論 文

Mechanical Properties and Castabilities of Al-12Mg-5.5Zn-xSi Alloys

Jeong-Min Kim†, Ki-Dug Sung, Joong-Hwan Jun, Ki-Tae Kim, and Woon-Jae Jung

Abstract

초정 Mg_2Si와 미세한 $MgZn_2$ 석출상을 갖는 고강도 내마모 Al합금을 개발하기 위하여 Al-12wt%Mg-5.5wt%Zn합금에 0-5wt%까지 Si을 첨가 시켰으며, 미세조직 및 기계적 성질에 미치는 영향을 조사하였다. Si의 함량이 증가함에 따라 형성되는 Mg_2Si상의 양이 증가하였으며, 동시에 고상선 온도가 점차적으로 증가함에 따라 효과적인 열처리가 가능해지는 것을 관찰할 수 있었다. 5wt%Si이 첨가된 합금의 경우 적절한 열처리를 통해 미세한 $MgZn_2$ 석출상이 기지에 균일하게 분포한 미세조직을 얻을 수 있었고 이를 통해 인장강도를 현저하게 증가시킬 수 있었다. 또한 Si이 첨가된 Al-Mg-Zn합금은 유동도 및 열간 균열저항성과 같은 주조성면에서도 다른 고강도 Al합금에 비하여 월등히 우수한 것으로 나타났다.

Keywords: Al, Mg_2Si, Heat treatment, Castability, Microstructure, Mechanical properties

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1. Introduction

Aluminum alloys have attracted considerable attention in the automobile and aerospace industries because of their low density and high strength. However, the demand for more diverse and versatile alloys to meet specific engineering requirements has not been satisfied, and it may act as an obstacle to extensive applications of aluminum alloys. For example, high strength can be obtained in Al-Zn-Mg-(Cu) based alloys, but their applications are still limited to wrought products because of low castability like hot cracking susceptibility[1]. If high strength alloys with a good castability are developed, the application field of aluminum parts will be significantly expanded.

Recently, Zhang et al.[2,3] introduced Al-Mg_2Si as a new class of light materials. Mg_2Si intermetallic compound, which exhibits low density, high hardness, low thermal expansion coefficient, etc., make this material possess many special properties. More recently, some efforts were made to improve the castability of high strength Al-5.5Zn-2.5Mg-1.5Cu alloys through the Mg and Si additions[4]. Proper adjustment of the chemical composition enabled the alloys to have the substantially enhanced castabilities, while keeping the high strength. In this research, high amounts of Mg and Si were added to develop Al-Mg_2Si based alloys that can be successfully cast and effectively heat treated for attaining the high strength and wear resistance.

2. Experimental Procedures

A7075, A535, and Al-12(wt%, hereafter)Mg-5.5Zn-xSi (x=0, 2.5, 5%) alloys were prepared by heat resistance melting from commercially pure(99.8%) metals under a dynamic protective gas atmosphere (a mixture of CO_2 + SF_6), followed by pouring the melt into a metallic mold (rectangular cavity of width 60, thickness 24, and height 100 mm). T6 heat treatment was subsequently carried out and microstructural characteristics of as-cast and heat-treated specimens were investigated by optical microscopy, XRD, and TEM.

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Table 1. Chemical compositions of investigated alloys

Alloy	Mg	Zn	Si	Cu	Al
Base	11.97	5.09	--	--	Balance
+2.5%Si	12.04	5.07	2.64	--	"
+5%Si	12.07	5.85	5.07	--	"
A7075	2.78	5.95	--	1.66	"
A535	6.96	--	--	--	"

Fluidity of alloy was measured by using a vacuum suction fluidity test apparatus. When melt with a certain superheat is ready, the crucible is raised so that a quartz tube is dipped into the melt, and then vacuum suction is initiated. Applied suction pressure was about 40 kPa and the inner diameter of the tube was 3 mm. Hot cracking susceptibility test was also conducted by casting ring-type specimens(outer diameter of 60 mm, 30 mm high, 5 or 10 mm thick). In this test, liquid metal is poured into the open ring between the inner and outer parts of the metallic mold, and then some cracks will occur all around the ring casting if the constraint becomes large enough during solidification. The hot cracking susceptibility of alloy is assessed by measuring the total crack length[5]. The pouring and mold temperatures were fixed at 100°C and 150°C above the liquidus temperature, respectively.

Plate-type specimens for mechanical tests were machined from the castings before and after the heat treatment depending on their chemical compositions. Tensile test was carried out with a cross head speed of 1 mm/min. according to ASTM B 557 M and the sliding wear test was also conducted using a pin on disc machine. The discs of 30 mm diameter were prepared from the casting specimens and made to slide against AISI52100 bearing steel ball (63 HRC) with 6 mm diameter. The normal load of 1N was applied and total wear distance was 30 m. The surfaces of the worn samples were examined with SEM.

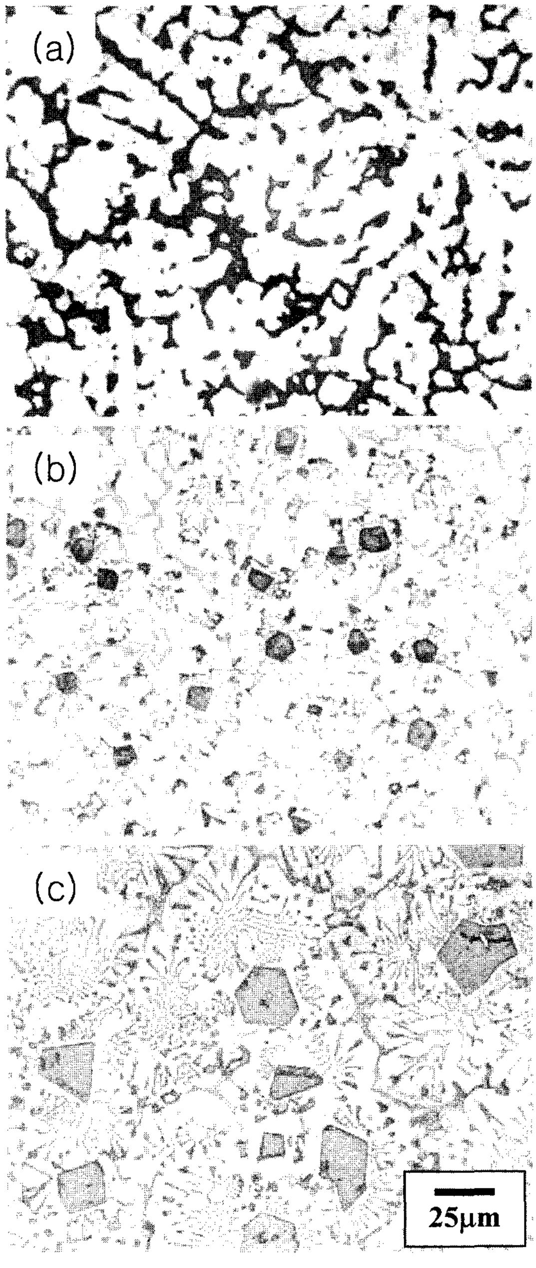

Fig. 1. Typical microstructure of as-cast Al-12Mg-5.5Zn-xSi alloys: (a) no Si (b) 2.5%Si (c) 5%Si.

3. Results and Discussion

3.1. Microstructure and Mechanical Properties of Experimental Alloys

Typical microstructure of as-cast Al-12Mg-5.5Zn-xSi alloys is shown in Fig. 1. The base alloy containing no silicon exhibits primary dendrites, while Si-added alloys show primary Mg_2Si particles with Al-phases surrounding them. In Si-added alloys the amount and size of the particles are seen to increase with increasing the Si

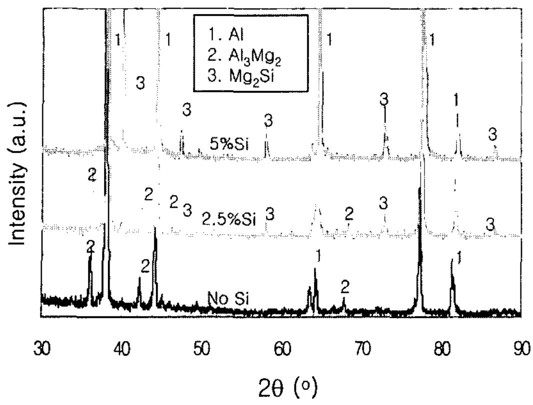

Fig. 2. XRD analysis of Al-12Mg-5.5Zn-xSi alloys.

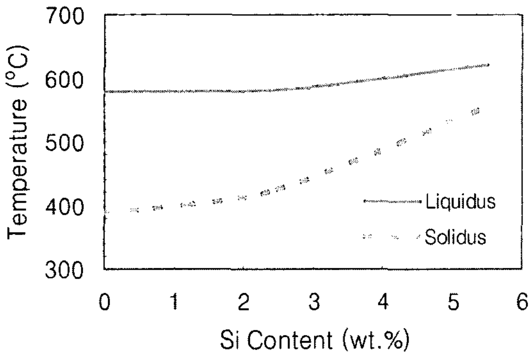

Fig. 3. Effect of silicon content on the liquidus and solidus temperatures of Al-12Mg-5.5Zn based alloys (from Thermo-Calc with TTAL database).

content. XRD analysis in Fig. 2 shows that Al_3Mg_2 phase was found in the base alloy, however it disappeared in the Si-added alloys. Because Mg_2Si particles form earlier than Al_3Mg_2 phase during the solidification, the Mg content that will be used for Al_3Mg_2 phase is reduced by the formation of Mg_2Si particles. The disappearance of Al_3Mg_2 phase is desirable since the phase has been known for promoting the stress corrosion cracking[6].

Fig. 3 shows the equilibrium liquidus temperature, which was calculated using a commercial software (Thermo-Calc), is almost constant until 2.5%Si and then slightly increases as the Si content increases. In contrast to this, the increase rate of solidus temperature as a function of Si is substantially high. One important feature shown here is that the solidus temperature is

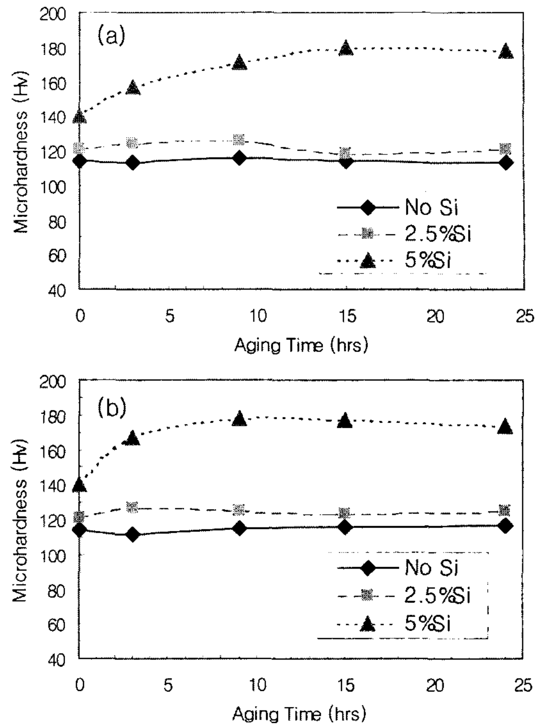

Fig. 4. Effect of aging heat treatment on the microhardness of Al-12Mg-5.5Zn-xSi alloys: (a) at 120°C (b) 140°C.

considerably low at low Si contents. This implies the solution heat treatment has to be performed at a low temperature, which is ineffective. In this study the solution treatment was carefully conducted just below the solidus temperature for more than 3 hours, and aging was carried out. Fig. 4 indicates that the microhardness is increased remarkably by aging only for the Si-added alloys. The initial hardness before aging was generally proportional to the Si content probably owing to hard Mg_2Si particles, however the increase of hardness after aging should be attributed to the precipitation of strengthening phases. The aging time required for obtaining the maximum hardness in the 5%Si alloy was apparently longer at 120°C than 140°C, as can be expected.

Tensile test results(Fig. 5) also show that the tensile strength was significantly improved by the heat treatment only for the 5%Si added alloy. The elongation was only about 1% or less for all specimens, thus the brittleness seems an important problem that has to be solved for

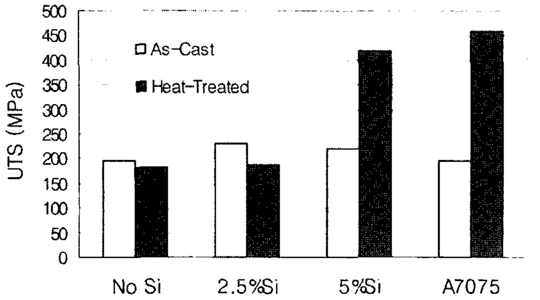

Fig. 5. Tensile strength of Al-12Mg-5.5Zn-xSi alloys and A7075.

practical applications. An ultimate tensile strength obtained in Al-12Mg-5.5Zn-5Si alloy appears relatively high compared to typical mechanical properties of most Al casting alloys. In A7000 series of high strength alloys, the main strengthening mechanism that has been known is the precipitation hardening by $MgZn_2$ or its transition phase[7,8]. The reason that the tensile strength can be significantly increased in Al-12Mg-5.5Zn-5Si alloy by the heat treatment is also because of the fine $MgZn_2$ type precipitates. TEM micrographs(Fig. 6) of the as-cast and heat treated specimens revealed that a few precipitates were found in only limited areas of the as-cast while finer precipitates were evenly distributed in all investigated areas of the heat-treated. The precipitates were identified as $MgZn_2$ phases through the TEM-EDS and diffraction pattern analyses.

3.2. Castabilities of Al-12Mg-5.5Zn-xSi alloys

A hot cracking, or hot tear, is one of the most serious defects that happen to a casting during its solidification. A7000 series of aluminum alloys have been known as hot-cracking-prone alloys[1]. To compare the hot cracking susceptibility of Al-12Mg-5.5Zn-xSi alloys with that of a reference alloy, A7075, a ring mold test was conducted and the results are shown in Fig. 7. Unlike A7075, any hot cracking was not occurred on the test specimens with 10 mm thickness in the case of Al-12Mg-5.5Zn-xSi alloys. It has been reported that the hot cracking susceptibility is generally proportional to (t_V/t_R), where t_R is the time period that stress-relaxation can be occurred, and t_V is the vulnerable time period that cracks can propagate through grain boundaries[5]. The possibility

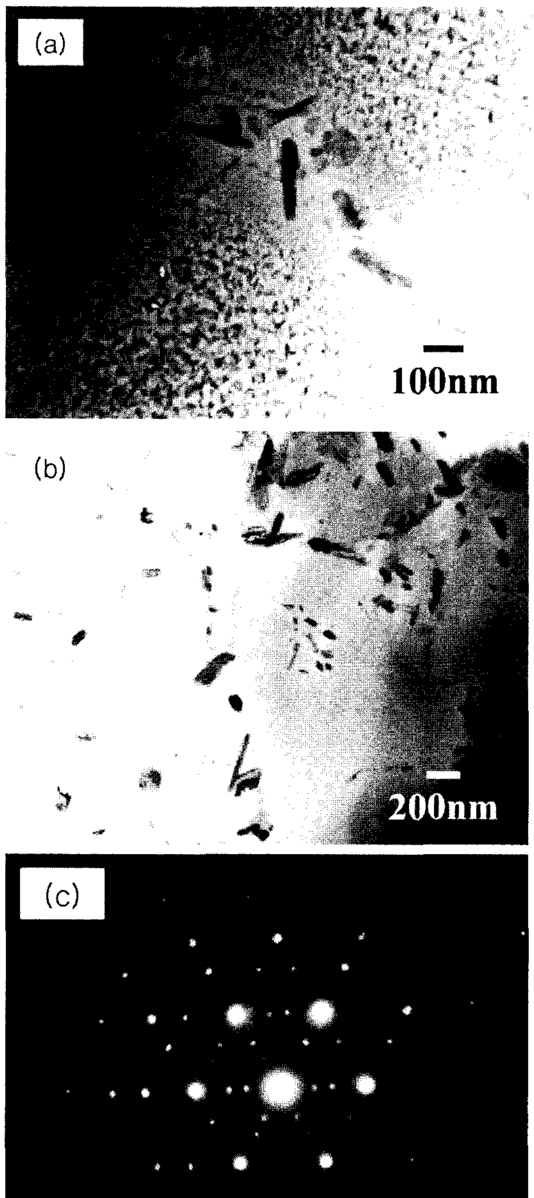

Fig. 6. TEM micrographs showing the influence of heat treatment on the precipitation of Mg-Zn phase in Al-12Mg-5.5Zn-5Si alloy : (a) as-cast (b) heat-treated (T6) (c) diffraction pattern for fine precipitates.

that cracks take place and propagate becomes small as t_R is increased by facilitated feeding or stress accommodation at grain boundaries. Although a number of factors affect the hot cracking resistance, two of the most

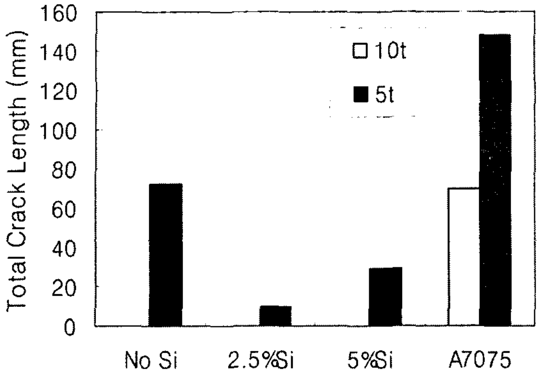

Fig. 7. Hot cracking resistance of Al-12Mg-5.5Zn-xSi and A7075 alloys.

important factors is the freezing range and the amount of last solidifying liquid[9]. As shown in Fig. 3, the freezing range becomes short with increasing the Si content, resulting in improved cracking resistance. Meanwhile, from the microstructural observations(Fig. 1), the amount of last freezing liquid seems to decrease with increasing the Si content. It is postulated that the combination effect of the two important factors have resulted in the lowest susceptibility at 2.5%Si. The shape and amount of primary Mg_2Si particles should be also important because a hot tear can occur more easily in the stressed body with lower ductility.

Al-12Mg-5.5Zn-5Si alloy was selected as a promising material with a high strength and a good hot tearing resistance, and another important casting capability, fluidity, was compared to other commercial alloys. In the casting industry 'fluidity' is defined as an ability to fill the mold cavity successfully. As indicated in Fig. 8, fluidity is seen to increase with increasing superheat in all investigated alloys. It is clear that the developed alloy possesses superior fluidity over other alloys at all degrees of superheat. Even though the fluidity is influenced by various factors including solidification mode, heat of fusion, surface tension, etc., the obtained result is believed mainly due to the high heat of fusion of Si[10]. Since the solidification mode of all investigated alloys is pasty type, a metal flow through a mold channel would be stopped by the solidification of the metal front. And the solidification should be delayed by a large amount of heat release from Si in the Al-12Mg-5.5Zn-5Si alloy. Surface tension is another important variable affecting the fluidity, however it is meaningful only when liquid metal flows through a very narrow mold channel. In most cases liquid metal is not wetted with mold material, and a back pressure is acting against the metal flow. Generally, the back pressure occurred in the fluidity test can be defined as $2\gamma/R$, where γ is the surface tension of liquid metal and R is the radius of a cylindrical flow channel. If the surface tension for pure Al (~868 mN/m) [11] is taken for γ in the equation, the pressure drop due to it would be about 1.16 kPa (R=1.5 mm). Since the suction pressure used is about 40 kPa, the effect of surface tension is not significant in the present fluidity test.

3.3. Wear Resistance of Al-12Mg-5.5Zn-xSi alloys

Fig. 9 shows an excellent wear resistance of Al-

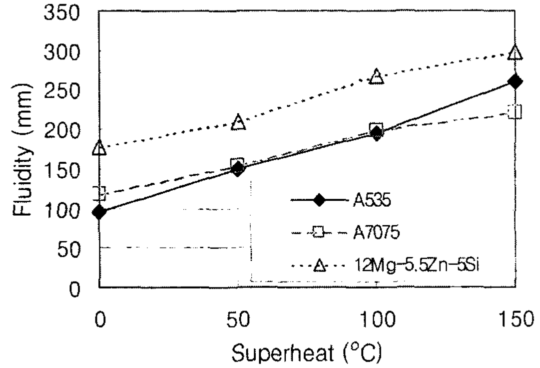

Fig. 8. Fluidity of Al-12Mg-5.5Zn-5Si and commercial Al alloys.

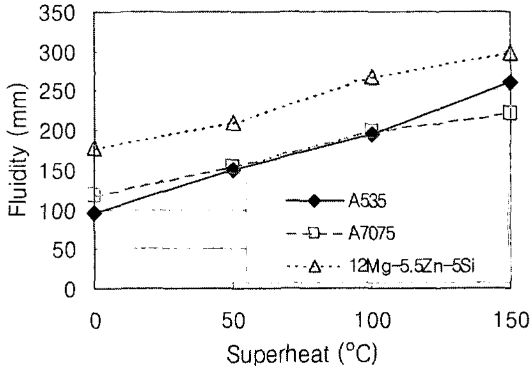

Fig. 9. Wear resistance and friction coefficient of Al-12Mg-5.5Zn-5Si and commercial Al alloys.

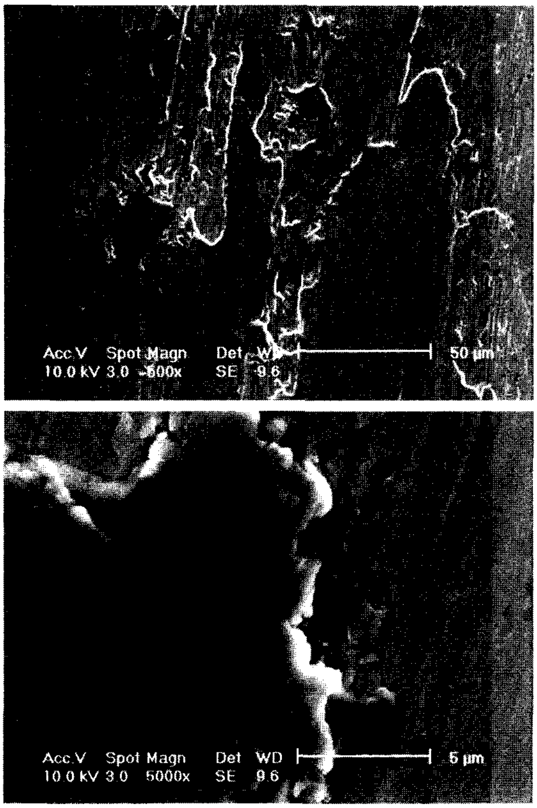

Fig. 10. SEM photographs of worn surfaces of Al-12Mg-5.5 Zn-5Si alloy.

12Mg-5.5Zn-5Si experimental alloy. Even though the microhardness of the experimental alloy is similar to the A7075's, the wear resistance (weight loss) of the alloy is apparently superior to both commercial alloys probably attributed to the hard primary Mg_2Si particles. The obtained friction coefficient of the alloy was also indistinctly smaller than the commercial alloys. SEM investigation on the worn surfaces of Al-12Mg-5.5Zn-5Si alloy was carried out and evidence of plastic flow and cracking was observed, as indicated in Fig. 10. It is suggested that cracks caused by severe plastic deformation grow large until a deformed layer of metal is removed and this process is repeated during the wear test. Even though more intensive investigation is necessary to fully understand the wear characteristics of the alloy, it is postulated that even higher wear resistance can be obtained by controlling the morphology and size of the Mg_2Si particles.

4. Summary

The plan for obtaining a good combination of strength and castability appeared feasible and the following observations were made.

1. In Al-12Mg-5.5Zn-xSi alloys, more primary Mg_2Si phase formed with reduced Al_3Mg_2 phase, as Si content increased. And somewhat high Si content is necessary for an effective solution heat treatment because the solidus temperature is very low at low silicon contents.

2. A high tensile strength could be obtained in the heat-treated Al-12Mg-5.5Zn-5Si alloy attributed to fine $MgZn_2$ particles that precipitated uniformly in the matrix.

3. Al-12Mg-5.5Zn-Si alloys showed excellent casting capabilities such as hot cracking resistance and fluidity compared to the reference commercial alloys.

4. The wear resistance of Al-12Mg-5.5Zn-5Si alloy was superior to that of A7075 alloy, and even higher resistance is expected if the morphology and size of primary Mg_2Si phase is carefully controlled.

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