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Effects of Alloying Additions and Cooling Rate on the Microstructures and Mechanical Properties of the Cast Al-Mg-Si Alloys

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Cast aluminum alloys are widely applied for the transportation industry. Alloys with silicon and magnesium as the main alloying elements are the most important of the aluminum casting alloys because of their high fluidity. However, Al-Si-Mg alloys have exhibited medium strength level at room and, especially, at elevated temperature. Recently, new casting alloys with high magnesium and silicon have been developed. The Al-Mg-Si alloys with the eutectic structure of α-Al + Mg_2Si are of practical interest due to their excellent strength and good fluidity comparable to Al-Si-Mg alloys. In the present work, the Al-Mg-Si alloys with various amounts of copper and/or nickel have been fabricated using the step mold in order to impose the different cooling rate. The effects of alloying elements and cooling rate on the microstructures and mechanical properties of Al-Mg-Si alloy have been investigated.

Keywords: *casting; Al-Mg-Si; Copper; Nickel; elevated temperature*

1. Introduction

Alloys with silicon as the main alloying element are the most important of the aluminum casting alloys mainly because of the high fluidity imparted by the presence of relatively large volume of the Al-Si eutectic. These age-hardenable Al-Si alloys usually doped with Mg, Cu, Zn, Fe, Ni, Mn and Ti exhibit good casting properties, excellent corrosion resistance and strength. Thus, they are widely used in the automotive industry to improve fuel efficiencies and to reduce vehicle emissions. However, components operating at elevated temperatures such as piston of high performance engine require mechanical properties which can hardly be reached for commercial Al-Si casting alloy systems [1, 2]. In addition, alternative commercial casting alloy system such as Al-Cu alloys exhibit higher strength at elevated temperatures but are limited in application due to poor casting properties.

Much attention has been paid on to develop new casting alloy systems which improve elevated temperature properties [1, 3]. Recently, new casting alloys with high magnesium and silicon have been developed. The Al-Mg-Si alloys with the eutectic structure of α-Al + Mg_2Si are of practical interest due to their excellent strength and good fluidity comparable to Al-Si-Mg alloys [3]. Copper is mainly added to increase the strength at room temperature by heat treatment and at elevated temperature through formation of compounds with iron, manganese and nickel [4]. Addition of nickel improves the elevated temperature properties of aluminum alloys [4].

In the present work, the Al-Mg-Si alloys with various amounts of copper and/or nickel have been fabricated in order to improve the mechanical properties at elevated temperature above 200^{o}C. The effects of alloying elements and cooling rate on the microstructures and mechanical properties of Al-Mg-Si alloy were investigated.

2. Experimental

Commercial pure Al, Al-20wt.% Si, Al-10wt.%Ni, Al-30wt.%Cu and pure Mg were used as starting materials. Al-7wt.%Mg-3wt.%Si was the base alloy, and addition of Cu and Ni varied to 0~4wt.% and 0~3wt.% to the base alloy, respectively. About 8 kg of the alloys were melted at 800^{o}C in a graphite crucible in an electric resistance furnace. The melt was degassed with Ar gas using GBF (gas bubbling filtration) for 15 minutes and poured into the metallic mold. Two types of metallic mold were used to impose the cooling rate. Fig. 1 shows the shape of the molds. The step mold is made by steel and the wall thickness of the mold varies from 25 to 43mm. The measured cooling rates of the step mold were approximately 4.5, 5.5, 9.0 and 20K/s, respectively. Water-cooling mold was made by copper.

Standard metallographic techniques were employed to examine the microstructures of the specimens. The microstructures were characterized using an optical microscope, a scanning electron microscope (JSM 5800) equipped with energy dispersive X-ray spectrometer (EDS). Measurement of lattice parameter was carried out using a Rigaku X-ray diffractometer (XRD) with Cu-Kα radiation at 40kV and 30mA. The mechanical properties of the specimens were evaluated by means of compression tests (strain rate of $7\times10^{-3}s^{-1}$) performed on polished specimens of 8mm in diameter and 12mm in length.

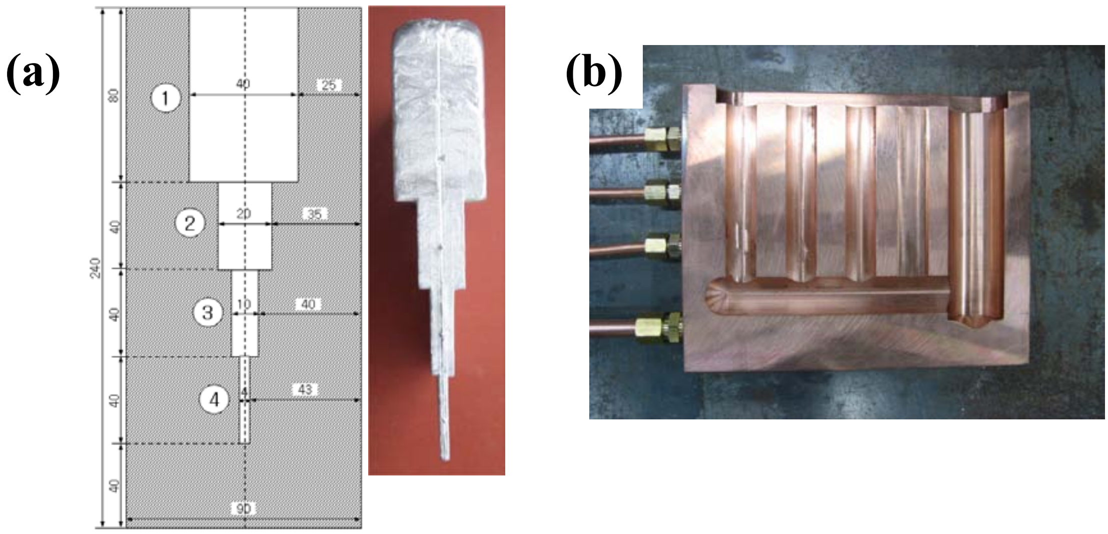


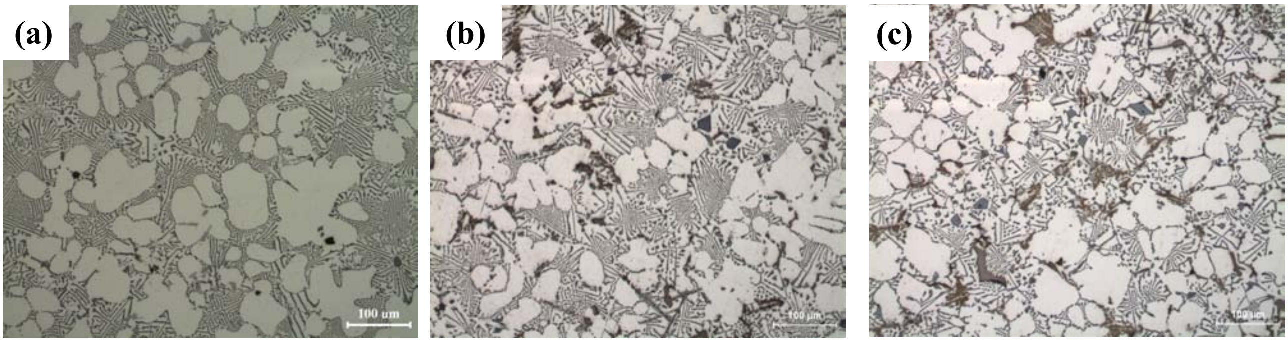
Fig. 1 Shapes of (a) the step-mold and (b) water-cooling mold.

3. Results and discussion

Figure 2 shows the as-cast microstructures of Al-7wt.%Mg-3wt.%Si with the addition of copper and nickel. In the base Al-Mg-Si alloy, the microstructure is composed of α-Al and eutectic Mg_2Si. With the addition of Cu and/or Ni new second phases were formed in the microsturctures. The phases were confirmed as Al_3Ni, CuMgAl and CuNiAl by the observation of SEM/EDS. In addition, with increasing Cu and/or Ni contents the formation of primary Mg_2Si is clearly observed.

Figure 3 shows the as-cast microstructures of Al-7wt.%Mg-3wt.%Si-0.5wt.%Cu-0.5wt.%Ni with cooling rate. With increasing cooling rate the microstructures become fine and especially the size of Al_3Ni. However, no significant change occurred for the volume fraction of Al_3Ni phase (Fig.4). Similar results were obtained for other alloys.

In the heat-treatable alloys such as Al-Cu, Al-Cu-Mg, Al-Mg-Si and Al-Mg-Si-Cu, the dissolved elements in aluminum exhibit a decreasing solubility with decreasing temperature. Accordingly, when the alloy is given a solution heat treatment and then quenched to room temperature, it will be supersaturated with respect to the dissolved elements and, consequently, will undergo structural transformations. The main hardening is occurred with the precipitation of θ”($CuAl_2$), S” ($CuMgAl_2$), β” ($MgSi_2$) and Q’ ($Cu_2Mg_8Si_6Al_5$) from solid solution of Al-Cu, Al-Cu-Mg, Al-Mg-Si and Al-Mg-Si-Cu alloy system, respectively [5-7].



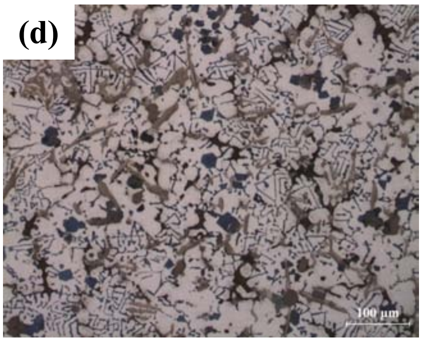
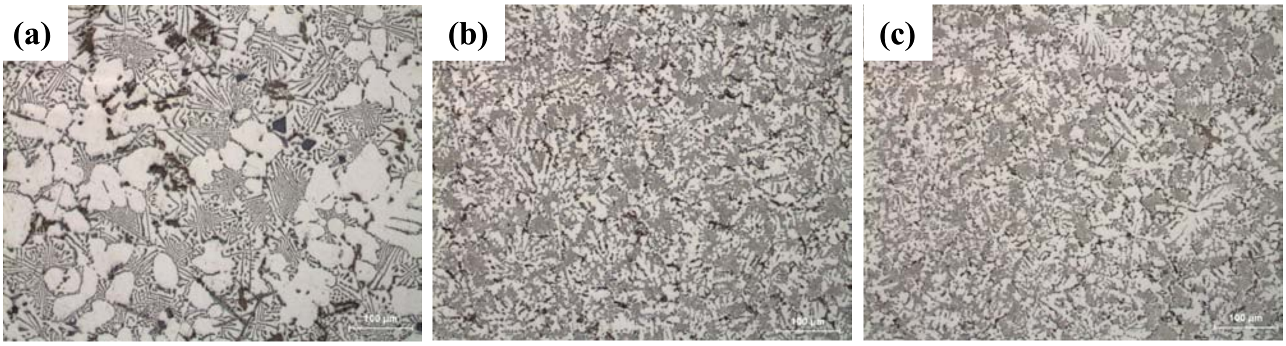


Fig. 2 as-cast microstructures of Al-Mg-Si-Cu-Ni
(a) base alloy (b) 0.5Cu-0.5Ni (c) 1Cu-1Ni (d)



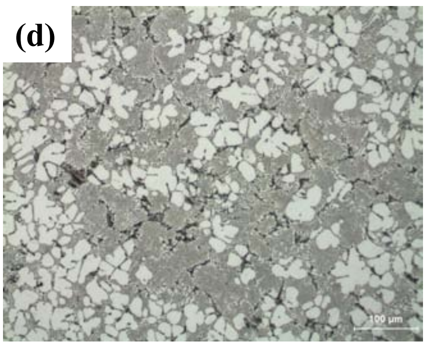


Fig. 3 as-cast microstructures of Al-Mg-Si-0.5Cu-0.5Ni with cooling rate
(a) step mold 1 (4.5K/s) (b) step mold 3 (9.0K/s)
(c) step mold 4 (25.0K/s) (d) water-cooling mold

In the Al-Mg-Si alloys with addition of Cu and/or Ni some alloying elements can be dissolved into aluminum. Lattice parameters were measured with different cooling rate by X-ray diffraction method (Table1). The lattice parameter increased with increasing cooling rate and somewhat differs with addition of Cu and/or Ni. This means that some alloying elements dissolved in aluminum to form solid solution during solidification. Among the element atomic radius of Si, Ni and Cu is smaller than Al while that of Mg is bigger than Al [4]. Thus, some Mg element is expected to be dissolved in aluminum with other alloying element. The dissolved elements can be precipitated during subsequent heat treatment.

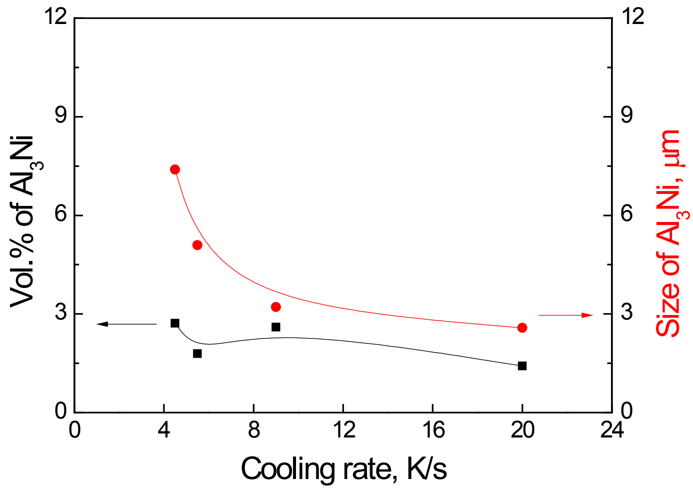


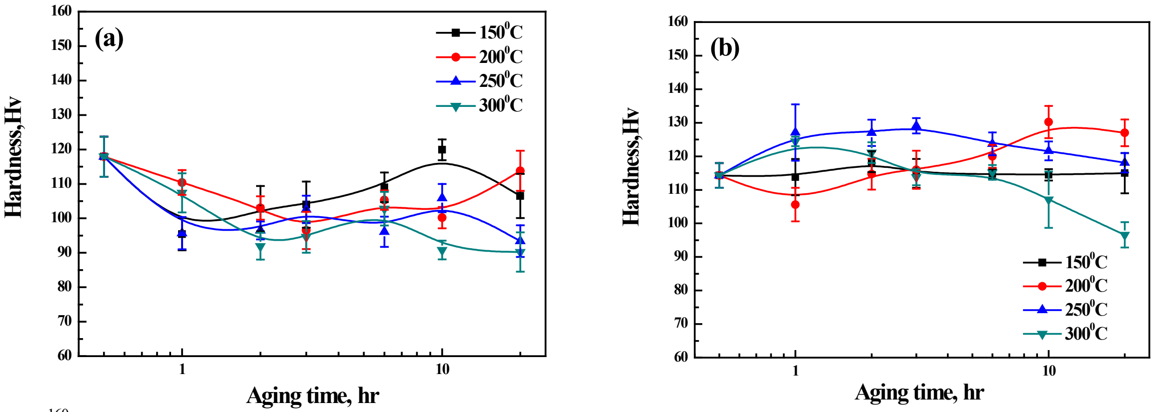
Fig. 4 Vol.% and size of Al_3Ni for as-cast Al-Mg-Si-0.5Cu-0.5Ni

Table 1. Lattice parameter for Al-Mg-Si alloys

Alloy	condition	Lattice parameter (A)	Alloy	condition	Lattice parameter (A)
Base (step mold1)	as-cast	3.999	4Cu-3Ni (step mold1)	as-cast	4.0558
Base (water-cooling)	as-cast	4.0754	4Cu-3Ni (step mold4)	as-cast	4.0539
0.5Cu-0.5Ni (step mold1)	as-cast	3.998	4Cu-3Ni (water-cooling)	as-cast	4.0802
0.5Cu-0.5Ni (water-cooling)	as-cast	4.0983	4Cu-3Ni (step mold1)	150^oC/6hr	4.0557
2Cu-2Ni (step mold1)	as-cast	4.0142	4Cu-3Ni (step mold1)	200^oC/6hr	4.0523
2Cu-2Ni (water-cooling)	as-cast	4.0813	4Cu-3Ni (step mold1)	300^oC/20hr	4.0245

Figure 5 shows the variation of hardness with ageing time/temperature for as-cast Al-Mg-Si alloys. The hardness changed with ageing temperature and time, however, the age hardening effect is not significant. The age hardening/softening is associated with the precipitation and coarsening of Mg containing precipitates. Fig. 6 shows the DSC traces for the Al-Mg-Si alloy containing 4wt.%Cu and 3wt.%Ni in as-cast and heat-treated conditions. One exothermic peak associated to phase formation/precipitation phenomena and one endothermic peak, related to dissolution phenomena, was observed. In the low temperature aged specimens below 200^oC, the two peaks were still observed while above 250^oC the peaks were disappeared. This means that the precipitation hardening and softening occur around 250^oC. The lattice parameter of heat-treated specimens (Table1) also confirms the precipitation and coarsening of Mg containing precipitates; the lattice parameter decreases with increasing ageing temperature. It needs further clarification for the exact precipitates formed in Al-Mg-Si alloy containing Cu and/or Ni.

The ultimate compressive strength of the Al-Mg-Si alloys is exhibited in Fig. 7 along with the A356(Al-Si-Mg) alloy. The strength is increased with Cu and/or Ni, and maintained good stability up to 200^oC compared to A356 alloy. Fig. 7 (b) compares the variation of hardness with holding at 250^oC up to ten days for Al-Mg-Si alloys. The hardness of A356 sharply decreased for 2-3 days while the Al-Mg-Si alloys maintained their hardness up to 10 days. In general, strength at elevated temperatures is improved mainly by solid-solution and second phase hardening because for temperatures exceeding those of the precipitation hardening range, the precipitation reactions continue into the softening regime.



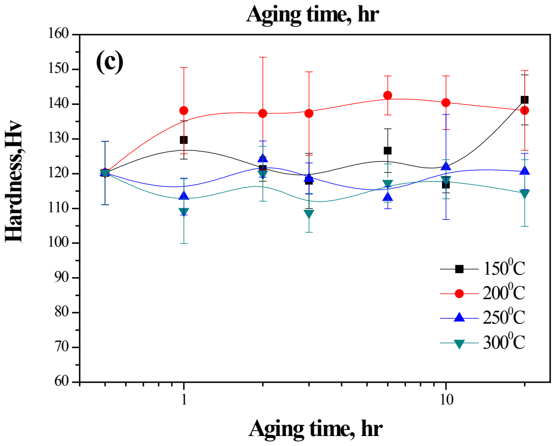


Fig. 5 variation of hardenss
(a) 1Cu-1Ni (step mold 1: 4.5K/s)
(b) 1Cu-1Ni (water-cooling mold)
(c) 4Cu-3Ni (step mold 1: 4.5K/s)

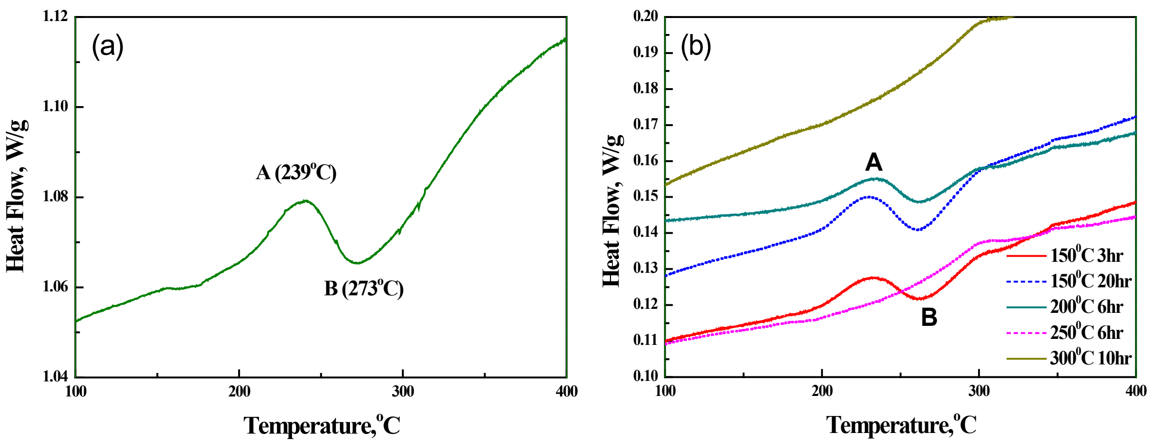


Fig. 6 DSC traces for 4Cu-3Ni alloy: (a) as-cast and (b) heat treated.

The main hardening of A356 alloy is precipitation of β" ($MgSi_2$) phase while the main hardening of Al-Mg-Si alloys is second phase hardening and the contribution of precipitation hardening is not significant, thus the elevated temperature properties of the Al-Mg-Si alloys are better than those of A356 alloy.

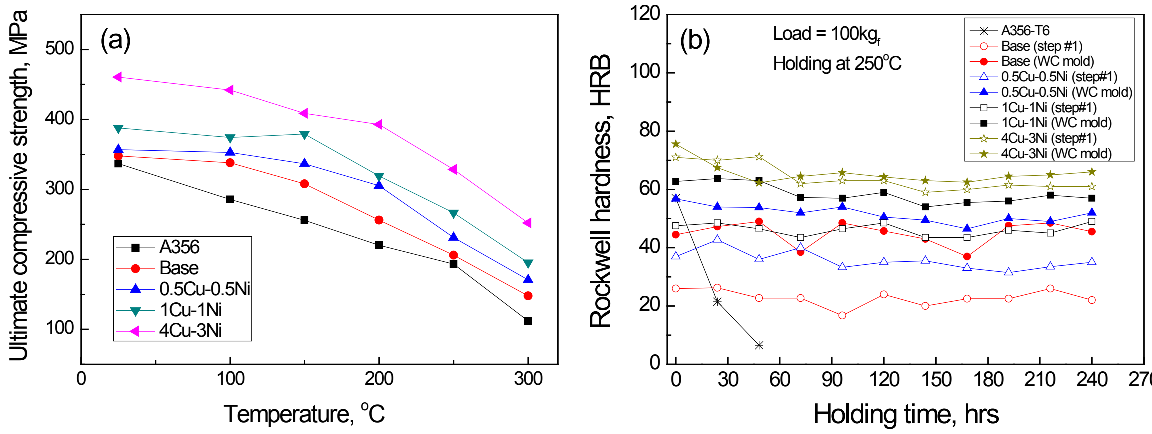


Fig. 7 (a) compressive strength and (b) rockwell hardness for Al-Mg-si alloys.

4. Summary

In the Al-Mg-Si alloy, the microstructure was composed of α-Al and eutectic Mg_2Si. With the addition of Cu and/or Ni new second phases such as Al_3Ni, CuMgAl and CuNiAl were formed in the microsturctures. With increasing cooling rate the microstructures become fine and the size of Al_3Ni decreased. During solidification of the Al-Mg-Si-Cu-Ni alloys some alloying elements were dissolved into aluminum and precipitated during subsequent heat treatment. However, the age hardening effect was not significant. The ultimate compressive strength and the elevated temperature stability of the Al-Mg-Si alloys improved with the addition of Cu and/or Ni, and their properties were better than A356 alloy.

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