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JOINING VACUUM HIGH PRESSURE DIE CAST A356 UNDER T4 TREATMENT TO WROUGHT ALLOY 6061

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Abstract

Vacuum high pressure die cast A356 alloy with T4 solution treatment was fusion-joined with wrought alloy 6061 by the Gas Metal Arc Welding (GMAW) process. In the present work, the microstructures of Base metal (T4 A356 and 6061), Heat Affected Zone (HAZ) and Fusion Zone (filler metal ER4043) was analyzed by Scanning Electron Microscopy (SEM) and optical microscopy. The results of tensile testing indicate that the ultimate tensile strength (UTS), yield strength (YS) and elongation (Ef) of T4 A356 are relatively low, compared to both wrought alloy 6061 and the filler metal (ER 4043). The microstructure analysis shows that the reduction in the tensile properties of T4 A356 should be mainly attributed to the lack of strengthening intermetallic phases (Mg_2Si) and coarse grain structure, which resulted from T4 solution treatment.

Introduction

In the past two decades, aluminum (Al) alloys as a light weight material have been increasingly used in the automotive industry. The usage of Al in automobiles in North America has gone from 45kg (101 lbs) in the 1970s to 150 kg (326 lbs) in 2009, and will top 170 kg (376 lbs) per vehicle by 2020. Among the 150 kg aluminum usage in each vehicle, almost 35% of automotive Al components were manufactured by conventional high pressure die-casting (C-HPDC), which is one of the most cost-effective processes compared to other casting processes (permanent mould and sand casting)[1]. In resent years, joining of cast Al components with wrought and/or cast similar metals becomes an urgent task for the auto industry to reduce vehicle weight. But, it is well known that the mechanical properties of C-HPDC are strongly influenced by a variety of casting defects and artifacts, which reduce strengths and ductility. These include entrapped gas porosity, shrinkage porosity, oxides, dross inclusions, hot tearing and planar defects such as cold shuts and folded oxidized surfaces. The C-HPDC components are especially prone to high levels of porosity due to high velocity turbulence of molten metal entering the die and oxide inclusions resulting from melting and liquid metal transfer systems [2]. More importantly, the entrapped defects make cost-effective joining of C-HPDC Al components very challenging. Therefore, new HPDC processes, such as high vacuum (V-HPDC), have been emerged to produce high integrity structural automotive components with enhanced properties and significantly reduced number of defects[3, 4].

To develop light-weight complex and large-scale chassis and body structures for automobiles, joining of cast Al components with wrought and/or cast similar metals is often considered a good strategy for design engineers, which enables them to take advantages of different manufacturing processes such as casting, extrusion and forming. Up to now, most studies on joining cast Al alloys [5, 6] have been focused on friction stirring welding of the Al components made by relatively costly casting processes such as permanent mold, and squeeze casting, which contains low amount of porosity in materials. Relatively expensive friction stir welding has been attempted on joining C-HPDC Al alloy ADC 12 despite of its high cost. Meanwhile, fusion welding of C-HPDC Al alloys is difficult due to the formation of blowholes by entrapped gases and the presence of brittle intermetallics in the weld metal [7]. V-HPDC as an emerging technology minimizes the entrapment of porosity, which could improve mechanical properties and engineering performance of welded die cast aluminum alloys [8-10]. However, work on applying fusion welding processes to join vacuum high pressure die cast aluminum alloys is very limited.

In this work, vacuum high pressure die cast aluminum alloy A356 with a T4 treatment was joined to wrought alloy 6061 by using the Gas Metal Arc Welding (GMAW - MIG) welding method. The microstructure of the welded alloys was characterized by optical and electron scanning microscopies (SEM). The mechanical properties of the alloys were determined by tensile testing. The fracture behavior of the joined alloys was analyzed by fractography using the SEM. The mechanism responsible for the resulted tensile and fracture behaviors were discussed based on the optical and SEM microstructural characterization.

Experimental Procedure

Two types of aluminum alloys, casting alloy A356 and wrought alloy 6061 were employed in this study. The nominal chemical compositions of alloys A356 and 6061 are shown in Table 1. The A356 alloy was vacuum high pressure die cast in the shape of a plate with the dimensions of 300 mm long, 100 mm wide and 4 mm thick. The cast plates were also subjected to a solution treatment (4) at 470 °C for two hours to investigate the effect of solution treatment on mechanical properties of the vacuum die cast A356. To facilitate the welding of the cast plates and the selected wrought alloy, commercially-available 4-mm thick 6061 was sectioned into rectangular plates with the same dimensions as the cast ones as shown in Figure 1.

Table 1: Chemical composition of the investigated alloys (wt. %)

Alloy	Si	Mg	Mn	Cu	Zn
A356	6.5-7.5	0.2-0.4	0.1	0.2	0.1
6061	0.4-0.8	0.8-1.2	0.15	0.15-0.4	0.25

Gas Metal Arc Welding (GMAW)

A ®Lincoln electric power wave 300 welder with semi-automatic wire feeding system was employed for welding operation. The applied filler alloy, ER4303, of which chemical composition was given in Table 2, was selected due to its composition similarity to A356. The shielding gas of Argon was applied during welding with a gas flow rate of 25 L/min. The welding speed was set at 8.6 mm/s.

Table 2: Chemical composition of the filler alloy (wt. %)

Filler Alloy	Si	Mg	Mn	Cu	Zn
ER 4043	5.0	0.05	0.05	0.3	0.1

Tensile Testing

The welded plates were marked perpendicularly along the welding bead. The marked plates as shown in Figure 1, were sectioned to prepare specimens for testing and analyses. In addition, for the purpose of comparison, specimens prepared from the T4 treated cast A 356 and wrought 6061 plates were also tensile tested.

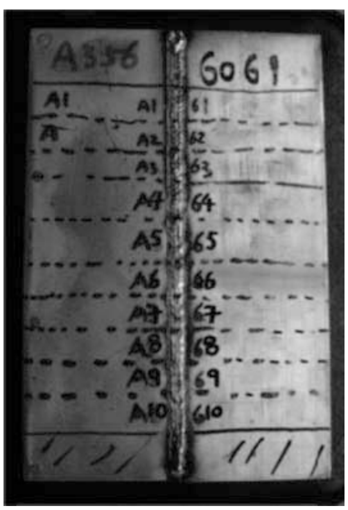


Figure 1: Photograph showing a welded plate with the vacuum high pressure die cast A356 and wrought alloy 6061.

According to the ASTM standard B557M, subsize tensile specimens were prepared. The specimens were tested at room temperature on an Instron 30KN Materials Test System equipped with a data acquisition system. The load cell and test speed were set up at 10KN and 2 mm/min. The output data, including the displacement measured by extensometer, and tensile load, were analyzed. The ultimate tensile strength (UTS), 2% offset yield strength (YS) and elongation (El%) were determined for all tested specimens based on the average of five tests.

Microstructure Analysis

Specimens for microstructural analyses were cut from the interior of the plates and prepared following the standard procedures. The specimens were grounded using 240, 320, 400 and 600 grit silicon carbide papers and polished using 0.5µm and 1µm Al2O3 suspension. After etching the sample with sodium hydroxide solution (5ml NaOH and 95ml ethanol), the detailed microstructure changes were examined by using optical microscopy and scanning electron microscopy (SEM), which is equipped with an energy dispersive x-ray (EDX) system for elemental analysis.

Results and Discussion

Tensile Properties

Figure 2 presents a typical engineering stress-strain curve (Y2) of welded T4 A356/6061. Tensile properties and fracture location of A356 alloy with T4 heat treatment and wrought alloy 6061 are summarized in Table 3. It can be seen that T4-A356 had the UTS, YS and elongation of 169.5 MPa, 106.2 MPa and 9.3%, respectively. They were lower than the welded 6061, of which the UTS, YS and elongation were 216.5 MPa, 117.1 MPa and 16.31% respectively. As such, the fracture of the joined T4-A356/6061 took place in T4-A356 due to its lower tensile properties than 6061 and the filler alloy (ER 4043).

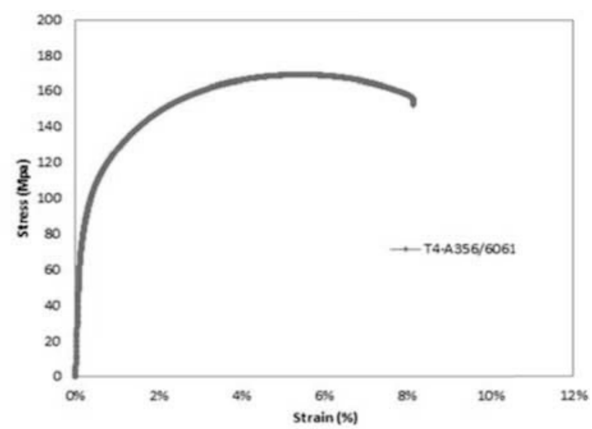


Figure 2: Typical Engineering Stress-strain curve for welding T4 heat treatment A356/6061 alloy.

Table 3: Tensile properties of welding T4 heat treatment A356/6061 alloy

Specimens	YS (MPa)	UTS (MPa)	E_f (%)	Breaking Location
Y1	107.8	169.1	10.29	1-A356
Y2	104.9	169.9	9.48	1-A356
Y3	105.9	171.4	10.85	1-A356
Y4	105.7	169.4	8.11	1-A356
Y5	106.5	167.8	7.77	1-A356

Microstructure

Figure 3 show the microstructures of the joined T4 heat treatment A356 cast alloy revealing from the Base Metal, Heat Affected Zone (HAZ) to Fusion Zone, respectively. It has been reported [4, 9] that fine eutectic silicon along with fine primary aluminum grains improved mechanical properties.

Comparing the size of grain and silicon particles from three effected zones in Figure 4, an increasing trend of size in grain size implies from Fusion Zone, Heat Affected Zone (HAZ) to Base Metal. Accordingly, there were 74.98% and 157.02% increments from 10.87 microns to 19.02 and 27.17 microns. The improvement in the tensile properties should be attributed to the fine grain structure of thin specimen.

Based on the optical microstructural analyses, the grain size and silicon particle in the fusion zone (ER4043) were finer than those base metal, which resulted in an increase in strengths of the fusion zone of the filler alloy ER 4043. As a result, the fracture occurred in the T4 A356, which had lower strengths.

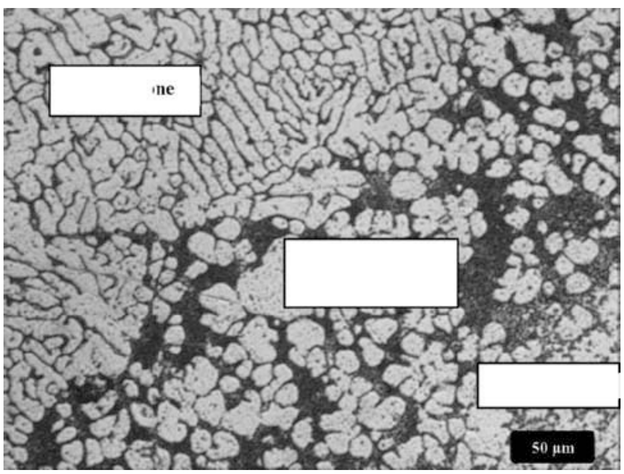


Figure 3: Optical micrograph showing the grain structure of the welded T4 A356 cast alloy with filler metal ER 4043.

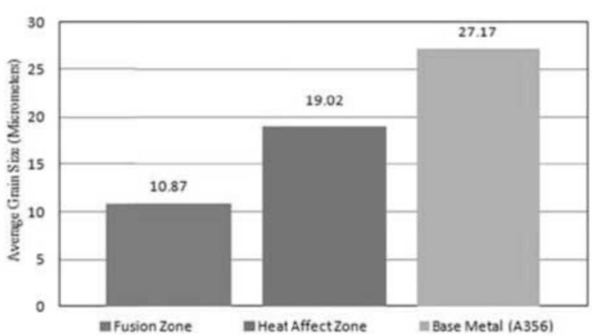


Figure 4: Size measurement of grain in fusion zone, heat affected zone and base alloy (A356).

Figure 5 and 6 shows the presence of phases in the A356 alloy after T4 heat treatment. SEM and EDS analyses on the specimens treated at T4 thermal treatment schemes indicated that, no Mg_2Si, a strengthening intermetallic phase, was detected, despite that it was found in the as-cast A356 in the previous study [9]. No presence of the Mg_2Si phase in the T4 A356 alloy suggested that the dissolution of the Mg_2Si might take place during the solution treatment. As a result, the strengths of the T4 A356 alloy were reduced.

The longitudinal section of the fractured casting can be seen in Figure 7, which identified the size of grain size and silicon particles after applying load. The fracture path was mainly along the boundary between the α-Al grains and the eutectic mixture which are clearly observed in these Figures. The coarser grain in fractured part resulted relatively low tensile properties.

Fractographs in Figure 8 identified the difference in the fracture behavior of T4 A356 cast alloy and 6061 wrought alloy. A ductile fracture surface containing deeper dimples with dramatic height variation resulted from the elongated fracture surface in 6061 wrought alloy than those in the fracture surface of T4 A356 cast alloy. This SEM observation indicated the T4 A356 cast alloy was less ductile than 6061wrought alloy. This is in agreement with the result of tensile testing, which the fracture occurred in the T4 A356 cast alloy.

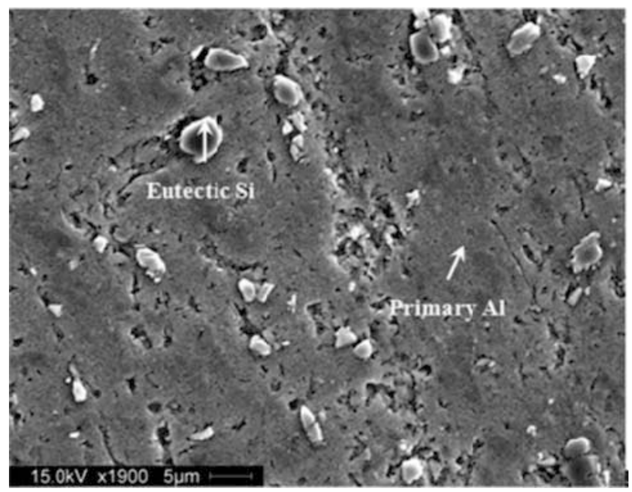
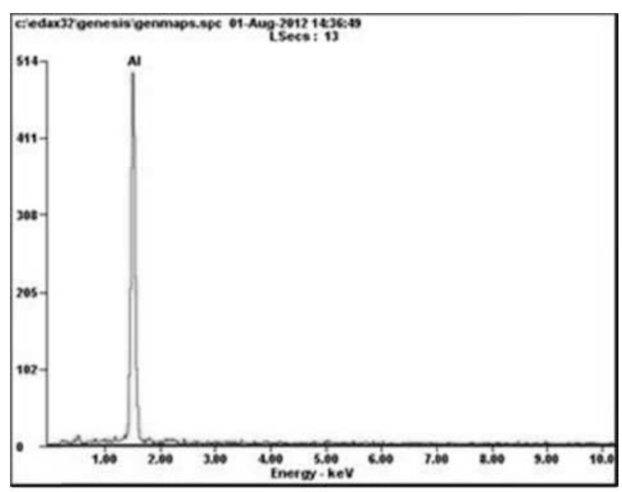
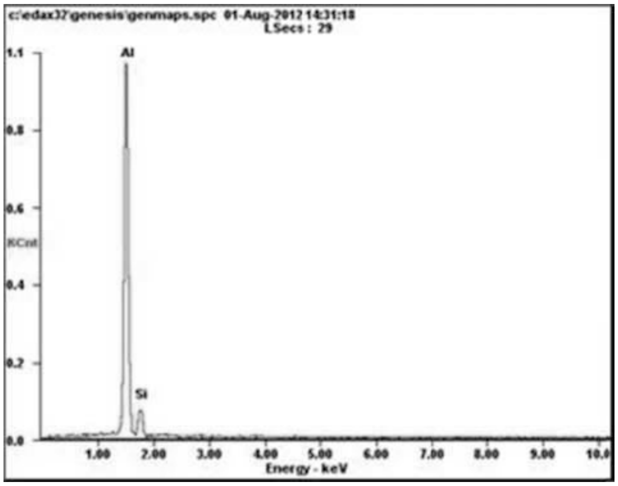


Figure 5: SEM micrograph showing phases present in the T4 cast alloy in joining part.



(a)



(b)

Figure 6: EDS spectra for identified phases, (a) primary Al and (b) eutectic Si.

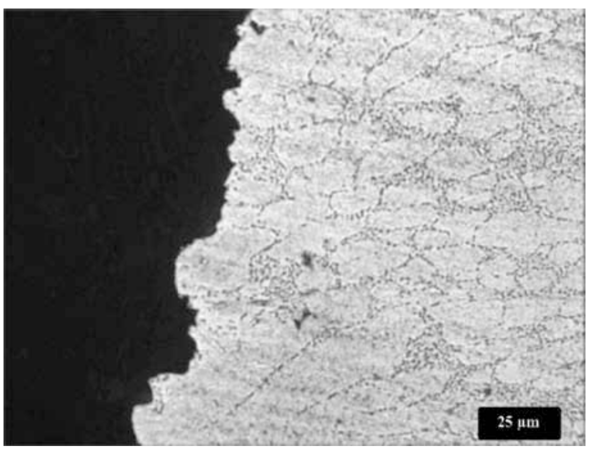
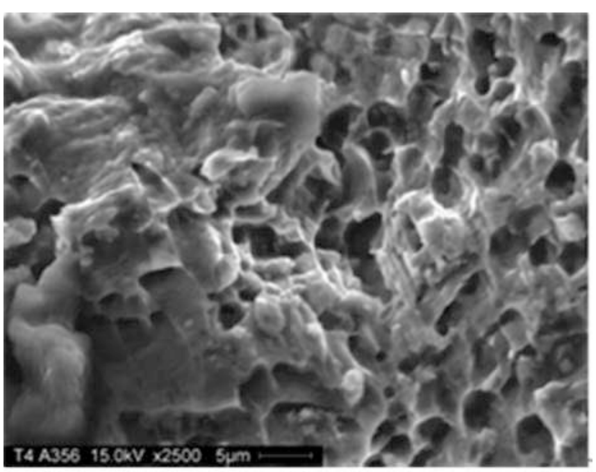
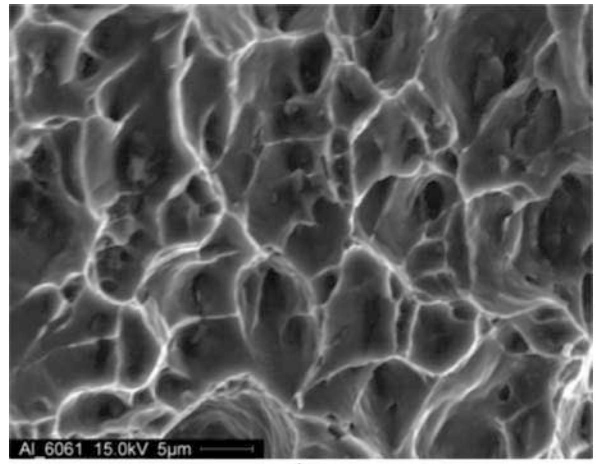


Figure 7: Optical micrograph showing the longitudinal section of a fractured casting.



(a)



(b)

Figure 8: SEM fractograph showing the fracture surface of a) T4 cast alloy A356 and b) 6061 wrought alloy.

Conclusions

The influence of mechanical properties by joining T4 heat treatement A356 cast alloy and wrought alloy 6061 was investigated on the tensile properties and microstructure analysis. It can be seen that T4-A356 had the UTS, YS and elongation of 169.5 MPa, 106.2 MPa and 9.3%, which were lower than the welded 6061, of which the UTS, YS and elongation were 216.5 MPa, 117.1 MPa and 16.31% respectively. As such, the fracture of the joined T4-A356/6061 took place in T4-A356 due to its lower tensile properties than 6061 and the filler alloy (ER 4043). The content of magnesium based intermetallic phase, their morphology and distribution throughout the matrix affected the mechanical properties as well. The reduction in the strengths ofthe alloy treated at T4 condition should be at least attributed to the absence of the Mg2Si intermetallic phase. However, the dissolution of the Mg2Si phases would cause the strength reduction in A356 cast alloy. Based on the microstructural analyses, the grain size and silicon particle in the fusion zone (ER4043) were finer than those of the base metal, which resulted in an increase in strengths of the fusion zone of the filler alloy (4043). The fracture took place in T4 A356 cast alloy, which indicated that the strength of the fusion zone and 6061 wrought alloy was stronger than T4 A356 cast alloy. Also, the fractured faces of T4 A356 were shallower and smaller than those in wrought alloy 6061, which meant the T4 A356 cast alloy was less ductile than 6061wrought alloy.

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