Grain refinement and heat treatment of gravity die cast A356

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Abstract

The purpose of this investigation is to evaluate the effects of grain refiner TiCal315 (3%Ti, 0.15%C) and Al-5Ti-1B on the metallurgical properties of as-cast A356 gravity die castings as well as the improvement brought about by T6 heat treatment. The TiCal315 and Al-5Ti-1B grain refiners were added separately into the A356 melt in different weight percentages of 0.25, 0.5, 0.75 and 1.0 to produce the gravity die casting samples. The geometry of the casting is designed to be cylindrical shape according to JIS H5202. The results show that TiCal315 is relatively more effective than Al-5Ti-1B to improve the tensile strength, hardness and elongation of A356 alloy by 10~20%. T6 heat treatment is confirmed to have more significantly improved the mechanical properties of A356 alloy compared to grain refinement. An Olympus imaging software was used to measure the average grain size of α-Al phase and the results do not show significant difference between TiCal315 and Al-5Ti-1B to grain-refine the A356 dendritic structures. The morphology of T6 heat treated A356 was changed where the irregular eutectic was converted into spherodized Si particles due to the solution treatment. This results in significant improvement in mechanical properties.

Keywords: Heat treatment, Mechanical properties, Gravity die casting, Grain refinement, Microstructure

1. Introduction

Al-Si alloys are very important in metal casting industry due to their superior characteristics of high fluidity, low shrinkage, high corrosion resistance, good weldability, easiness in brazing and low coefficient of thermal expansion [1]. A356 is an Al-7Si alloy with 7 wt% of silicon contained in its chemical composition. It is widely employed in numerous automotive and aircraft industries for weight sensitive applications because of its low density and excellent castability [2]. Under normal casting conditions, the solidification of hypoeutectic Al-Si alloys will produce coarse columnar or twinned columnar grains (TCGs) of α-Al phase in large fraction. The properties of the casting to a larger extent will be adversely affected by the coarse columnar or twinned columnar grains and result in reduced fabricability, poor yield strength and tensile elongation to fracture [3]. The inherent defects of coarse grains in Al-Si alloys castings can be solved by grain refinement method. Grain refinement will lead to the suppression of TCG and formation of fine equiaxed α-Al grains resulting in high yield strength, high toughness, good surface finish, better machinability and various other desirable properties in the castings [4].

The Al-Ti-B master alloys containing soluble TiAl3 and insoluble TiB2 particles have been widely used in aluminium foundries with different ratios of Ti:B to grain refine aluminium castings produced by various casting processes such as sand casting, high pressure die casting and gravity die casting. The dissolved TiAl3 particles are reported to increase the amount of titanium in the melt and serve to restrict the growth of α-Al grains after their nucleation [5]. The TiB2 particles present in the master alloy remain stable and undissolved in the melt and serve as active nucleants to promote heterogeneous nucleation of α-Al grains [6]. However, certain problems are encountered with Al-
Ti-B alloys such as agglomeration of the borides, blockage of filters, defects during subsequent forming operations and poisoning by certain elements like Zr, V and Cr. This problem leads to the development of alternative grain refiner of Al-Ti-C alloys. TiC particles in this new class of grain refiners are smaller than the TiB₂ particles and are less prone to agglomeration [7]. The Al-Ti-C grain refiners contain soluble TiAl₃ and insoluble TiC particles that are not affected by poisoning effect of Zr, V and Cr.

Another method of improving the mechanical properties of Al-Si castings is by T6 heat treatment. The precipitation hardening through heat treatment will precipitate the alloying elements in the form of fine coherent particles of Mg₂Si and Al₂Cu inside the grains during the aging stage to harden the alloy [8]. The long term solution heat treatment is believed to alter the morphology of the Si phase into spheroidal shape. An interview with the local caster in Malaysia has found that it is not known what is the relatively most effective and economic way to improve the mechanical properties of Al-Si castings through grain refinement or heat treatment. The optimal utilization of Ti-B and TiC grain refiners has not been determined. The present study will investigate the separate effects of Ti-B/Ti-C grain refinement and T6 heat treatment on the mechanical properties of A356 gravity die castings.

2. Experimental Procedures

In this study, the commercial A356 aluminium alloy was used as the base metal in all castings. The liquidus and the solidus temperatures of the alloy were found to be 615°C and 538.5°C respectively according to manufacturer’s data. The grain refiners used are TiCal315 supplied by AMG Advanced Metallurgical Group and Al5Ti1B master alloy supplied by KBM AFFILIPS. The manufacturer’s data of the compositions of the A356 alloy, TiCal315 and Al5Ti1B master alloy are given in Table 1.

<table>
<thead>
<tr>
<th>Elements, wt%</th>
<th>Si</th>
<th>Fe</th>
<th>Mn</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>A356</td>
<td>7.22</td>
<td>0.15</td>
<td>0.01</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Al5Ti1B</td>
<td>0.1</td>
<td>0.16</td>
<td>-</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>TiCal315</td>
<td>0.05</td>
<td>0.16</td>
<td>0.01</td>
<td>0.0005</td>
<td>0.15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ti</th>
<th>Ni</th>
<th>Zn</th>
<th>Sr</th>
<th>Mg</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.13</td>
<td>0.016</td>
<td>0.04</td>
<td>0.01</td>
<td>0.45</td>
<td>Bal.</td>
</tr>
<tr>
<td>5.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.45</td>
<td>Bal.</td>
</tr>
<tr>
<td>3.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Bal.</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

The gravity die casting mould 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 14mm. The internal configuration of the mould and its preparation for pouring are shown in Figure 1.

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Fig. 1. (a) Internal configuration; (b) Mold preparation before pouring

The surface of the mould was coated with a layer of mould release agent in order to facilitate casting knock-out after pouring and solidification. The A356 aluminium alloy 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. After complete melting, 0.25, 0.5, 0.75 and 1.0 wt% of TiCal315 and Al5Ti1B were added separately to the melt in each experiment. The holding time for the grain refiner in the melt was 10 minutes and stirred with a steel rod to ensure complete mixing and dispersion in the melt. The molten alloy was then directly poured into the gravity die casting mould.

The castings are purposely designed for ultimate tensile strength test. They were subjected to fettling and cleaning and subsequently machined to a diameter of 20mm at the gripping ends. The as-cast samples and machined samples are shown in Figure 2. The tensile test machine used is INSTRON 5582 with a maximum pulling force of 100kN. 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 kgf.

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Fig. 2. (a) As-cast A356 gravity die casting. (b) Castings after fettling and machining

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 beuhler alpha alumina particles of 0.3 micron. The samples were chemically treated with etchant consisting of 200 ml distilled water and 5 ml HF [9]. Microstructural studies were conducted by using an optical microscope with a maximum magnification power of 2000X.

To obtain the T6 heat treatment condition, the as cast sample of A356 without grain refinement were solution treated in a Carbolite oven at 540 °C for 6 hours and then water quenched before artificially aged at 160 °C for 6 hours [10]. The heat treated samples were also subjected to similar tests described above.

3. Results and discussions

The main results obtained from this study are mechanical properties of ultimate tensile strength, hardness and elongation (strain at fracture). The effects of grain refinement and T6 heat treatment on morphology is derived from the microstructural examination of cast samples. The original A356 data is used as benchmark to determine the performance of TiCal315 and Al5Ti1B grain refinement and T6 heat treatment in A356 gravity dies casting.

3.1. Hardness

For each grain refined casting, ten hardness readings were measured and the averaged values are plotted in Figure 3.

![Fig. 3. Hardness](image)

The unrefined non-heat-treated and T6 heat-treated A356 castings have the average hardness values of 16.47 and 33.93 respectively. For both grain refiners, the hardness increases steadily from around 16.8 to about 19.3 when the addition levels are increased from 0.25 to 1.0 wt%. It can be seen that 0.25 wt% of Al5Ti1B grain refiner will not improve the harness with any significant effect. The grain refining power of Tical315 is more potent than Al5Ti1B. The unrefined and non-heat-treated A356 has the lowest hardness of 16.47. T6 heat treatment enhances the hardness most significantly to 33.93, an improvement of 106%. It is learned that 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. It can be said that grain refinement has less efficiency than heat treatment to improve the hardness of A356 gravity die castings. However the decision to choose between them to improve hardness will depend on the hardness requirement of the casting for its final application and service conditions.

3.2. 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 Figure 4. Compared to the unrefined and non-heat-treated A356, grain refinement with TiCal315 and Al5Ti1B and T6 heat-treatment are all able to improve the tensile strength. TiCal315 is observed to be more effective than Al5Ti1B to enhance the tensile strength by 17% on average. Similar result was reported by Lina Yu et al [11]. The original unrefined and non-heat-treated A356 achieves a tensile strength of 123.0 MPa and T6 heat-treatment improves it tremendously to 253.5 MPa, achieving 106% improvement. The as cast A356 tensile strength is lower than 230 MPa as reported in literature probably is due to the melt used in this experiment is without degassing and the structure is weakened by porosity. However, heat-treatment is found to be more effective than grain refinement to improve the tensile strength of A356 gravity die castings in this condition of melt. The microstructure in Fig.6 (b) shows that after aging at 160°C/6 hr the super saturated solid solution of aluminium coherent particles segregated and gives rise to maximum tensile strength of the A356 casting.

![Fig. 4. Tensile strength](image)

3.3. Elongation

Ductility of a metal can be measured by its elongation or strain at specific point in the stress –strain curve. In this study, strain at fracture is taken into consideration to analyze the effect of TiCal315/Al5Ti1B grain refinement and heat-treatment on the ductility of A356. The original unrefined and non-heat-treated A356 has a tensile strain of 0.07. Initial stages of grain refinement up to 0.75 wt% addition level do not improve elongation significantly. Only at 1.0 wt% addition level do both grain refiners show significant strain improvement of 85~114%. Heat treatment is still the most effective way to improve ductility
property by 214% in terms of tensile strain. The strain behaviour is shown in Figure 5.

![Graph showing elongation vs. addition level](image)

**Fig. 5. Elongation**

### 3.4. Microstructural Analysis

The microstructures of the A356 and its TiCal315/Al5Ti1B-grain refined and T6 heat treated specimens are shown in Figure 6 (a)-(j). The original A356 gravity die casting has dendritic microstructure with very fine and rod-like eutectic phase. 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 α-Al matrix. Similar result was reported in literature of semi solid casting of A356 [12]. Comparing the grain-refined microstructures of TiCal315 and Al5Ti1B, generally they look similar to each other in many aspects. At low addition level of 0.25 wt%, the eutectic phase is observed to be of larger area occupying the interdendritic space. The α-Al phase is in dendritic form and also exists in separate globule shape surrounded by eutectic phase. When 1.0 wt% of Al5Ti1B is added, the dendrites in α-Al phase appears to be more coercive to each other and the eutectic phase is observed to be finer and occupies lesser area compared to lower level of addition. The 0.5 wt% TiCal315 grain-refined microstructure exhibits the finest dendritic structures among all addition levels. When 1.0 wt% of TiCal315 is added, the microstructure remains dendritic but the α-Al phase is more globular and the globules exist very close to each other with eutectic phase clamped in between them. Based on the mechanical properties measured, it can be deduced that when higher level of grain refiner is added, the morphology of the A356 microstructure will change into globular α-Al phase with finer eutectic phase, this leads to an improvement in hardness, tensile strength and elongation is achieved. 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 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°C to 200°C (artificial aging). As it can be seen from Fig.6 (b), the morphology of A356 was completely changed into precipitated Si particles embedded in α-Al phase. The eutectic phase and dendritic structure have completely disappeared. By using the Olympus Analysis Five Digital imaging solutions software, it is possible to measure the grain size of α-Al. The unit of measurement is μm². Table 2 shows the measurement results for all samples. Generally TiCal315 can grain refine the A356 gravity die castings to finer microstructure compared to Al5Ti1B. Both grain refiners achieve smallest average grain size at 0.5 wt% addition level. However, the smallest grain size does not necessarily correspond to the best mechanical properties measured in terms of hardness, tensile strength and elongation. At 0.5 wt% addition level, the grain size of the dendrites is smaller but the surface area of eutectic phase basically remains unchanged, which is obviously larger than that of 1.0 wt% addition level. The mechanical properties are significantly improved when both grain size and eutectic phase areal density are reduced at the same time.
Fig. 6 (a)-(i). Microstructures of test specimens.

Table 2. Grain size.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Average grain size, µm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al5Ti1B - 0.25 wt%</td>
<td>324</td>
</tr>
<tr>
<td>Al5Ti1B - 0.5 wt%</td>
<td>280</td>
</tr>
<tr>
<td>Al5Ti1B - 0.75 wt%</td>
<td>401</td>
</tr>
<tr>
<td>Al5Ti1B - 1.0 wt%</td>
<td>354</td>
</tr>
<tr>
<td>TiCal315 - 0.25 wt%</td>
<td>290</td>
</tr>
<tr>
<td>TiCal315 - 0.5 wt%</td>
<td>149</td>
</tr>
<tr>
<td>TiCal315 - 0.75 wt%</td>
<td>187</td>
</tr>
<tr>
<td>TiCal315 - 1.0 wt%</td>
<td>225</td>
</tr>
<tr>
<td>A356 NHT</td>
<td>780</td>
</tr>
<tr>
<td>A356 T6 HT</td>
<td>-</td>
</tr>
</tbody>
</table>
4. Conclusions

The effect of grain refiners Al5Ti1B and Ti6Al315 and 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, the following conclusions can be drawn:

1. Ti6Al315 is more effective than Al5Ti1B to improve hardness of A356 gravity die castings by an average of 20% for 0.25~1.0 wt% addition levels.

2. Grain refinement with 1.0 wt% addition level of Ti6Al315 and Al5Ti1B shows the greatest improvement in tensile strength by 71% and 56% respectively as compared to the original A356. Ti6Al315 is observed to be more potent than Al5Ti1B to improve the tensile strength of A356 at addition level >0.25 wt%.

3. Highest tensile strength is observed at 1.0 wt% addition level for both grain refiners whereby the microstructures show minimum areal density of eutectic phase and the most densely packed α-Al dendritic grains. A356 grain refined with Ti6Al315 shows better ductility than that grain refined with Al5Ti1B.

4. T6 heat-treatment shows evidence that precipitation by artificial aged hardening is able to improve the mechanical properties of A356 much more significantly than grain refinement method. The hardness, tensile strength and elongation are improved to the greatest extent of 106%, 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 spheroidized Si eutectic phase. This morphological transformation renders significant improvement in mechanical properties of gravity die cast A356.

References


