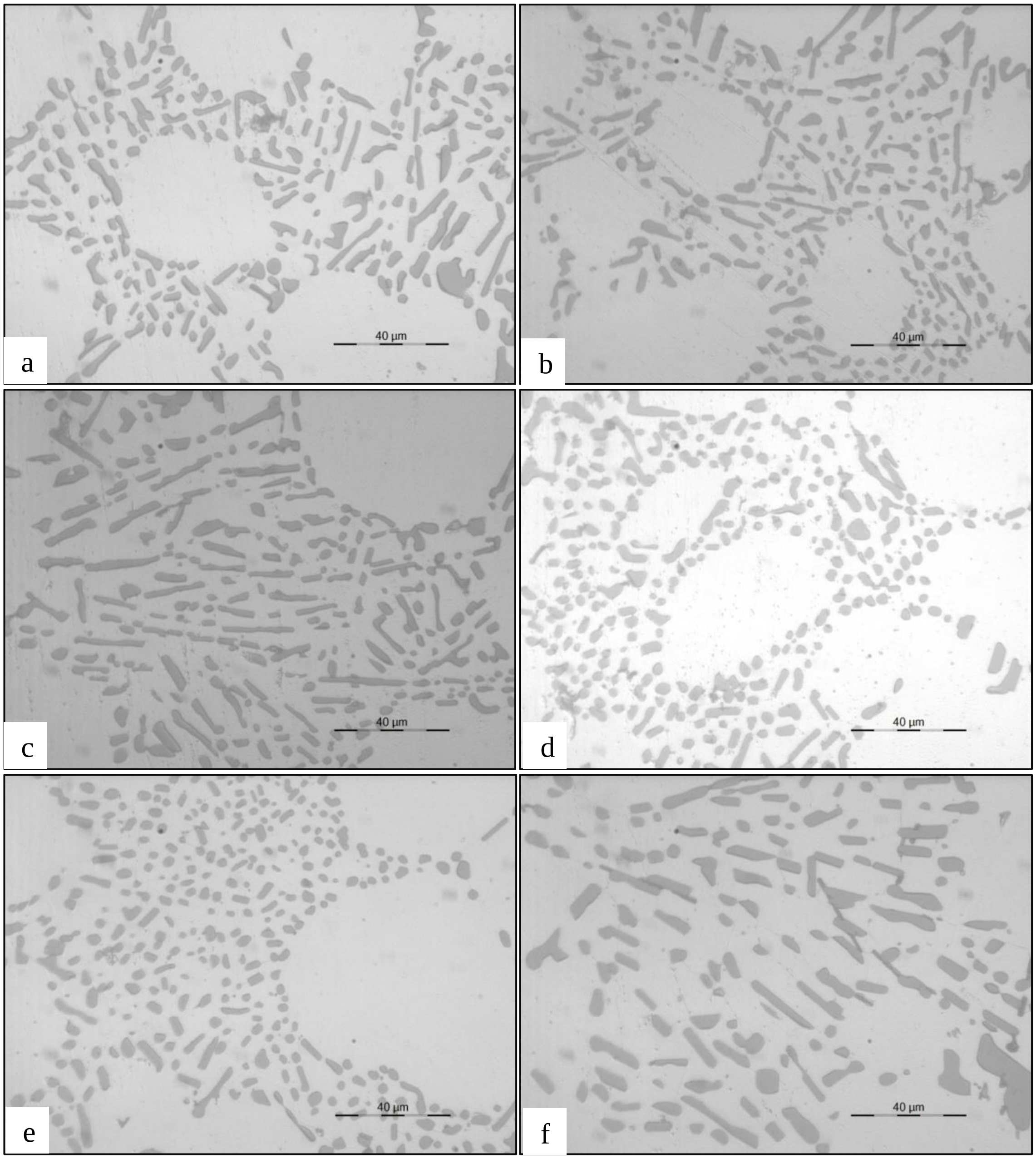

Figure 4.(a) 530 ST, (b) 530 T6, (c) 540 ST, (d) 540 T6, (e) 550 ST, and (f) 550 T6, with magnification of 50×

Table 3 shows the statistic of Si particle for different condition. Si particle with size ranging up to 100 µm² are further divided into five size ranges. Figure 5 shows distributions of Si particle for solution treatment condition while Figure 6 shows the distribution for complete T6 condition.

Table 3. Si particle statistic

Specimen	No. of Eutectic Si Particle						Average Si particle Size
	0 ≤ A <20 µm²	20 ≤ A < 40 µm²	40 ≤ A <60 µm²	60 ≤ A < 80 µm²	80 ≤ A < 100 µm²	Total 0 ≤ A ≤ 100	
AC 4	66	36	18	14	8	142	74.186
530 ST	277	67	32	19	15	410	28.632
540 ST	342	106	54	34	10	546	25.488
550 ST	515	123	40	17	14	709	20.528
530 T6	356	90	42	13	10	511	23.594
540 T6	629	131	46	24	9	839	18.654
550 T6	187	72	35	29	19	342	38.674

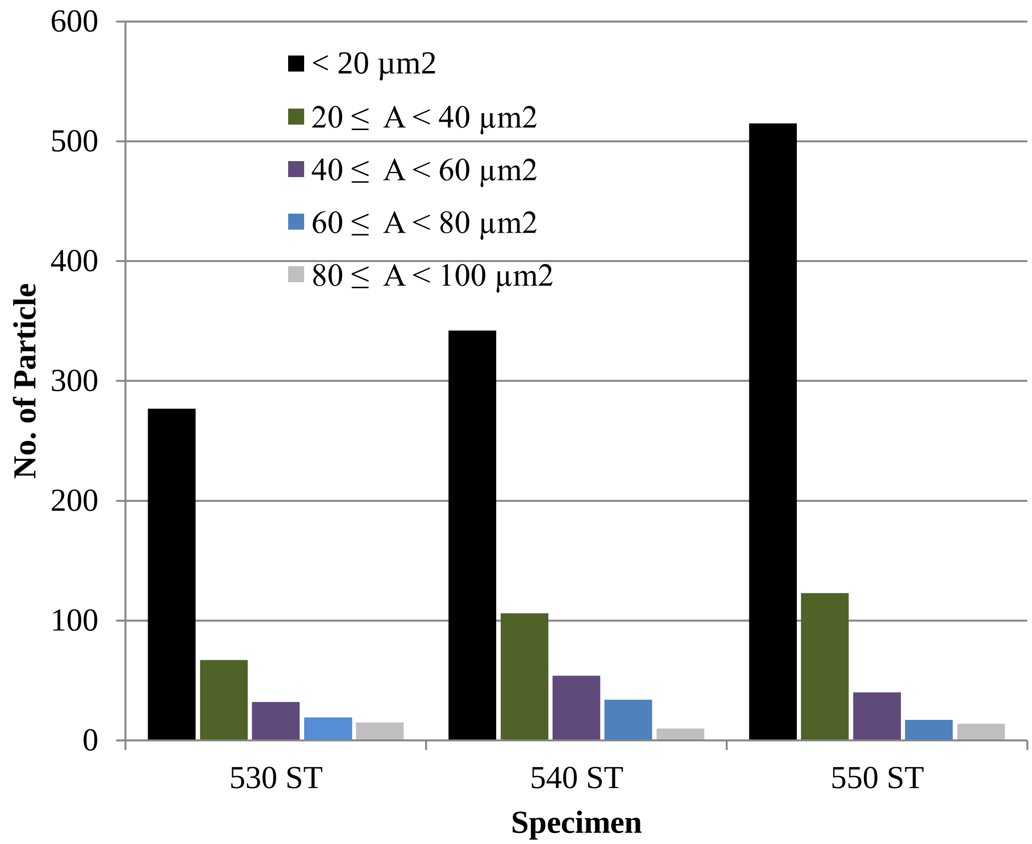

Figure 5. Si particle distribution (ST condition)

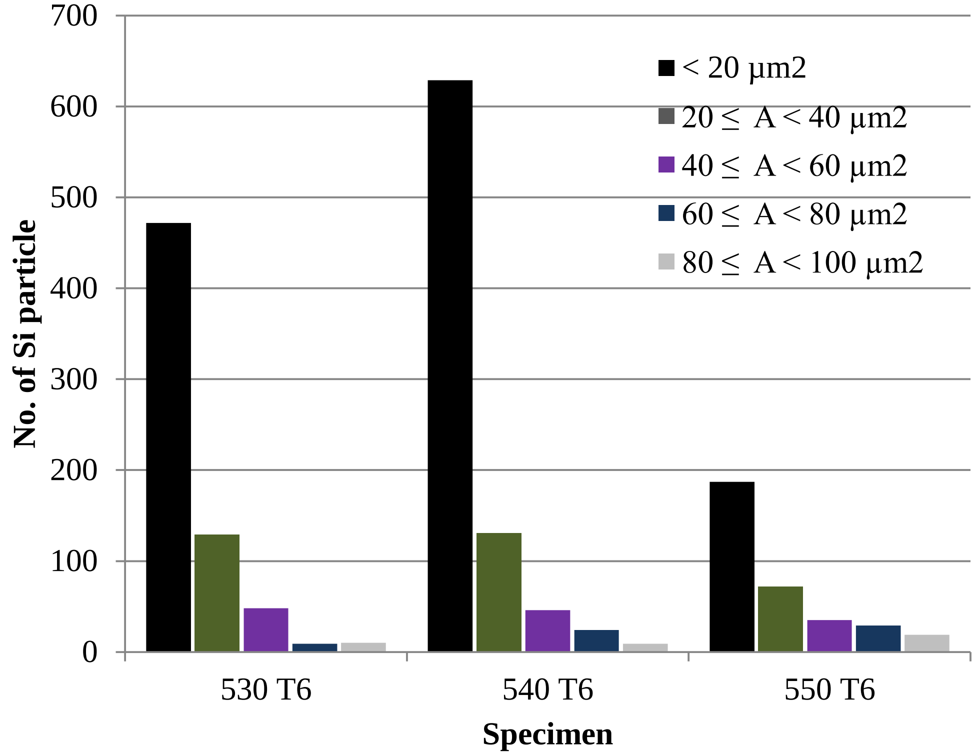

Figure 6. Si particle distribution (T6 condition)

Number of Si particle with area range of $0 \leq A < 20$ µm² increased as solution treatment temperature increased. This particular range ($0 \leq A < 20$ µm²) is chosen to be the interest of this study because of its relatively high number of Si particle exist in the range compared to the others. The range is also chosen because of its strong relation with micro hardness, which will be discussed in the later part of this paper. High solution treatment temperature provide higher diffusion rate, causing the eutectic Si particle to be dissolved and diffuse into the α-Al matrix at higher rate compared to lower solution treatment temperature. These are the reasons for high existence of Si particle in the $0 \leq A < 20$ µm² size range for solution treatment temperature of 550 °C. Si particle dissolved in a much lower rate for lower ST temperature, resulting in less number in the discussed range.

After completing T6 heat treatment, eutectic Si particle in the $0 \leq A < 20$ µm² size range is large in number compared to the other size range. The number of Si particle in the $0 \leq A < 20$ µm² range increases as solution treatment temperature increasedprior to completion of T6 treatment and it is expected to be higher for 550 T6 condition but that is not the case (Figure 6). There is major different in Si particle number in the size range of interest for 550 °C solution treated specimen after artificial ageing compared to the other two specimen. There is not much of a different in eutectic Si particle number before and after completing T6 treatment for the other four ranges.The purpose of artificial ageing is to obtain a uniform distribution of small precipitates, which gives a high strength. Solution treatment at 550 °C produce eutectic Si particle with an average size of 20.528 µm² which is smaller than the size produced by solution treatment at 530 °C and 540 °C. Smaller eutectic. For different Si particle size went through the same artificial ageing regime, specimen with smaller eutectic Si particle size experiencing the same affect as if it went through longer artificial ageing regime at low temperature or, experiencing the same effect as if it went through a short artificial ageing regime at higher temperature. Due to its smaller eutectic Si particle size, the 550 °C solution treated sample experiencing over aged artificial ageing regime. Over ageing caused the eutectic Si particle to combine together and coarsen (increase in size as evident in Table 4 and Figure 4) and become weaker than in the peak aged condition (Kuntongkum, Wisutmethangoon, Plookphol, & Wannasin, 2008).(Kuntongkum et al., 2008)finds that number of eutectic Si particle decrease as solution treatment temperature prior to artificial ageing increased more than 540 °C (effect of over ageing). The same findings are obtained in the present study (Table 3). Over ageing also increase the dispersion of eutectic Si particle (Figure 4).

Micro Hardness Test

Table 4. Micro hardness test result

Condition	Micro hardness (HV)					Average
	1	**2**	**3**	**4**	**5**	
AC 4	52.9	61.1	62.5	62.8	56.2	59.1
530 ST	79.1	78.3	81.8	86.5	90	83.14
540 ST	83.2	78.1	79.1	76.2	89.5	81.22
550 ST	87.8	88.1	91.2	74.3	94.1	87.1
530 T6	131.8	131.4	131.4	141.4	137.1	134.62
540 T6	133.6	119.7	127.9	134.6	146.7	132.5
550 T6	112.2	107.5	97.4	105.8	106.4	105.86

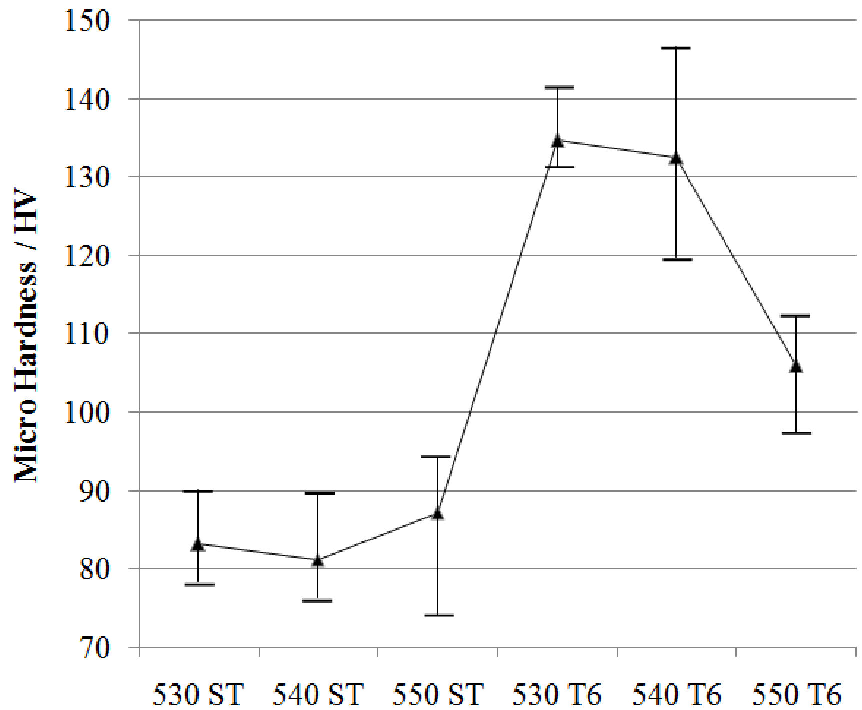

Figure 7.ST temperature versus micro hardness

The average hardness of 530 °C and 540 °C solution treated specimen are almost the same for solution treated condition as shown in Table 4. ST at 550 °C gives highest hardness value of 87.1 HV for solution treated condition. The size and shape of Si particle plays an important role in affecting the hardness of the alloy. It can be seen in Figure 4, the shape of Si particle for 530 °C and 540 °C solution treated specimen are almost the same, these explain the small difference in their hardness. Although their shape does not differ much, Si particle shape for 530 °C sample is slightly rounded and short and dispersed wider compared to that of 540 °C sample (Figure 4), result in slightly higher hardness.

The more globular shape and small sized Si particle in the 550 °C sample contribute to its high hardness in solution treated condition (Figure 4). The force exerted by the indenter is distributed evenly between the many and small Si particles in 550 °C ST sample, which increase the difficulty for the indenter to penetrate deeper into the alloy, resulted in small indentation, thus giving high value of hardness.

After completing the T6 heat treatment, again, it can be seen that the difference in hardness between samples solution treated at 530 °C and 540 °C is small. Although the size of Si particle does not differ much between the two samples, their shape do differs with 540 °C sample having more globular Si particle shape (Figure 4).

Sample that solution treated at 550 °C resulted in lowest hardness. The shape and size of 550 °C sample coarsen after completing the treatment and the Si particle are widely dispersed between each other (Figure 4). In this kind of microstructure, the indenter surface tends to land on the soft Al phase, which results in low hardness. Due to the wide dispersion of the Si particle, the area of Si particle available to distribute the forces exerted by the indenter become less and more force land on the soft Al phase, resulting in lower hardness. As mentioned in the previous subsections, unsuitable artificial ageing regime for the prior solution treatment could be the reason for result acquired. Specimen that solution treated at 550 °C is experiencing over aging, making the Si particle to combine and coarsen, thus, lowering its hardness.

Tensile Test

Table 5 shows the tensile test findings of A356 Aluminum alloy which went through complete T6 heat treatment under three different solution treatment temperature. The Ultimate Tensile Strength (UTS) of A356 alloy increased with increase in solution treatment temperature prior to artificial ageing (Figure 8). The elongation of this alloy on the other hand, decreases as solution treatment temperature increase. The yield strength (YS) of A356 aluminum alloy increases with increase in solution treatment temperature from 530 T6 until 540 T6 but decrease for 550 T6 as can be seen in Figure 7.

Table 5. Tensile test result

Name	Specimen1	Specimen 2	Average
UTS (MPa)			
530	213.47	206.296	209.883
540	230.819	209.074	219.947
550	223.423	225.213	224.318
YS (MPa)			
530	81.231	145.885	113.558
540	206.766	184.562	195.664
550	129.101	207.800	168.451
Elongation (%)			
530	3.11429	3.04829	3.08129
540	3.35579	2.42594	2.89087
550	2.47029	2.61763	2.54396

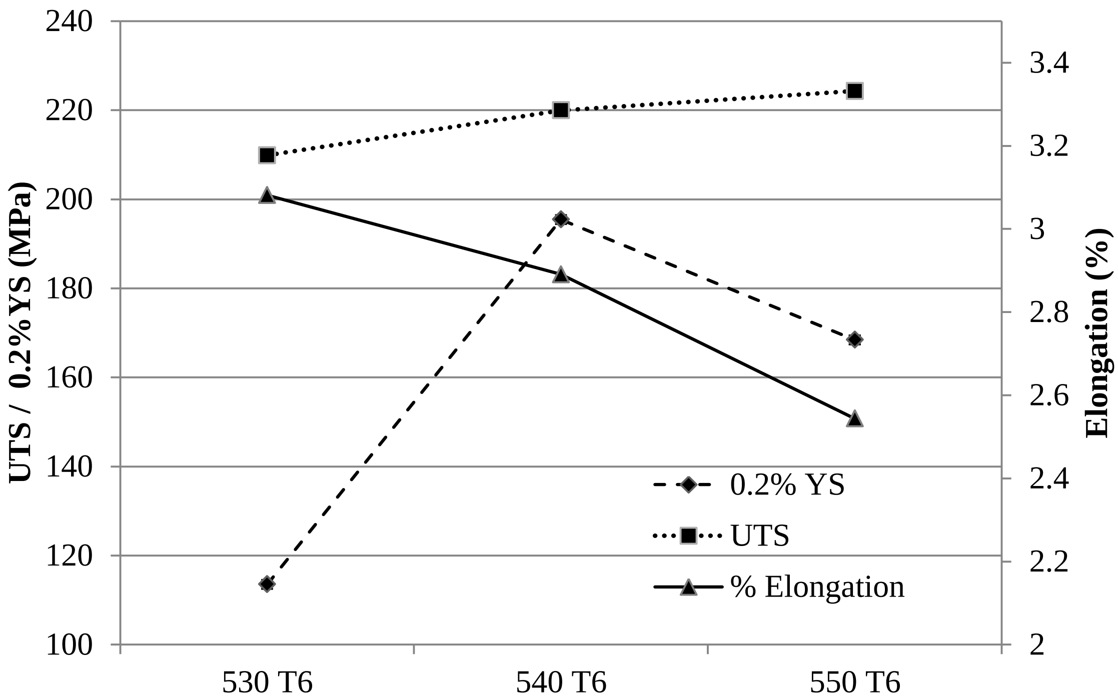

Figure 8. Yield Strength (0.2% YS), Ultimate Tensile Strength (UTS) and Elongation for 530 T6, 540 T6 and 550 T6

The trend of increase in UTS and decrease in elongation observed in this study is in good agreement with other researcher (Caceres et al., 1999; Sjölander & Seifeddine, 2010). (Sjölander & Seifeddine, 2011)and (Ran, Zhou, & Wang, 2008)were both agreed that coarse microstructure (having large and elongated Si particle) is the reason for low elongation to fracture and this is in good agreement with the findings of this study (Table 3, Figure 4f, and Figure 8). This could also be one of the reasons for the low yield strength acquired by the 550 T6 sample as can be seen in Figure 8.

Quenching rate also affect the yield strength of A356 alloy. If the quench rate is high enough, the solute is retained in solid solution and high number of vacancies would also be retained (Sjölander & Seifeddine, 2010). Conversely, too slow cooling rate cause the particle to precipitate heterogeneously at grain boundaries or at the dislocations; resulting in a decrease in the super saturation of solute and in the same time, resulting in lower yield strength after completing the heat treatment. Weakness with rapid cooling is that the thermal stresses are induced in the casting.Specimen solution treated at 530 °C and 550 °C were experiencing low and high quench rate, respectively. This explains for the low yield strength acquired by the sample solution treated at 530 °C and 550 °C.

The observed behavior highly depends on the size (area) of eutectic Si particle, the presence or formation of β’ (rods/elongated) eutectic Si particle, which decrease ductility as stated by (Kuntongkum et al., 2008) and the dispersion of Si particle. Larger Si particle size increases the tendency of crack formation(Goulart, Spinelli, Os´orio, & A.Garcia, 2006).

The elongation to fracture depends strongly on the ability of Si particles in the Al-Si eutectic to stop the motion of dislocations (Caceres et al., 1999). Solution treatment makes the

Si particles distributed more homogeneously in a fine microstructure and the dislocations interact with theSi particles individually. Consequently the dislocations pass the Si particles and accumulated at the grain boundaries where the fracture takes place, resulting in a high elongation to fracture (Caceres et al., 1999). According to (Caceres et al., 1999), the low elongation to fracture is caused by the coarse Si particles which become an obstacle for the dislocations causing it to pile up at the Al–Si eutectic (where fracture could occur).

CONCLUSION

- Si particle size, shape, and dispersion affect the mechanical properties of cast A356 alloy. Higher solution treatment temperature produce smaller and more globular Si particle before completing T6 heat treatment.Highest hardness before artificial ageing was achieved by solution treating the A356 alloy at 550 °C due to the small Si particle produced (average size of 20.528 μm²).
- Highest hardness was achieved by solution treatment at 530 °C following T6 heat treatment with average of Si particle size of 23.594 μm² produced.Lowest hardness after artificial aging is the result of ST at 550 °C (105.86 HV) due to its large (38.674 μm²) and highly dispersed Si particle.
- A356 alloy which were solution treated at 540 °C followed by T6 heat treatment shows higher tensile strength due to its globular Si particle shape and small Si particle (average size of 18.652 μm²).Elongation decreases while UTS increases as solution treatment temperature increased from 530 °C to 550 °C.
- A356 sand cast aluminum alloy having equiaxedα-Al structure solution treated at 530 °C have comparable hardness with sample solution treated at 540 °C before and after completing T6 heat treatment

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