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Effect of Degassing and Heat Treatment on Microstructure and Mechanical Properties of A356.0

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Abstract*: In this present research study, A356.0 was systematically studied on mechanical properties in order to establish the database for further investigation in degassing, heat treatment and microstructure. Because of specific microstructure and characteristics, the heat treatment condition of A356.0 was explored through the observations of microstructure and the measurement of micro-hardness. In the investigation of heat treatment, it was observed that the eutectic silicon was refined and spheroidzed which is unlikely for conventional processing. This study shows the systematic approach to find the root cause of major defects in aluminium alloy wheels which were identified as shrinkages, inclusions, porosity/gas holes and cracks etc using defect diagnostic approach. As hydrogen forms gas holes and porosity in the aluminium castings the amount of hydrogen present in the molten metal is studied by finding specific gravity of the samples collected. The general type of heat treatments applied to aluminium and its alloys is preheating or homogenizing and also to reduce chemical segregation of cast structures and to improve their work ability. Test of mechanical properties is done through various tests like hardness test, tensile test, impact test, ductility Test.

***Keywords*: A356.0, Degassing, Heat Treatment, Mechanical Properties, Microstructure.**

I. INTRODUCTION

Molten Aluminium contains a large amount of dissolved iron, which should be expelled before it is poured into mold. This process is called Degassing process. During the solidification of aluminium alloys dissolved hydrogen creates porosity that, if left unchecked is detrimental to the mechanical properties of aluminium alloy casting. The inert gas when purged through the melt collects the soluble hydrogen atom, allowing a hydrogen molecules to form the inside lower pressure of the collector gas bubbles. Pure argon is frequently injected into liquid alloy through a submerged lance or bubbler, so that dissolved hydrogen enters the argon bubble prior to discharge into the environment. Specimens of both before and after degassing process are collected and examined for Chemical composition, K-Mold and Specific gravity. The general type of heat treatments applied to aluminium and its alloys is preheating or homogenizing to reduce chemical segregation of cast structures and to improve their work ability. Annealing is done to soften the strain-hardened (work-hardened) and heat treated alloy structures to relieve stresses and to stabilize properties and dimensions. Solution heat treatments are to effect solid solution of alloying constituents and improve mechanical properties. Heat treatment involves solutionzing furnace, Quenching tank and Ageing Furnace. Specimens are collected before and after degassing, heat treatment. These collected Specimens are processed for surface preparation, grinding, cloth polishing and etching. Finally specimens are observed under the microscope for its microstructure. Test of Mechanical properties is done through various tests like Hardness, tensile, Impact, Fatigue, and Ductility.

II. DEGASSING

Alloying elements, such as Si and Mg, adding in aluminium melt significantly increases the inclusion particles and develop a high pore density in solidified castings. Rotary degasser as shown in *fig 1* is used for degassing the impurities by passing the inert gas argon in it. As the bubbles break the surface, aluminium is lost to oxidation by the furnace gases and entrapment in dross. Additionally the use of chlorine creates environmental issues. One of the advantages of this technique is that flux may be injected simultaneously.

The Foseco metal degassing unit (MDU) has a graphite rotor, which will introduce inert gases near the bottom of the vessel which generates very small bubbles and blends them with molten aluminium drawn into the rotor. As the bubbles float to the surface, they enlarge with a decrease in pressure that attracts the dissolved hydrogen to the bubbles and into the bubbles that escape .

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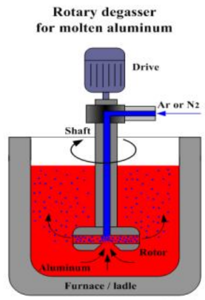
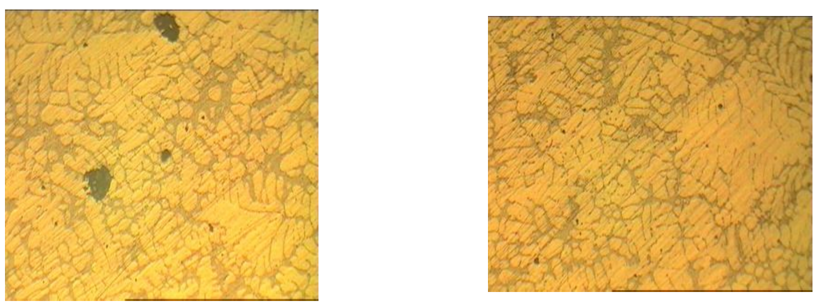


Fig.1 Rotary Degassing Unit

Table I: Specifications of Circular Degassing Rotor

Flux feed rate	Rotor speed	Argon gas flow	Cycle time	Gas pressure	H_2 after degassing
500 grms /550 kgs	500- 600 rpm	25-30 lpm	12 mins	2- 4 bar	0.08-0.13cc/ 100 grms

A. Results and Discussions of Degassing



(a) (b)

Microstructure of A356.0

Fig. 2 (a) Microstructure before Degassing and (b) Microstructure after Degassing

Magnification shows the results of the metallographic investigation. The structure of base unmodified alloy is dendrite. Under the influence of the shear forces caused by the rotation of the mixer a transformation of dendrite to a non dendrite structure of the primary phase particle took place. Large elliptically shaped primary particle are formed and a coarsening of the structure is obvious. An overview of the morphologies in fig shows the difference in the microstructure of before and after degassing. The microstructure of before degassing has impurities in the form of porosity, holes and inclusions as shown in *fig. 2(a)*, after degassing process the impurities disappear from the liquid metal as shown in *fig.2(b*).

Table II: Test for Chemical Composition of A356.0 before degassing

Elements	Al	Si	Mg	Fe	Cu	Ti	Na	Pb	Mn	Ni	Cr	Sn
Wt (%)	91.81	7.36	0.400	0.009	0.002	0.153	0.0001	0.024	0.029	0.017	0.007	0.062

Table III: Test for Chemical composition of A356.0 after degassing

Elements	Al	Si	Mg	Fe	Cu	Ti	Na	Pb	Mn	Ni	Cr	Sn
Wt (%)	91.78	7.36	0.407	0.105	0.003	0.154	0.0001	0.025	0.020	0.018	0.007	0.068

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At a room temperature of 20 ± 3ºC this test is done by using Spectro Meter. Specimens are shown below

(a) (b)

Fig. 3(a) Specimen of A356.0 on Spectro Meter and (b) Specimen of A356.0 for Chemical Composition Test

Table IV: Test for Specific Gravity of A356.0 before degassing

Wt in Air (grms)	Wt in Water (grms)	Specific gravity
103.74	39.17	2.648

Table V: Test for Specific Gravity of A356.0 after degassing

Wt in Air (grms)	Wt in Water (grms)	Specific gravity
106.64	39.17	2.654

Beaker with water and weighing machine is used for weighing the weights of specimens as shown in figure below

Formula: $\rho = (W_A \rho_L - W_L \rho_A)/ (W_A - W_L)$

Where,

ρ=Density

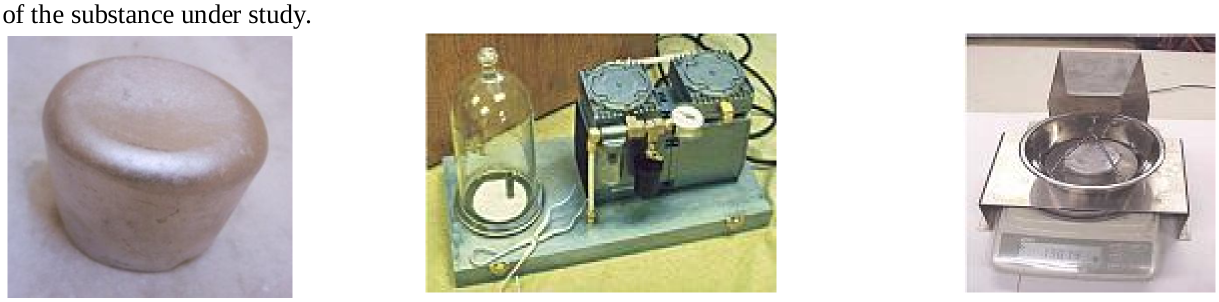
W_A =Weight in Air

ρ_L= Density of Liquid

W_L=Weight in Liquid

ρ_A = Density of Air

Being a ratio of densities, specific gravity is a dimensionless quantity. Specific gravity varies with temperature and pressure; reference and sample must be compared at the same temperature and pressure or be corrected to a standard reference temperature and pressure. Substances with a specific gravity of 1 are neutrally buoyant in water. Those with SG greater than 1 are denser than water and will, disregarding surface tension effects, sink in it. Those with an SG less than 1 are less dense than water and will float on it. In scientific work, the relationship of mass to volume is usually expressed directly in terms of the density (mass per unit volume) of the substance under study.



(a) (b) (c)

Fig.4 (a) Specimen of A356.0 for Specific Gravity test (b) RPT (Reduced Pressure Test) equipment and (c) Balance

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Table VI: Test of K-Mold of A356.0 before degassing

Holes	Inclusions
3/8	2/8

Table VII: Test of K-Mold of A356.0 after degassing

Holes	Inclusions
0/8	0/8

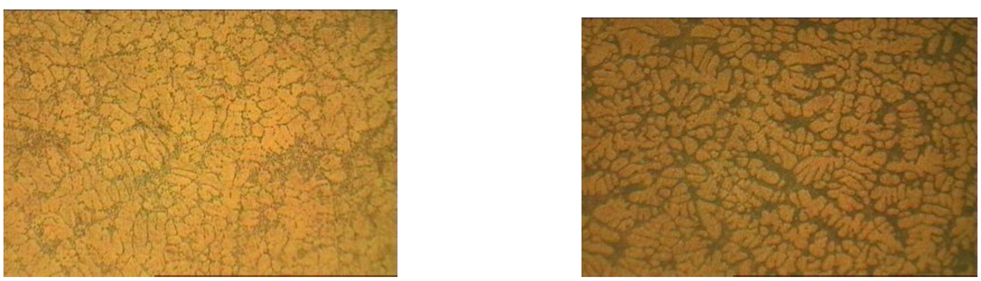
K-Mold is a fracture test method. Liquid metal is cast into a mold containing notches. An inclusion is a solid particle in liquid aluminium alloy. It is usually non-metallic and can be of different nature depending on its source. In order to get a good quality product, removing the inclusions become necessary by degassing process. The impurities like holes and inclusions are removed after degassing process as shown in Table VII.

Fig.5 Specimen of A356.0 for Test of K-Mold

III. HEAT TREATMENT

Heat treating is a group of Industrial and Metalworking processes used to alter the physical and sometimes chemical properties of a material. Heat treatment techniques include Annealing, Case hardening, precipitation strengthening, tempering, normalizing and quenching. Metallic materials consist of a Microstructure of small crystals called "grains" or Crystallites. The nature of the grains (i.e. grain size and composition) is one of the most effective factors that can determine the overall mechanical behaviour of the metal. Heat treating is often used to alter the mechanical properties of a metallic alloy, manipulating properties such as the hardness, strength, toughness, ductility and elasticity.

A. Results and Discussions of Heat Treatment



(a) (b)

Microstructure of A356.0

Fig.6 (a) Microstructure before Heat Treatment and (b) Microstructure after Heat Treatment

The microstructures of A356.0 and the T6 heat-treated specimens are shown in *Fig. 6 (a) and (b).*According to literature, the original A356.0 has dendrite microstructure with very fine and rod-like eutectic phase which is rich in Mg and Fe. Fe is combining with other elements to form irregular particles of AlFeSi or lamellar particles of $Fe_2si_2al_9$ or $FeAl_3$.Magnesium is instead present in particles of Mg_2Si or with aluminium in the form of Mg_2Al_3.

The morphology of the microstructure changes obviously after T6 heat treatment. The irregular eutectic phase was converted into fine spheroidzed Si particles uniformly distributed in the Al matrix. When the A356.0 is solution treated at 540^0C for 6 hours, all of the precipitates will dissolve into a single phase. The subsequent quenching will form a supersaturated solid solution and trap excess vacancies and dislocation loops which can later act as nucleation sites for precipitation. The precipitates can form slowly at room temperature (natural aging). However, the precipitates will form more quickly at elevated temperatures, typically 100^o *C*-200^o*C* (artificial aging).

As it can be seen from *Fig 6 b*, the morphology of A356.0 was completely changed into precipitated spheroidzed Si particles embedded in an Al phase due to solid state diffusion phenomenon.T6 heat treatment which induce precipitation of soluble alloying elements from the solid solutions significantly improving the mechanical properties. When the A356.0 is solution treated at 540°*C* for 6 hours, all of the precipitates will dissolve into a single structure have completely disappeared.

IV. MECHANICAL PROPERTIES

A. Hardness Test

Hardness of the A356.0 was measured using a Standard Brinell hardness tester as per ASTM E10 -14 and ISO 6506 – 1:2005 standards. The Brinell hardness test is an indentation hardness test that can provide useful information about metallic materials. A load (P) of 500*kg* is applied on the specimens for 30sec. The diameter of the Aluminum ball indenter (D) is 10*mm* and d=2.88*mm*. The Brinell hardness number (BHN) is calculated for the A356.0 using formula given below. An average of five readings was taken of each sample for hardness test.

Fig.7 Hardness Test Specimens

$$\mathrm{BHN} = \frac{2P}{\pi D(D-\sqrt{D}\times D-d\times d)}$$

1) Result of Hardness Test: = 75 HB (Hardness Brinell)

B. Tensile Test

Standard test bars shown in fig were machined following ASTM B557-94 standard, with length of 155-160*mm*. diameters at two ends and centre portion are 18*mm* and 12.8*mm* respectively. Experiments were done using a Zwick- 1475 materials testing machine. Specimen was held at two ends by automatic hydraulic clamps, and the conditions were inputs from a computer. Cross-held speed was 1*mm/min* and the gage length was set to 50.8 *mm*. The elongation measurement is used to calculate the engineering strain (ε), using the following equation:

$$\varepsilon = \frac{\Delta L}{Lo} = \frac{L-Lo}{Lo}$$

Where ΔL is the change in gauge length, L_0 is the initial gauge length, and L is the final length. The force measurement is used to calculate the engineering stress, σ, using the following equation:

$$\sigma = \frac{F}{A}$$

Where, *F* is the tensile force and A is the nominal cross-section of the specimen. The machine does these calculations as the force increases, so that the data points can be graphed into a stress-strain curve.

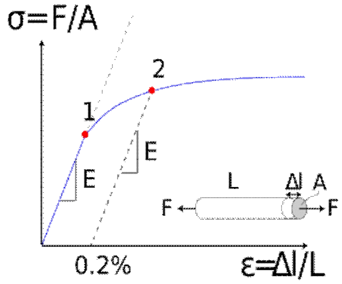


Fig.8 Stress Strain Curve

Fig.9 Tension Test Specimen

Stress–strain curve showing typical yield behaviour for aluminium alloys. Stress (σ) is shown as a function of strain (ε).
Elastic (proportionality) limits
Offset yield strength (0.2% proof strength)

1) *Results of Tensile Test:* The tensile properties of A356.0 under different states are given in Table 8. The yield strength of Al alloy A356.0 was only 128 *MPa*, which is a little lower than that of conventional alloys, but the tensile strength 254 *MPa* was close to that of conventional one. It was noted that the elongation of Al alloy A356.0 was 13.3%, which is about 2~3 times of the conventional alloys. After applying the T6 treatment, solid solution treatment at 540 °C for 12 hours and aging treatment at 155 °C for 12 hours, the elongation of A356.0 was reduced to 11.5%, however, the yield and tensile strength were dramatically increased to 276 *MPa* and 341 *MPa*, respectively. That is, there is an improvement about 115% and 34% on yield and tensile strength, respectively, although having a 14% reduction on elongation. It also indicated that the changes in mechanical properties were limited as the aging duration was changed from 12 hours to 19 hours.

Table VIII: Tensile Properties under Different States

State of specimen	Yield strength (*mpa*)	Ultimate strength (*mpa*)	Elongation (*%*)
ASTM spec value	165-185	228-262	3.5-5.0
Al alloy	128	254	13..3
T6 treatment (aging 12 hr)	176	641	11.5
T6 treatment	280	343	10.8

Reduction of macro-defects: The hydrogen dissolution into aluminum alloys is increased significantly in a liquid state, and leads to a large amount of gas porosity during solidification stage. However, A356.0 is formed and solidified in a semi-solid state. The hydrogen dissolution is relatively decreased, leading to less gas porosity. Moreover, the shrinkage porosity is also reduced due to lower forming temperatures.
Refinement of microstructure: The microstructure of A356.0 was refined via a specific process, either mechanical stirring or MHD (Magneto Hydro Dynamics). The lattice space was about 10 μm. In addition, the distribution of eutectic silicon was uniform with a particle size around 3~5 μm. Material with particle dispersion strengthening effect would be improved on strength significantly.

C. Toughness test

The Charpy impact test, also known as the Chirpy V-notch test, is standardized high strain-rate test which determines the amount of energy absorbed by a material during fracture Specimen dimensions were 10×10×55 *mm* with a V-shape notch as shown in *fig. 10*, based upon ASTM E8-96 standard. Tests were performed using a CHARPY-TINIUS OLSEN 64 Impact Testing machine with impact energy of swinging Pendulum 358 *Joules*, impact speed 5.12 *m/s* and testing temperature 20 °*C.*

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Table IX: Comparison of impact value under different states for A356.0 (T6 treatment: solution treatment 540ºC /12 hr & Aging temperature 155ºC)

State of specimen	Impact value
ASTM spec value	3.8
Al alloy	11.5
T6 treatment (aging 19 hr)	4.0

Fig.10 Toughness Test Specimen

1) *Results of Toughness Test:* The toughness of A356.0 is listed in Table X. The impact was 11.5 Joule, which is much value of Al-alloy A356.0 higher than that of conventional A356.0 with T6 treatment, having 3.8 Joule only. After applying T6 treatment to Al-alloy A356.0 the impact value was dropped to 4 Joule, which is close to that of conventional alloys as compared to the elongation with a slight reduction before and after T6 treatment.

Table X: Comparison of Crack Propagation under different States for A356.0 (Radius: 0.1R, Frequency: 3Hz)

State of specimen	State of specimen	Maximum load (*KN*)	Load cycle	Crack length
1	Al-Alloy	2.5	7,000	2.0
		2.5	3000	-
2	Al-Alloy	1.5	7,000	1.5
		1.5	1,300	2.0
		1.2	5,300	2.5
3	T6 Treatment	2.5	22,500	1.0
		2.0	3,000	2.5

Note: Solution condition: 540ºC /12 hr and aging condition: 155ºC /19 hr.

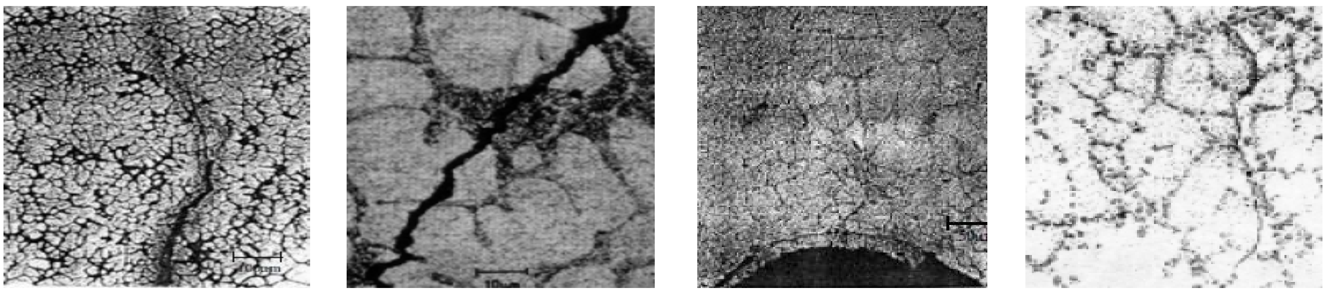
This obvious drop on toughness of A356.0 after T6 treatment might be related to strain rate under the test and fracture mechanism of almost completely spheroidzed eutectic silicon Further study on improvement of toughness is required to be conducted for reaching an optimum treatment conditions upon material strength and toughness

D. Fatigue Test

Dimensions of specimens prepared according to ASTM E812-91 standard were the same as in the impact tests. An MTS-810.15 fatigue testing machine was to perform the 3-points bending tests with a 40*mm* span at the bottom. The maximum loading F_{max} was 1.2~2.5 *KN*, radius 0.1*R*, frequency 3*Hz*, and loading frequency 7000~25000 *cycles.*

A series of fatigue tests, using impact test specimens, was conducted to investigate the fracture mechanism of A356.0 under different loads. In the test a natural crack was initialized on the specimens, then following a fatigue test. If the specimen was not broken off, an Optical Electron Microscope (OEM) was utilized to observe and measure the crack propagation with different multiplication factors.

1) *Results of Toughness Test:* The observed results are showed in Table 10.It indicates that Specimen 1 was as-cast A356.0 under a fatigue load of 2.5 *KN*. A natural crack was appeared with 2.0*mm* in length as the fatigue frequency at 7,000 *cycles*. If the test was continued under the same load, the test specimen was broken off at 300 *cycles* more. Crack propagation could not be observed from this test Specimen 2 in Table 3 was also as-cast A356.0 under an initial fatigue load 1.5 *KN*. A natural crack appeared with 1.5*mm* in length as the fatigue frequency at 7,000 *cycles*. The crack length propagated to 2.0*mm* as the test was continued 1,300 *cycles* more under the same load. Then, the test was continued 5,300 *cycles* added under a new load 1.2 *KN*, leading the crack with 2.5*mm* in length. *Fig. 2* showed the crack propagation of Specimen 2 under the combination load. It was evident that there were two segments with different width in the crack shown in *Fig. 2(a)*. The wide one was formed via the load 1.5 *KN* and the narrow one via 1.2 *KN*. *Fig. 2(b)* showed that the crack propagation was in the way of trans-granular, rather than along the grain boundary.



(a) (b) (c) (d)

Fig.11 Crack Propagation of A356.0 under Initial Load 1.5*KN* and 1.2 *KN* followed (a) ×100, (b) ×1000, Crack Propagation of A356.0 with Heat Treatment (c) Fatigue Loads 2.5*KN* (×500) and (d) Fatigue Loads 2.5*KN* and then 2.0*KN*(×200)

This type of fracture mode led A356.0 with superior elongation and strength Fig.11 and in Table 3 was T6 treated A356.0, solid solution treatment at 540 ºC for 12 hours and aging treatment at 155ºC for 12 hours, which showed a significant raise on the fatigue property. A natural crack with 1.0*mm* in length only appeared as the fatigue frequency at 22,500 cycles under a fatigue load 2.5 *KN*. The crack propagation also revealed the typical type of trans-granular fracture, shown in Fig.11(c). Following the test with a fatigue load 2.0 *KN*, Fig.11 (d) showed that the crack propagation in accordance with the trans-granular fracture mode was more evident as 30,000 cycles more applied.

V. CONCLUSIONS

A number of key conclusions were derived from this study and are listed below. These conclusions have both fundamental and practical implications for the metal casting industry:

After Degassing process the amount of hydrogen content is removed in the form of dross.

The microstructure's before and after degassing process reveals that there is elimination in impurities like porosity, holes, inclusions etc.

Through heat treatment process stresses are relieved and deformation of metal is minimized, Annealing process has produced a refined microstructure. Quenching was done to produce martensite transformation; this will often produce a harder metal and aging process designed to increase the strength of the metal. The microstructures before and after heat treatment are shown.

Raw materials used in this study were A356.0, which were categorized into two sets of ASTM specimens. One set underwent a T6 treatment, solid solution treatment at 540ºC for 12 hours and aging treatment at 155º C for 12 hours, and an-other set was as-cast without any treatment. Two sets of specimens were investigated under the same conditions for tensile, impact and fatigue testing. The significant results were outlined as follows

It explored that both yield strength and ultimate tensile strength were substantially increased for T6 treated A356.0. The measured yield strength and ultimate tensile strength were respectively about 115% and 34% greater than those of conventional alloys. It was also observed that the elongation was 2~3 times larger than the ASTM specified data, also leading to improvements on the relative fatigue properties.

It showed that the improvement on the mechanical proper-ties of A356.0 was correlated to the reduction of gas and shrinkage

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porosity, refinement of microstructure, and spheroidization of eutectic silicon. That is, the mechanical properties were affected by the shape and distribution of silicon inside the aluminum matrix. In general, a uniform distribution of silicon with refinement and spheroidization would go towards to improvement on elongation, impact and fatigue due to lower interface energy. The improvement on the impact and fatigue properties as compared to conventional A356.0 would be expected

According to the analysis of fracture mode via fatigue test, it can be concluded that the crack propagation was in the way of trans-granular, which is a typical type of ductile fracture, rather than along the boundary between eutectic silicon and matrix. This phenomenon was observed for A356.0 with either T6 treatment or not.

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