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Mechanical and Die Soldering Properties of Al-Si-Mg Alloys with Vacuum HPDC Process

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To improve the fuel efficiency and reduce the emissions of automobile, demand for lightweight alloys in application on the transportation equipment has been greatly increased. Especially, researches on aluminum to use in chassis and frame components have drawn great attention. In reduction of weight of engine sub-frame and cross member, it is necessary to develop a cast node component which connects extrusions. This cast node needs to have both sufficient strength and toughness, therefore, high strength alloy design and vacuum high pressure die casing process technology are required to minimize the casting defects. Mechanical properties, microstructure and casting characteristics of Al-Si-Mg alloys were evaluated by varying the ratio of Fe and Mn contents which is important for improving die soldering. To achieve both strength and elongation, optimum heat treatment condition was also established. Casting simulation results showed that the turbulence and air pressure were significantly reduced in vacuum condition compared with air atmosphere, and the experimental results were coincident with the simulation analysis. Moreover, flow of the melt and the internal defects were quantitatively analyzed with and without vacuum during die-casting. Below 100mbar of vacuum condition, the casting defects and blister after T6 heat treatment were greatly reduced and the improved tensile and fatigue properties were resulted.

Keywords: *Al-Si-Mg alloy, Automobile, Vacuum high pressure die-casting, Die-soldering, Fatigue*

1. Introduction

As a result of more stringent requirements for improved fuel economy and emissions, there is a growing trend to substitute aluminum for conventional steel and cast irons in vehicles. Al-Si-Mg casting alloys as important light metals are widely used in automotive components due to their excellent mechanical properties and castability [1-4]. The high pressure die casting (HPDC) process is today the most common process for the manufacturing of casting components such as spaceframe nodes, engine mounts, chassis parts. A critical requirement is that the aluminum castings must not have defects that reduce fatigue and impact resistance. As a consequence, the solidification microstructure must be carefully controlled to improve strength as well as ductility. This includes dendrite arm spacing, grain size, and eutectic silicon morphology. In addition to alloy chemistry and castability, fluidity and die-soldering must be considered to limit defects and sticking to die. This paper examined the solidification and mechanical properties of aluminium casting alloys made by a HPDC and evaluated the effect of alloying elements such as Fe and Mn on cast behavior.

2. Experimental

Cylindrical type specimens for mechanical tests were machined and subsequently polished longitudinally up to 2000 grit crocus cloth to remove the machining notch effect. The composition and the heat treatment schedule of the alloys are shown in Table 1. Axial HCF tests were carried out under the load control of 60Hz frequencies and also tensile tests were conducted with the strain rate of 2 mm sec^{-1} at room temperature using the dynamic and static machines, respectively. To evaluate the fluidity and shrinkage test, a metallic mold was constructed and its fluidity length and shrinkage trend was analyzed and die-soldering test was conducted using the mold material. After the dip test, the interface between the end of the pin and the soldered aluminum was examined using optical microscope (OM) and scanning electron microscope (SEM).

Table 1. Chemical compositions and the heat treatment steps of Al-Si-Mg alloys (wt %).

	Cu	Si	Mg	Zn	Fe	Mn	Ni	Ti	Al
Modified-A356	0.023	9.0	0.30	0.004	0.15-0.60	0.30-0.70	0.036	0.13	Rem
Heat treatment									
Solution treatment : 520℃/6hr → water quenching									
Aging : 180℃/5hr → air cooling									

3. Results and Discussion

3.1 Castability

1. Fluidity

After making rectangular cuts with different height as long as 200 mm on the metallic pattern of the size of 140 by 300 mm sample, a certain amount was injected in the cuts. The sum of lengths of filled metal is analyzed as the fluidity test. Fig. 1 demonstrates the effect of fluidity in terms of Fe and Mn portion. The alloy of 0.3Mg-0.15Fe-0.5Mn shows the longest with the fluidity length of 775 mm. As the portion of Fe and Mn increases, the corresponding fluidity length gradually decreased. This result seems to be associated with the phase transformation according to the change of composition of alloys. The increase of portion of Fe, Mn in alloy seems to have reduced the fluidity according to the increase of portion of β-Al_5FeSi phase and α-$Al_{15}(Mn,Fe)_3Si_2$ phase.

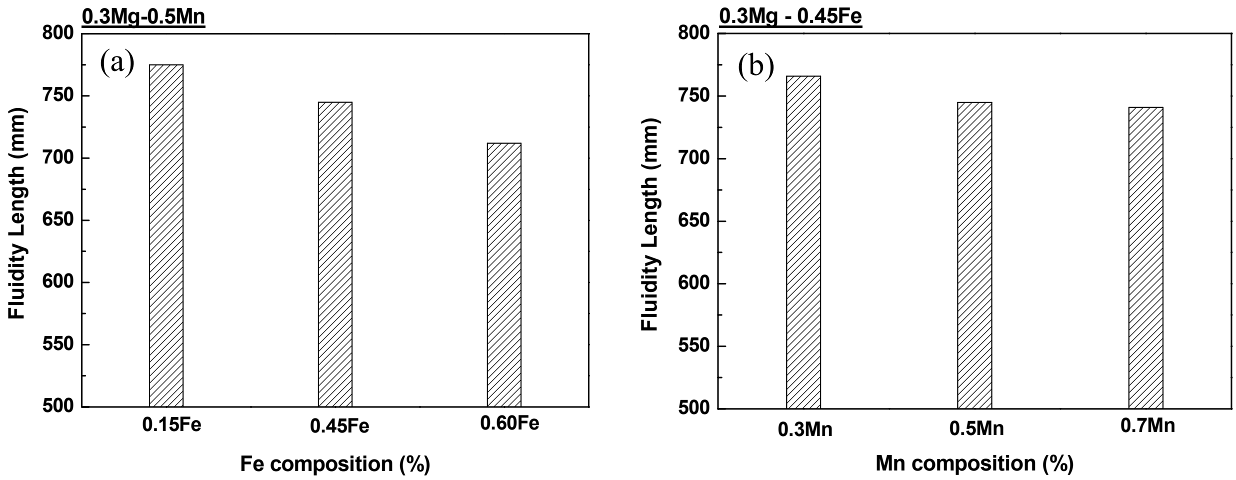


Fig. 1. Effects of Fe and Mn contents on melt fluidity of (a) Al-9Si-0.3Mg-0.5Mn alloy, (b) Al-9Si-0.3Mg-0.45Fe alloy.

2. Shrinkage

In shrinkage test, the pouring temperature was 710 ℃, that of mold was at the normal temperature, and that of graphite crucible was 400 ℃ when the test was carried out. Fig. 2 illustrates the effect of shrinkage rate according to the change of Fe and Mn content. As the Fe and Mn content increases, macro-shrinkage reduces significantly and micro shrinkage increased on the other hand. This can be explained in a sense that the rise of Fe, Mn content expedites the formation of alloys and the coagulation of the alloy hampers the feeding of molten metal. Thereby it helps to raise the volume relatively by building up the micro porosities.

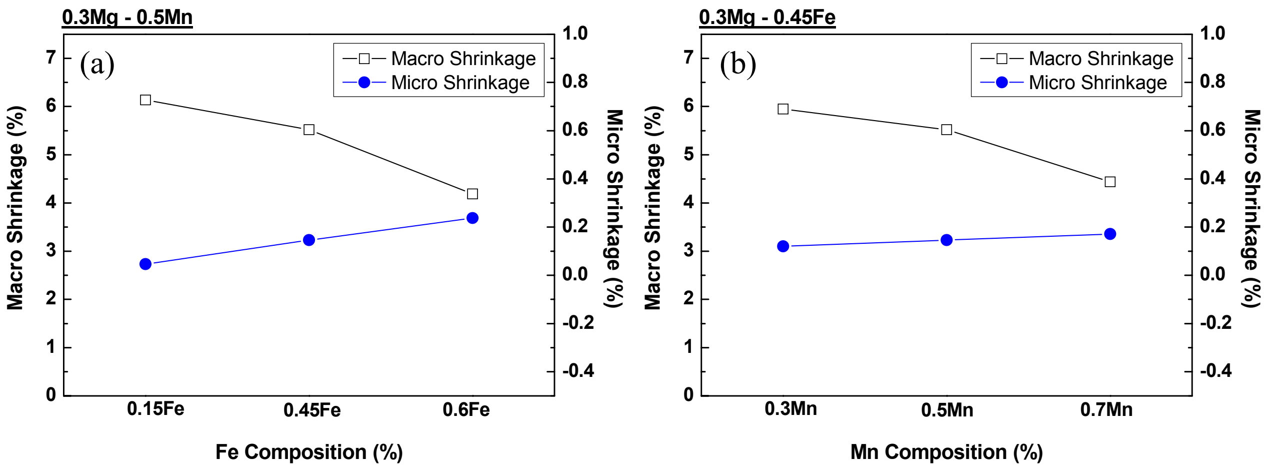
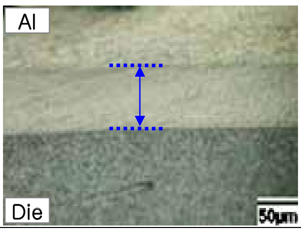
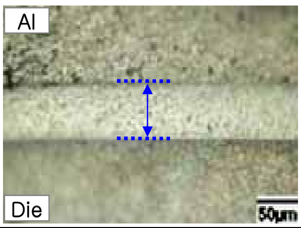
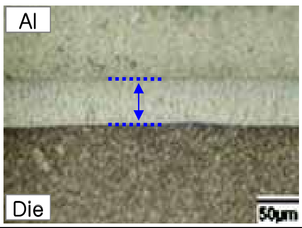


Fig. 2. Effects of Fe and Mn contents on shrinkage of (a) Al-9Si-0.3Mg-0.5Mn alloy, (b) Al-9Si-0.3Mg-0.45Fe alloy.

3. *Die soldering*

Die soldering test was conducted in the following way: SKD61 die sample (D 16 mm x L 65 mm) is inserted by 40 mm and kept at 680℃ for 0.5hr and cooled down at the water [5, 6]. After the surface of SKD61 sample has been cut using a low speed cutter and polished, it was examined using OM. Fig. 3 shows the result of die soldering test at the condition of 680 ℃, 0.5 hr. As the portion of Fe, Mn increases, the thickness of soldered part was reduced. On the surface of the die at the thermal activation temperature, Al-Fe alloy reaction layers are built by reaction and spreading of aluminum alloys [7]. This is in line with the result that Fe content is reduced when Mn content in aluminum alloys is high.

Composition	0.3Mg-0.15Fe-0.5Mn	0.3Mg-0.45Fe-0.5Mn	0.3Mg-0.60Fe-0.5Mn
Image			
Thickness	64.5 ㎛	57.3 ㎛	46.9 ㎛

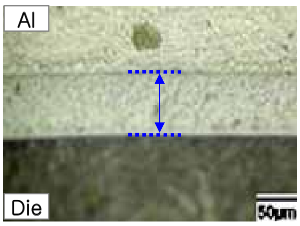
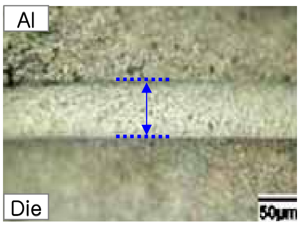
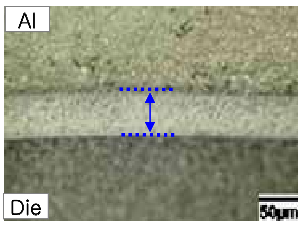
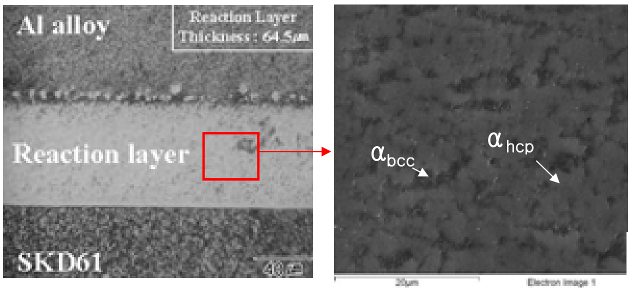
Composition	0.3Mg-0.45Fe-0.3Mn	0.3Mg-0.45Fe-0.5Mn	0.3Mg-0.45Fe-0.7Mn
Image			
Thickness	66.1 ㎛	57.3 ㎛	48.3 ㎛

Fig. 3. Effects of Fe and Mn content on soldering layer.

Fig. 4 shows the result of soldering layer of Al-9Si-0.15Fe-0.5Mn alloy using SEM/EDX and XRD. As can be seen in the figure, we can see that Al_8Fe_2Si composition was formed and grown up. In its outside, there are tissues with molten Al tissues being fixed.



	Al	Si	Fe	Mn	Cr
α_{bcc}	57.66	11.30	27.12	2.44	1.48
α_{hcp}	58.38	11.21	22.52	4.40	3.49

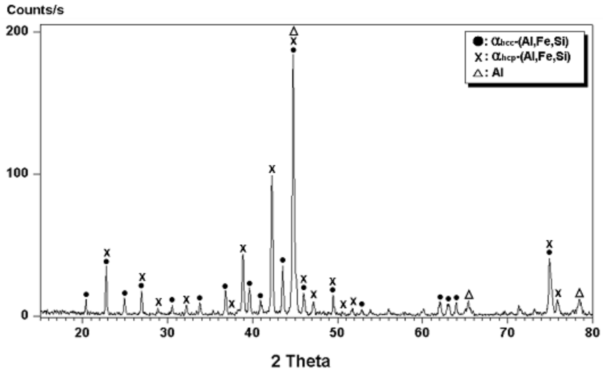


Fig. 4. SEM/EDX and XRD results of soldering specimen of Al-9Si-0.3Mg-0.15Fe-0.5Mn alloy.

3.2 Analysis of HPDC

1. Simulation results of vacuum HPDC

Based upon the casting characteristic experimental result of the above material, a stair-type mold as shown in Fig. 5 was manufactured in order to make a sample using actual vacuum HPDC and evaluate its characteristics. We conducted an investigation in terms of changing thickness and checking the pressure.

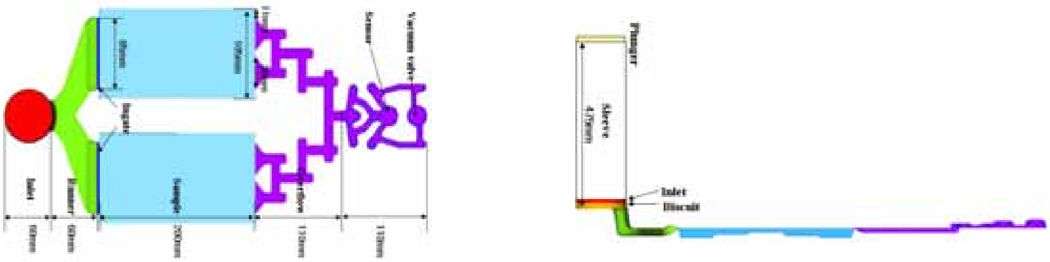
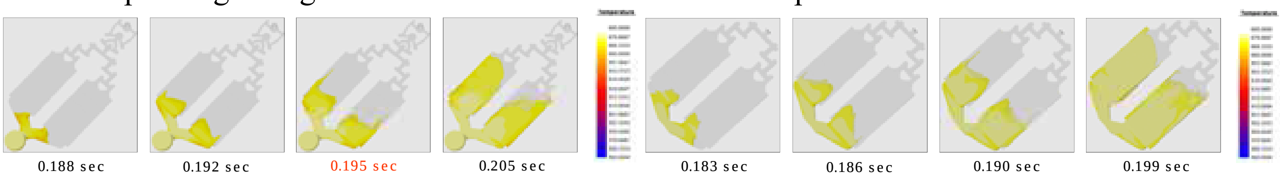


Fig. 5. Schematic illustrated modeling for HPDC simulation.

(1) Solidification

Fig. 6 graphically indicates the analysis result on the condition that the moving velocity of plunger inside sleeve is 12 cm/sec from 0 to 330 mm, low-high velocity transition from 330 to 334.32 mm, 300 cm/sec from 334.32 mm to 460 mm. As a result, turbulence was seen on the mold wall and it took 0.23 sec to finish the filling to the over flow level. On the other hand, under the same condition except vacuum of being below 100 mbar, it took only 0.225 sec. That is about 0.005 sec faster than the air pressure condition. We may explain that the turbulence on the wall is mitigated by the vacuum and the corresponding filling behavior is better than that in the air pressure.

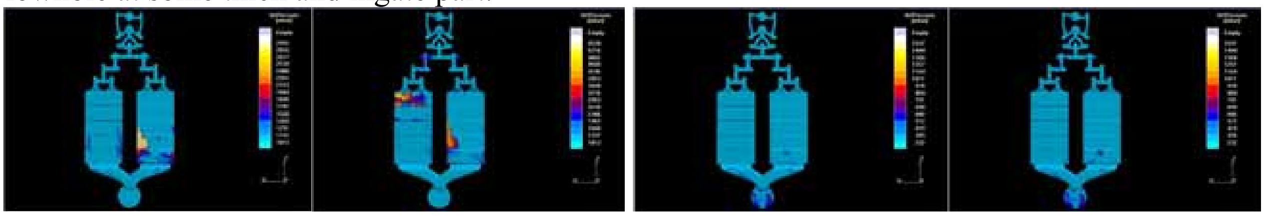


(a) (b)

Fig. 6. Filling behaviors of air and vacuum condition, (a) air, (b) vacuum: 100mbar.

(2) Air pressure

The result of air pressure analysis is illustrated in Fig. 7 in terms of air atmosphere and vacuum condition at the filling state of 64 % and the finishing time. At the air pressure, a portion of air is trapped inside the sample and lots of air seems to exist until the end of the filling. Particularly, internal blowholes are expected due to the high pressure at the left and right thick part. On the other hand, at the vacuum state of 100 mbar, the internal pressure is quite low. There are only a small portion of blowhole at some thick and ingate part.



(a) (b)

Fig. 7. Simulation results of air pressure, (a) atmosphere, (b) vacuum condition.

2. Internal defects

Fig. 8 displays the internal defects in the center using OM and 3-dimentional X-ray CT (computer tomography). There is a lot of blowholes in the samples under air atmosphere condition but it significantly reduced at the vacuum condition. This agrees the presented analysis result.

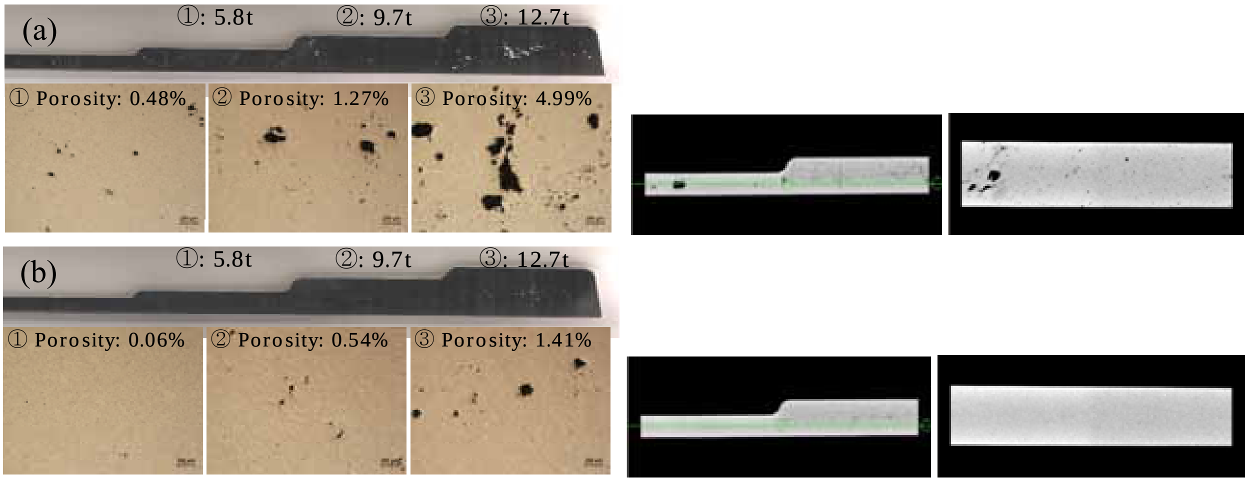


Fig. 8. Porosity analysis by OM and CT, (a) atmosphere, (b) vacuum condition.

3. Surface morphology after heat treatment

The surfaces of samples after T6 heat treatment including solution treatment 520 ℃/7hr and aging 180 ℃/8hr are shown in Fig. 9. In the sample under the air pressure, blister is coarsely built and blown up. On the other hand, it is seen that there is little blister and the initial features are kept at the vacuum pressure.

(a) (b)

Fig. 9. Surface analysis of cast node after T6 heat treatment, (a) atmosphere, (b) vacuum condition.

4. Mechanical properties

Based upon the above result, it was highlighted that HPDC process is essential that can removes internal porosity and allows the corresponding heat treatment. Fig. 10 shows the mechanical characteristic of the vacuum pressure casting sample. After solution treatment and aging of 6 to 8 hours, the optimal strength and elongation is obtained as illustrated in Fig. 10-(a). After high cycle fatigue characteristic test, when R is -1, fatigue limit was 60 MPa. From these results, vacuum decompression is essential in the manufacturing of thin aluminum parts and it is possible to have a heat treatment for the sake of securing the strength level. Since the potential defects in the manufacturing of automobile parts is fatal by rapidly lowering the fatigue characteristic, we should develop the process minimizing their occurrences.

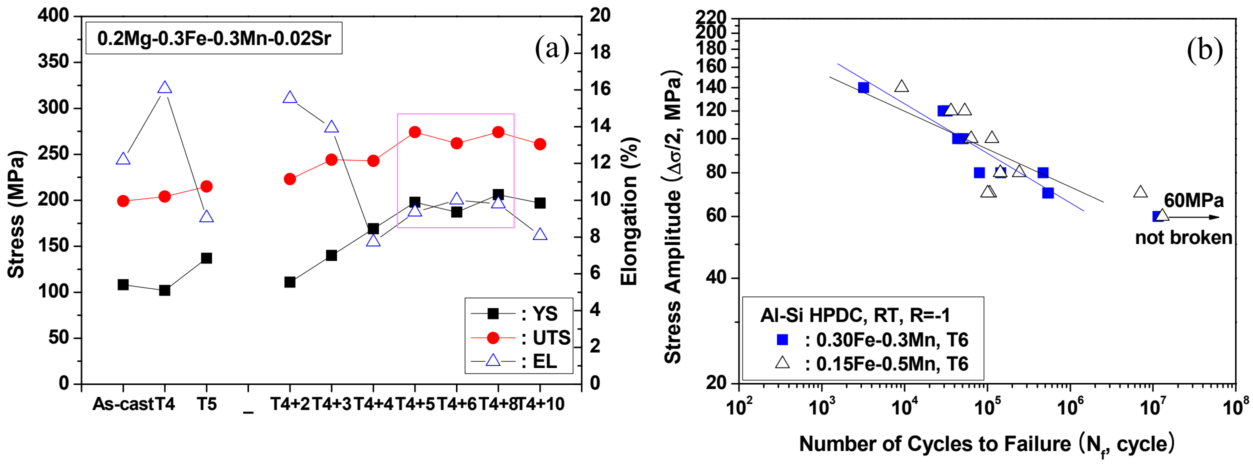


Fig. 10. Results of mechanical properties, (a) tensile, (b) high cycle fatigue.

4. Conclusions

(1) The increase of Fe and Mn content, the fluidity and shrinkage turned out to be lowered and die soldering improved. The soldering layers has both of α_{hcp} Al_8Fe_2Si alloy and α_{bcc} Al_8Fe_2Si in part due to the mutual spread of Fe, Al in SKD61 and molten aluminums.

(2) We obtained some satisfying result at the time when the portion of Fe is less than 0.45 %, Mn less than 0.5 % and the sum of Fe and Mn is less than 0.65 % for the mechanical and casting characteristic of Al-9Si alloys.

(3) Based upon HPDC analysis, at the lower pressure of 100 mbar, turbulence is calm down, internal air pressure, coarseness on the surface and the rate of internal blowholes is significantly reduced. Even after T6 heat treatment, blister was not built on the surface and consequently we got the improved mechanical characteristic.

Acknowledgments

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