A study on the squeeze casting of Al-7.0Si-0.4Mg alloy for fuel system parts

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Aluminum alloy casting is gaining increased acceptance in automotive and electronic industries and especially, squeeze casting is the most efficient method of mass manufacturing of such parts. In this study, the microstructures and mechanical properties of Al-7.0Si-0.4Mg(AC4C) alloy fabricated by squeeze casting process for development of fuel system parts(fuel rail) are investigated. The microstructure of squeeze cast specimen was composed of eutectic structure aluminum solid solution and Mg_2Si precipitates. The tensile strength of as-solid solution treatment Al-7.0Si-0.4Mg alloy was 298.5MPa. It was found that Al-7.0Si-0.4Mg alloy had good corrosion resistance in electrochemical polarization test.

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1. Introduction

Currently, domestic and worldwide automotive industry is meeting the time of rapid change. Nowadays, the development of technology in automotive mechanical industry is very important for worldwide global outsourcing of related parts. Among desired technologies, light weight of the vehicle can contribute largely to enhancement of the automotive driving efficiency, emission reduction, stabilization of the vehicle with easily balanced structure and the efficient dissipation of collision energy. The light weight of automotive parts has been achieved actively by using aluminum and magnesium parts instead of cast-iron and steel parts, and plastic parts instead of metal parts where possible[1,2]. The light weight of vehicle has a direct effect on the improvement of vehicle fuel economy.

Therefore, recent researches on the light weight material are being concentrated on casting alloys such as aluminum and magnesium. Aluminum alloy has much better properties in strength, castability, machinability, weldability and corrosion crack resistance among many light weight materials. Therefore, it has been widely applied to automotive parts. For the wrought products, the 6000 series(Al-Mg-Si alloy), whose formability like extrusion and forging is very good, are used much for mechanical parts such as bar, plate, wire, and pipe products[3-5]. The strength of the material is a bit lower compared with the 2000 series(Al-Cu alloy) and 7000 series(Al-Zn-Mg alloy), but they can be strengthened by T6 heat treatment(solid solution and aging treatment)[6,7]. Also, for the casting products, the mechanical properties and cutting ability of Al-Si-Mg series(AC4C, AC4A, AC4CH alloys, etc.) alloy can be improved by heat treatment and the precipitation of Mg_2Si intermediate phase which can be produced by adding a small amount of Mg to Al-6~10%Si alloys. The AC4C alloy is an Al-Mg-Si alloy composed of Si(6.5~7.5%), Mg(0.2~0.4 %), Mn(0.35%) and aluminium. The Si component improves the characteristics of aging precipitation hardening, castability and wear resistance. It is well known that Mg component affects the enhancement of corrosion resistance and the welding property without reducing the ductility. Also, a small amount of Mn is added to prevent grain boundary brittleness fracture due to the segregation of Si components at the grain boundary.

The AC4C alloy forms Mg_2Si(a metal compound) of a F.C.C.(Face Centered Cubic) lattice and is strengthened by precipitation. Lately, many reports on the precipitation process have been published[8-10]. AC4C aluminum material is applied to many automotive parts such as wheels, hydraulic components, transmission cases, flywheel housings, brackets, cylinder blocks, pump bodies and handles, etc.. On the other hand, the manufacturing techniques for light weight automotive parts are being developed widely and rapidly. Especially, new casting techniques that can induce the reduction of thickness through high strength by the development of the molding material, optimized structure of total molding, improvement of the manufacture method through the application of a new material and light weight alloy molding materials, etc.[11]. Parts that are made by new casting method occupy over 15% of the total weight of a car. Especially, most parts of the engine, transmission, and chassis are made by casting method and its ratio is over 80%. In this research, a squeeze casting process is applied that can reduce 20% weight of a part because it ensures superior casting quality with the characteristics of rapid cooling, dense interior microstructure, and removal of the blow holes[12,13].

In this research, a light weight fuel rail was developed using the squeeze casting process with investigations of the microstructure, mechanical properties, aging hardening characteristics, and the corrosion crack resistance characteristics of the AC4C Aluminum alloy.

2. Experimental Methods

2.1 Material selection and alloy manufacture

The selected test material is the AC4C alloy of Al-Si-Mg alloy system of the casting aluminium alloys which are largely used for automotive parts. The AC4C alloy(Al-7.0%Si-0.4%Mg) is much stiffer than

AC4A alloy due to less Si content. Although AC4A alloy has good molten metal fluidity due to Si inclusion of 8~10%, it has shrinkage defects because of the small precipitation quantity of α phase. The HVSC melting furnace(Japan UBE Co., model : HVSC 800) is shown in Fig. 1. The crucible is used for melting the preheated AC4C ingot. Table 1 shows the chemical composition of the specimen which is made by squeeze casting with the furnace. The Fe content of the material, which affects the tensile strength, elongation and impact properties, was restrained as best as it could be.

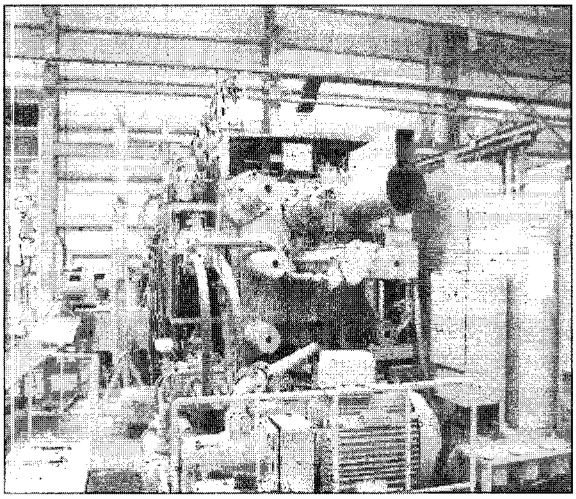

Fig. 1 Photo of HVSC for melting

Table 1 Chemical composition of Al-7.0Si-0.4Mg alloy

elements / specimen	Si (%)	Mg (%)	Zn (%) (max)	Fe (%) (max)	Mn (%) (max)	Others (%)	Al (%)
ASTM specimen	6.5–7.5	0.2–0.45	0.35	0.55	0.35	0.80	bal.
Test specimen	7.01	0.40	0.35	0.32	0.36	0.61	bal.

2.2 Microstructure observation

The microstructures of the fabricated and the solid solution treated specimens were observed by optical and scanning electron microscope. The observed parts were picked out from the middle region of the specimens and corroded by Keller solution(2mℓ-48%HF, 3mℓHCL, 20mℓ HNO_3, 175mℓH_2O).

2.3 Investigation of the mechanical characteristics

The tensile test(specimen size : ASTM B557-94) was performed using a bar shape AC4C alloy specimen of which the cross section area is 28±0.5mm² and gauge length is 6±0.1mm. Its gauge range was 50mm and cross head speed was 0.5mm/min. The tensile characteristic such as UTS, YS, and elongation were arithmetically averaged with the values obtained from 3 or 4 specimens.

2.4 Investigation of aging hardening characteristics

For the investigation of the aging hardening characteristic, the AC4C alloy was done the solution heat treatment at 540℃ for 30 minutes and supersaturated by the quenching at 20℃ water. And then it was done the aging heat treatment using silicon oil bath at 160℃, 170℃, 180℃ for 0~28 hours and the hardness change of each specimen was measured 10~15 times using the microvickers at the load of 500g and the loading time of 10 seconds. The aging hardening characteristic was arithmetically averaged with the measured values of the specimens.

2.5 Investigation of corrosion characteristics

Because the AC4C alloy was not surface treated, to examine the stress corrosion crack, a polarization test was performed using an electrochemical polarization device(potentiostat : EG&G potentiostatic/galvanostat model 273) which was controlled by a computer. The electrode reaction area of the working electrode was set to 0.95cm² and the specimen holder was machined as a plate type. A carbon bar was used for the counter electrode and a saturated calomel electrode was used for the reference electrode. For the specimen, a disk with a diameter of 15mm and a thickness of 3mm was manufactured and it was polished with of 0.3μm Al_2O_3 grinding compound. The corrosion resistance test was performed at room temperature with 0.03% NaCl electrolyte. The dissolved oxygen of the electrolyte was minimized by pouring the argon gas 30 minutes before the test.

3. Experimental Results and Discussion

3.1 Microstructure observation

The microstructures of the fabricated and solid solution treated Al-7.0%Si-0.4%Mg alloy are shown in Fig. 2. As shown in Fig. 2(a), the microstructure of the fabricated specimen shows that needle phase particles were produced, which were two-phase particles or chemical heterogeneous substances((Fe,Mn)Al_6, $FeAl_3$, α-Al(Fe, Mn, Si), Al_7Cr_2Fe) formed during the casting procedure. In Fig. 2(b), the microstructure of the solid solution treated specimen shows that some of the chemical heterogeneous parts were eliminated, but two-phase particles and inter-metallic compounds with high melting points still remained. In addition, the optical microstructures showed that the casting defects were effectively eliminated. Especially, the microstructure of the solid solution treated specimen had more refined and sound grains than the fabricated one. It was judged that chemical heterogeneous parts of the impurity and microporosity were eliminated efficiently in the solid solution treatment[15]. Fig. 3 shows the scanning electron microscope(SEM)

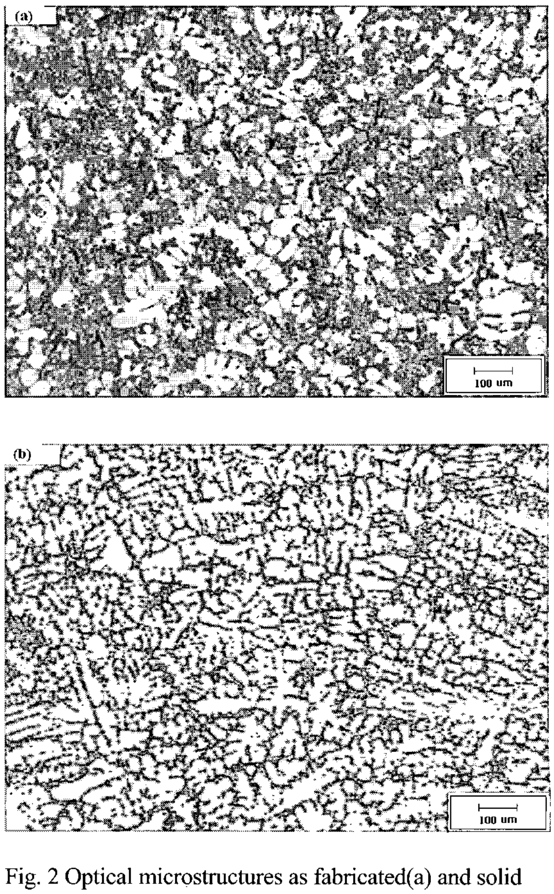

Fig. 2 Optical microstructures as fabricated(a) and solid solution treated(b) Al-7.0Si-0.4Mg alloy

micrograph and EDS analysis result of solid solution treated Al-7.0Si-0.4Mg alloy. In the micrograph, it is shown that almost all the compound phases exist at grains boundaries, but some were observed inside the grains. In the EDS analysis result, the peaks of Mg and Si could be found. It was judged that areas at the grain boundary would be precipitated areas of β phase(Mg_2Si : intermediate phase precipitated during the solid solution treatment) and areas inside the grains were precipitated areas of α phase(aluminium solid solution). Such formations of eutectic structures of α phase and Mg_2Si could result from non-equilibrium solidification. It was caused by the growth of dendritic structure which was produced under the super-cooling condition.

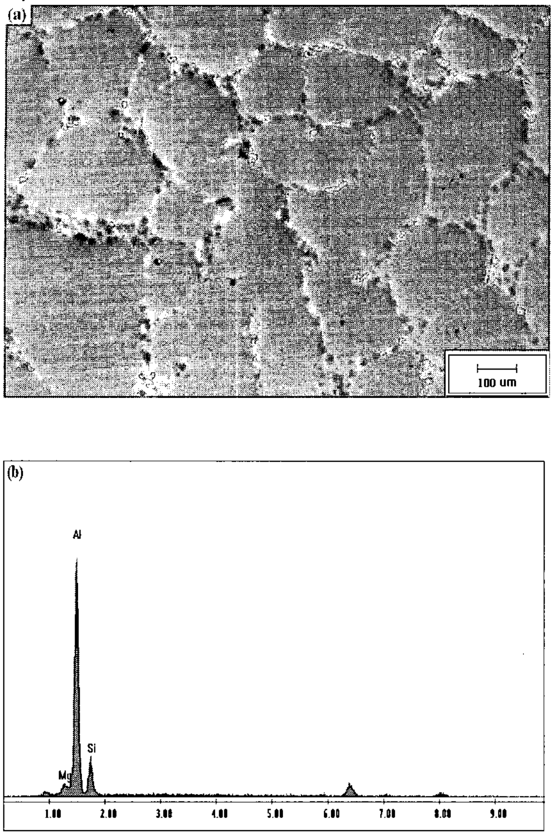

Fig. 3 SEM micrograph(a) and EDS analysis(b) of solid soution treated Al-7.0Si-0.4Mg alloy

3.2 Mechanical characteristics

Mechanical characteristics of the AC4C alloy which was used in this research were compared with ASTM standard. As shown in Table 2, UTS and YS are 298.5MPa and 231.4MPa, respectively, which are greater than ASTM standard value of 285MPa and 225MPa. Also, the elongation of 6.2% is a little lower than the standard value. These results may be due to the increase in the precipitation ratio of the β phase(Mg_2Si) after the solid solution treatment. Fig. 4 shows the SEM micrograph of Al-7.0%Si-0.4Mg alloy specimen after the tensile test of the solid solution treated specimen. The main pattern of fracture was considered as brittle in that the fracture occurred on the dendrite boundaries. It can be explained from the particles gathered densely around the grain boundaries. Also, some dimples were observed inside the grains.

Table 2 Mechanical properties of Al-7Si-0.4Mg alloy as solid solution treatment

Alloy	UTS (Mpa)	YS (MPa)	Elongation (%)	Heating Treatment
ASTM[16]	285.0	225.0	7.3	T6
Test specimen	298.5	231.4	6.2	T6

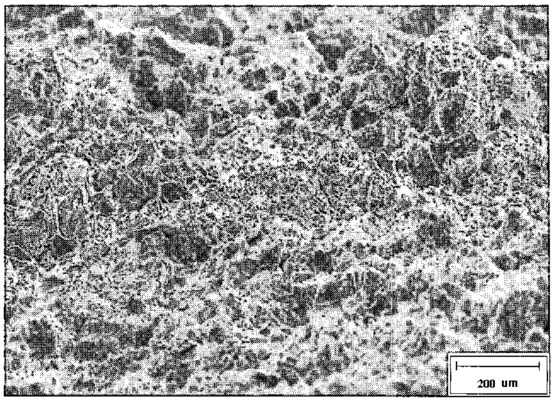

Fig. 4 SEM micrograph of Al-7.0Si-0.4Mg alloy

3.3 Age hardening characteristics

Fig. 5 shows the microhardness of the heat treated AC4C alloys according to the aging time. As mentioned before, the AC4C alloys were aged at 160℃, 170℃, 180℃ after the solid solution treatment. It shows that the hardness increased according to the aging time regardless of the aging temperature. Especially, the hardness of the aged alloys at aging temperature of 170℃ and 180℃ were rapidly increased. The maximum values were found at aging time of 7 hours and aging temperature of 180℃, and at aging time of 9 hours and aging temperature of 170℃. But the hardness of the aged alloys at aging temperature of 160℃ was gradually increased and its maximum value was found at 24hours of aging time. The maximum hardness value was measured at aging time of 9 hours and aging temperature of 170℃ and the hardness of 118.3Hv was comparable with the standard value[17] of 118Hv of AC4C molding material given by ASTM. The aging condition for the maximum hardness is at aging time of 12 hours and aging temperature of 170℃. The hardness value after the maximum hardness value was decreased slowly according to the elapsed aging time. The change of hardness according to the aging time had close relation with the precipitation behavior of the precipitates[18-20].

The initial rapid increase of the aging hardness would be caused by the increase of internal energy of the needle phase particles which were precipitated in the aluminium matrix. In addition, the maximum hardness value at each aging temperature was produced by precipitates of the needle phase and β phase precipitate. The decreasing of the hardness values after the aging time of the maximum hardness may be due to slow transformation rate of the β precipitate to the equilibrium phase or slow coarseness rate of the equilibrium precipitate phase. The aging time to reach the maximum hardness value became shorter as the aging temperature was increased due to the increase in nucleation rate[21]. grains.

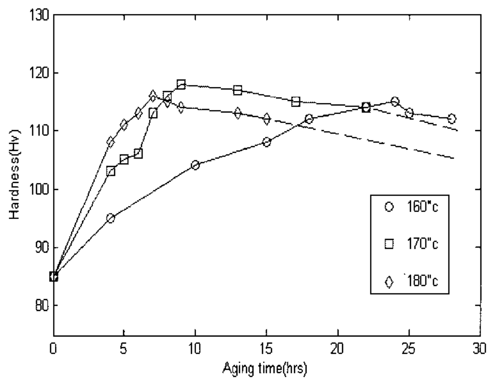

Fig. 5 Effect of aging time on hardness of AC4C Al alloy aged at 160, 170 and 180℃

3.4 Corrosion characteristics

Fig. 6 shows the electric potential change of the AC4C(M1) and 380Al(M2) alloys according to the current density change. The measurements of the specimens were proceeded in a deaerated 0.03 % NaCl buffered with KH_2PO_5·NaOH of pH 7. The AC4C(M1) specimen showed higher corrosion electric potential than the 380Al(M2) specimen. It showed that the activation area reduced considerably. Also, the corrosion rates of the AC4C(M1) specimen and 380Al(M2) specimen were 0.28(mpy) and 0.43(mpy), respectively. The corrosion rate was calculated from the corrosion current density of the polarization curve and the corrosion reaction area, density and equivalent of the specimens. It could be found that AC4C(Al-7.0%Si-0.4%Mg) alloy had relatively better corrosion resistance compared with other aluminium alloys. Based on the results of the experiments and the discussions, a trial fuel rail part of the AC4C(Al-7.0%Si-0.4%Mg) alloy was successfully manufactured by the squeeze casting process. Fig. 7 shows the fuel rail which is 2.1㎜ thick, 288㎜ long, and 123.1g in weight.

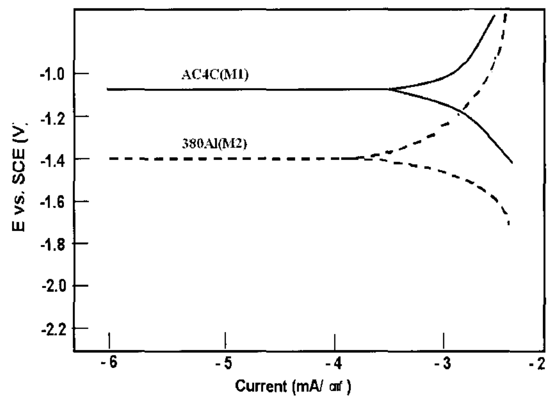

Fig. 6 Potentiodynamic polarization of AC4C(M1) and 380Al(M2) alloys in a deaerted 0.03% NaCl buffered with KH_2PO_5·NaOH(pH7.0)

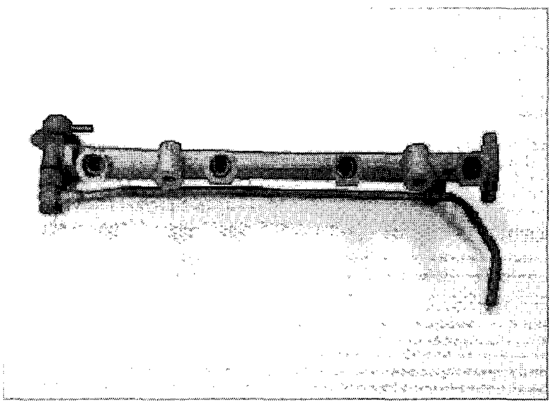

Fig. 7 Photo of fuel rail trial part manufactured by squeeze cas ting process

4. Conclusions

To investigate light weight materials for automotive parts, the microstructure, mechanical and corrosion characteristics of AC4C (Al-7.0%Si-0.4%Mg) alloy were examined and compared with other aluminum alloys. Also, a trial automotive fuel rail with AC4C alloy was manufactured by the squeeze casting process. The conclusions are as follows:

1) The microstructure of AC4C alloy was composed of the eutectic structures with α phase of aluminium solid solution and β (Mg_2Si) phase.

2) The maximum tensile and yield strength were 298.5 MPa and 231.4 MPa, respectively and those were higher than the ASTM standard values of 285MPa and 225MPa.

3) The corrosion characteristics assessed by the electrochemical polarization test showed that AC4C alloy has better corrosion resistance than 380Al alloy.

4) It was possible to manufacture a trial automotive fuel rail part with AC4C alloy by the squeeze casting process.

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