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Effect of T6 Heat Treatment on the Mechanical Properties of Gravity Die Cast A356 Aluminium Alloy

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Abstract: The purpose of this investigation was to evaluate the effect of T6 heat treatment on the mechanical properties of as-cast A356 gravity die casting. The geometry of the casting is designed to be cylindrical shape according to JIS H5202. The results show that T6 heat treatment can significantly improve the mechanical properties of A356 alloy. The hardness, tensile strength and ductility of A356 were improved by 106%, 106% and 214% respectively. The fatigue test shows that the T6 heat treated A356 casting can sustain 5kg-50Hz cyclic load up to 28020 cycles before fracture, achieving an improvement of fatigue strength of 23%. The morphology of T6 heat-treated A356 was changed in which the irregular eutectic phase was converted into spheroidized Si particles as a result of precipitation of silicon particles caused by solution treatment and artificial aging. The microstructural changes result in significant improvement in A356 mechanical properties.

Key words: Heat treatment, mechanical properties, gravity diecasting, grain refinement, microstructure

INTRODUCTION

A356 belongs to a group of hypoeutectic Al-Si alloys that has a wide field of applications in the automotive and avionics industries. A356 is one of the most common aluminium alloys used to obtain near net shape products because of its advantages of high fluidity and good castability owing to the high volume of Al-Si eutectic. Castings made of A356 exhibit many benefits such as wear and corrosion resistance, hot tearing resistance, good weldability and high strength to weight ratio (Zhang *et al*., 2008). The reliability and functionability of casting products are very much depending on the mechanical properties of the Al-Si alloys in as-cast condition. The mechanical properties are dependent on the microstructures of the casting. The commonly practiced methods in foundry to enhance the mechanical properties of Al-Si castings are grain refinement and modification. Grain refinement is done by adding Ti-B or Ti-C based grain refiners into the melt to refine the grain size of the casting into fine-equiaxed structure, whereas modification is to inoculate the melt with modifier containing strontium to change the silicon morphology from acicular flake to fibrous, resulting in improved ductility and toughness (Kori *et al*., 2000).

Another method of improving the mechanical properties of Al-Si castings is by conducting T6 heat treatment. The precipitation hardening through heat treatment will precipitate the alloying elements in the form of fine coherent particles of Mg_2Si and Al_2Cu inside the grains during the aging stage to harden the alloy (Zhao *et al*., 2009). The long duration solution heat treatment is able to alter the morphology of the Si phase into spheroidal shape and hence change the properties of the aluminium alloy. In this study, the casting process adapted is gravity die casting. The gravity die casting process is still one of the preferred processing routes, primarily because of its low cost. The major problem of the solidification process in gravity die casting is the achievement of a homogeneous sound microstructure without internal porosity defects that are normally caused by oxide films, gases and shrinkage during solidification (Chen and Im, 1990). The investigation aims to study the effect of T6 heat treatment on gravity die-cast A356 mechanical properties.

MATERIALS AND METHODS

In this study, the commercial A356 aluminium alloy was used as the base metal in all castings. The liquids and the solidus temperatures of the alloy were found to be 615°C and 538.5°C respectively according to the manufacturer's data. The manufacturer's data of the compositions of the A356 alloy is given in Table 1.

The gravity die casting mold used is designed according to JIS H5202 standard which contains two cavities of cylindrical shape tensile test piece of gage length 50 mm and diameter 14 mm.

The surface of the mold was coated with a layer of mold release agent in order to facilitate casting knock-out after pouring and solidification. The A356 aluminium alloy

Table 1: Composition of A356

Elements	wt. (%)
Si	7.22
Fe	0.15
Mn	0.01
B	-
C	-
Ti	0.13
Ni	0.016
Zn	0.04
Sr	0.01
Mg	0.45
Al	Bal

was put into a graphite crucible and melted in an induction furnace up to 720 ± 5°C. A K-type thermocouple was used to measure the melt temperature to ensure consistent superheat. The molten alloy was directly poured into the gravity die casting mold. The castings are purposely designed for ultimate tensile strength test. They were subjected to fettling and cleaning and subsequently machined to a diameter of 20 mm at the gripping ends.

The tensile test machine used is Instron 5582 with a maximum pulling force of 100 kN. The central part of the tensile specimen was cut to a thickness of 10 mm and subjected to fine 80 grit-size grinding on both sides to smoothen the coarse surfaces for hardness test. The hardness test was done on Indentec Universal Hardness Tester. The scale of all tests were set to be HRA 60 kg.

A sample of size 5mm x 5mm was cut from the transverse plane at the central part of each tensile specimen and mounted in resin to prepare for grinding, rough polishing and finally fine polishing to the fineness of 0.3 micron. The polishing agent was buehler alpha alumina particles of 0.3 micron. The samples were chemically treated with etchant consisting of 200 mL distilled water and 5 mL HF (Rostoker and Dvorak, 1977).

Microstructural studies were conducted by using an optical microscope with a maximum magnification power of 2000X.

Fatigue test was done by applying cyclic loading to the specimen to understand how it would perform under similar conditions in actual service condition. The load application can either be a repeated application of a fixed load or simulation of in-service loads. The load application may be repeated millions of times and up to several hundred times per second. The dimensions of test specimens are 4 mm in diameter at the center with gage length 20 mm, it was obtained by machining from the tensile test sample. The test condition is 5 kg load and 50 Hz frequency.

To obtain the T6 heat treatment condition, the as cast sample of A356 without grain refinement were solution treated in Carbolite oven at 540°C for 6 h and then water quenched before artificially aged at 160°C for 6 h (Metals Handbook, 1981). The heat treated samples were also subjected to similar tests described above.

RESULTS AND DISCUSSION

The main results obtained from this study are mechanical properties of ultimate tensile strength, hardness and elongation (strain at fracture), fatigue life and microstructural analysis.

Hardness: A total of six tests have been performed to evaluate the hardness of heat-treated and non heat-treated A356. The purpose of taking several tests is to get the average hardness value that can be more accurate to represent the hardness property of specimens. From the Fig. 1, the hardness value for the A356 aluminum alloy was 16.47 HRA and 33.93 HRA for the T6 heat-treated A356. It was noted that the hardness was increased 106% after applying solution heat treatment and artificial age hardening.

T6 heat treatment is able to provide hardening effect by precipitation of constituents from solid solution. Precipitation of constituents occurs during the artificial aging step. The sharp edge fiber eutectic Si has been transformed into spheroidized eutectic Si embedded among the homogeneous a-Al matrix. The precipitated constituents are believed to account for increase in hardness (Akhter *et al*., 2007).

Tensile strength: Two tensile test samples for each type of alloy were subjected to test and the averaged values are taken to plot the ultimate tensile strength chart as shown in Fig. 2. The non-heat-treated A356 achieves a tensile strength of 123.0 MPa and T6 heat-treatment improves it tremendously to 253.5 MPa, 106% improvement. Heat-treatment is found to be very effective to improve the tensile strength of A356 gravity die castings. The microstructure in Fig. 5 shows that after aging at 160°C/6 h the super saturated solid solution of aluminium matrix will develop a uniformly distributed spheroidized Si particles and gives rise to maximum tensile strength of the A356 casting (Tash *et al*., 2007).

The increase in tensile strength after heat treatment can be explained by dislocation theory. A precipitated particle acts as an obstruction to the motion of a dislocation. Such an obstruction provides resistance to the motion of dislocation and hence increases the tensile

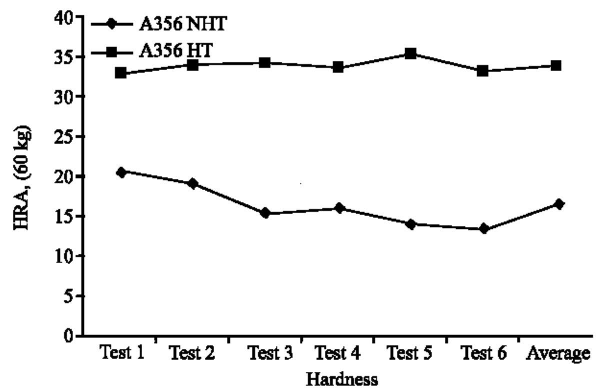

Fig. 1: Hardness of A356

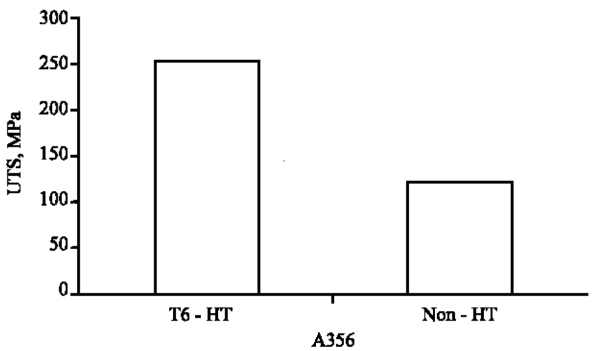

Fig. 2: Tensile strength of A356

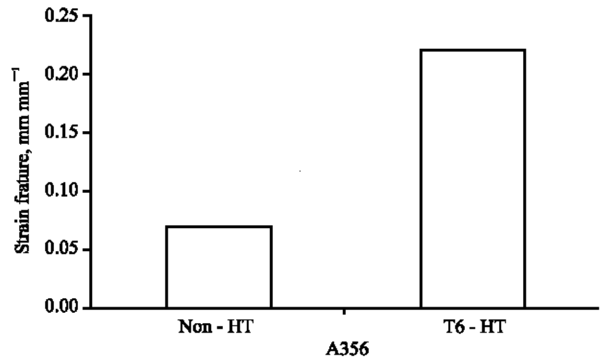

Fig. 3: Elongation of A356

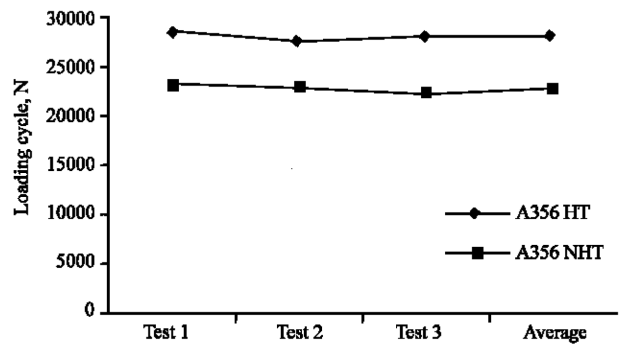

Fig. 4: Fatigue life of A356

strength. For a dislocation to move it must either cut through the precipitated particles or move between them. In both cases an increase in stress is required as compared to the matrix which does not contain precipitates (Hasegawa and Okazaki, 2001).

Elongation: Ductility of a metal can be measured by its elongation or strain at a specific point in the stress-strain curve. In this study, strain at fracture (mm mm^{-1}) is taken into consideration to analyze the effect of heat-treatment on the ductility of A356. From Fig. 3, the non-heat-treated A356 has a fracture strain of 0.07 while heat-treated A356 is able to achieve a much higher fracture strain of 0.22, an improvement of 214%.

Fatigue test: The fatigue test for the A356 aluminum alloy and A356 heat treatment aluminium alloy was carried out under 5 kg load and 50 Hz frequency. From the Fig. 4, the fatigue life for the non-heat-treated A356 aluminum alloy is 22747 cycles while for the heat-treated A356 aluminum alloy it is 28020 cycles, improved by 23%.

Fatigue failure of a material usually consists of crack initiation into a short crack, rapid short crack growth and coalescence into a long crack, and finally long crack propagation until fracture. All these complex multi-stage processes occur simultaneously, and interact with each other along the entire fatigue process.

According to fracture mechanics, the presence of casting defects will result in stress concentration in the surrounding matrix and eutectic silicon particles, and it consequently leads to earlier local yielding much before the applied stress reaches the yield stress of the alloy, especially on the edge of sharp notches of the shrink pores (Taylor *et al*., 2005).

As the crack initiation mainly accounts for most of the fatigue life when there are not many interior defects, it is necessary to find the crack initiation sites and to understand the mechanism involved. Because of the presence of lots of large pores, fatigue cracks primarily initiate at large pores which located near the specimen surface. These fatigue cracks quickly propagate, combine with adjacent large pores, and form large and round patterns.

A crack tends to initiate at a large pore, and propagates along eutectic Si particles. The acicular eutectic Si particles which are brittle and fragile serve as a bridge for fatigue crack propagation. Thus, the fatigue crack initiates at large pores adjacent to the specimen surface, and then continues propagating along eutectic Si particles and hence the fatigue strength is considerably lowered.

The influence of heat treatment on fatigue life results from not only matrix strength (yield strength) but also the resultant eutectic structure. In the long (1000 h) solution treated microstructure, no large Fe particles can be seen after dissolution and the silicon particles become coarse due to spheroidization. T6 solution treatment (6 h) produces an optimum combination of small Fe-rich and spherodized silicon particles in the a-Al matrix. This explains why T6 heat-treated A356 possesses higher fatigue life than non-heat-treated A356 (Estey *et al*., 2004).

Microstructural analysis: The microstructures of the A356 and the T6 heat-treated specimens are shown in Fig. 5 a and b. According to literatures, the original A356 gravity die casting has dendritic microstructure with very fine and rod-like eutectic phase which is rich in Mg and Fe. Fe is combined 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 the particles of Mg_2Si or with aluminium in the form of Mg_2Al_3

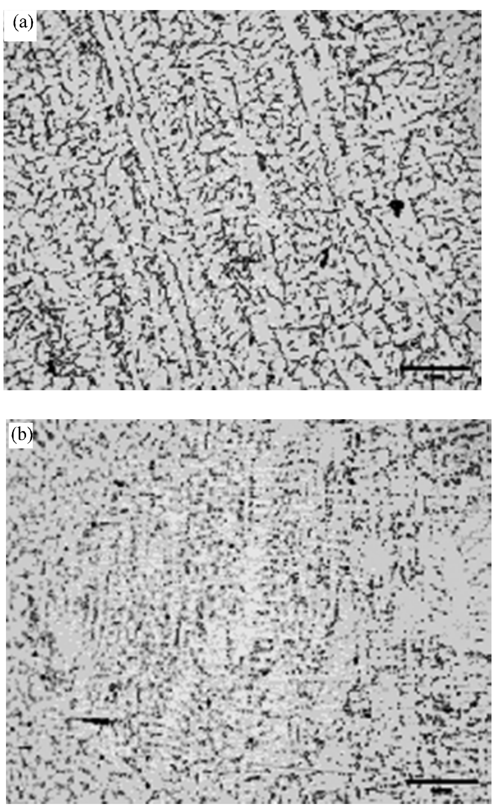

Fig. 5: Microstructures of test specimens. (a) Non heat-treated A356 and (b) T6 heat-treated A356

(Mandal *et al*., 2008). The morphology of the microstructure changed obviously after T6 heat treatment. The irregular eutectic phase was converted into fine spheroidized Si particles uniformly distributed in the Al matrix. Similar result was reported in literature of semi solid casting of A356 (Akhter *et al*., 2007). T6 heat treatment which induces precipitation of soluble alloying elements from the solid solutions significantly improves the mechanical properties. When the A356 is solution treated at 540°C for 6 h, 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°C to 200°C (artificial aging).

As it can be seen from Fig. 5 b, the morphology of A356 was completely changed into precipitated spheroidized Si particles embedded in a-Al phase due to solid state diffusion phenomena. The eutectic phase and dendritic 2008). The morphology of the microstructure changed obviously after T6 heat treatment. The irregular eutectic phase was converted into fine spheroidized Si particles uniformly distributed in the Al matrix. Similar result was reported in literature of semi solid casting of A356 (Akhter *et al*., 2007). T6 heat treatment which induces precipitation of soluble alloying elements from the solid solutions significantly improves the mechanical properties. When the A356 is solution treated at 540°C for 6 h, all of the precipitates will dissolve into a single structure have completely disappeared.

CONCLUSIONS

The effect of T6 heat treatment on the mechanical properties of A356 gravity die castings has been studied. Based on the mechanical testing and metallographic examination conducted for the specimens of the current study, the following conclusion can be drawn:

T6 heat-treatment show evidence that precipitation by artificial aged hardening is able to improve the mechanical properties of gravity die-cast A356. The hardness, tensile strength and elongation are improved to the greatest extent of 106 and 214%, respectively. The morphology of T6 heat-treated A356 microstructure has been modified by precipitation of its alloying elements and caused the originally rod-like Si eutectic to be converted into fine spherodized Si eutectic phase uniformly distributed in the aluminium matrix. This morphological transformation brings about significant improvement in the mechanical properties of gravity die cast A356.

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REFERENCES

Akhter, R., L. Ivanchev and H.P. Burger, 2007. Effect of pre/post T6 heat treatment on the mechanical properties of laser welded SSM cast A356 aluminium alloy. Mater. Sci. Eng., 447: 192-196.

Chen, Y.H. and Y.T. Im, 1990. Analysis of solidification in sand and permanent mold castings and shrinkage prediction. Int. J. Machine Tools Manufacture, 30: 175-189.

Estey, C.M., S.L. Cockcroft, D.M. Maijer and C. Hermesmann, 2004. Constitutive behaviour of A356 during the quenching operation. Mater. Sci. Eng., 383: 245-251.

Hasegawa, T. and K. Okazaki, 2001. Uniform tensile elongation obtained from experiment and its estimation using dislocation dynamics parameters. Mater. Sci. Eng., 297: 266-271.

Kori, S.A., B.S. Murty and M. Chakraborty, 2000. Development of an efficient grain refiner for Al-7Si alloy. Mater. Sci. Eng., 280: 58-61.

Mandal, A., M. Chakraborty and B.S. Murty, 2008. Ageing behaviour of A356 alloy reinforced with in situ formed TiB2 particles. Mater. Sci. Eng., 489: 220-226.

Metals Handbook, 1981. Heat Treating. 9th Edn., Vol. 4, American Society for Metals, Metals Park, OH.

Rostoker, W. and J.R. Dvorak, 1977. Interpretation of Metallographic Structures. Academic Press, London, Oxford, Boston, New York.

Tash, M., F.H. Samuel, F. Mucciardi and H.W. Doty, 2007. Effect of metallurgical parameters on the hardness and microstructural characterization of as-cast and heat-treated 356 and 319 aluminum alloys. Mater. Sci. Eng., 443: 185-201.

Taylor, D., P. Cornetti and N. Pugno, 2005. The fracture mechanics of finite crack extension. Eng. Fracture Mechanics, 72: 1021-1038.

Zhang, L.Y., Y.H. Jiang, Z. Ma, S.F. Shan, Y.Z. Jia, C.Z. Fan and W.K. Wang, 2008. Effect of cooling rate on solidified microstructure and mechanical properties of aluminium-A356 alloy. J. Mater. Process. Technol., 207: 107-111.

Zhao, H., H. Bai, J. Wang and S. Guan, 2009. Preparation of Al–Ti–C–Sr master alloys and their refining efficiency on A356 alloy. Mater. Characterization, 60: 377-383.