The Effects of Ni on Tensile Properties of Al-6Si-0.5Mg Cast Alloys During Precipitation Hardening

A. Hossain*, A. S. W. Kurny

Bangladesh University of Engineering and Technology, Department of Materials and Metallurgical Engineering, Dhaka 1000, Bangladesh

*Corresponding Author: ah_buetmmesgfl@live.com

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Abstract The microstructure, tensile properties and fracture behavior of the Al-6Si-0.5Mg and Al-6Si-0.5Mg-2Ni cast alloys were investigated and the results showed that the Mg_2Si , Al_3Ni and Si hard particles produced by precipitation hardening have great effects. The homogenized (24hr at 500°C) and solutionized (2hr at 540°C) cast alloys were subjected to ageing treatment from room temperature to 300°C. The yield strength and fracture strength of the alloys increased with the ageing temperature and maximum at peakaged condition (1hr at 225°C) where as ductility and impact toughness decreased with ageing temperature reaching the minimum at the peakaged condition. The properties of Ni content and Ni free Al-6Si-0.5Mg alloys were found to exhibit marked differences depending on the intermetallic phases and the heat treatment conditions. SEM-analysis revealed the existence of Al_3Ni -phases and the microstructure of broken tensile specimens show both the particle fracture and interface de-bonding affect the fracture behavior of the alloys.

Keywords Tensile properties, Al_3Ni particle, Precipitation hardening, Fracture behavior, SEM

1. Introduction

Al-Si based multi-component foundry alloys provide several advantageous characteristics such as good castability, high corrosion and wear resistance as well as high thermal conductivity and adequate strength at elevated temperatures [1]. Al-Mg-Si alloys have been widely used in transportation systems owing to their fair strength, weldability and corrosion resistance. The precipitation sequence of solution-treated Al-Mg-Si ternary alloys during artificial aging can be reported to be: α supersaturated solid solution (SSS) $\rightarrow$ GP-I zones $\rightarrow$ metastable needle-like β'' precipitates (or called GP-II zones; formed through the transformation of GP-I as nuclei) $\rightarrow$ metastable rod-like (or lath-like) β' precipitates $\rightarrow$ stable β phase [2].

When a heat-treatable A356 aluminum alloy undergoes

precipitation hardening (age-hardening), fine precipitants will dissolve completely in saturated matrix to achieve high strength in material [3]. The supersaturated solid solution undergoes aging treatment; a large amount of small and uniformly distributed precipitants will appear thus the mechanical properties of the material can be improved. Uniform and delicate Mg_2Si precipitants can be obtained in the matrix of a heat-treatable Al-Si-Mg casting part with T6 treatment (which involves solution treatment, quenching and artificial aging), leading to improvements in its tensile strength, elongation and toughness [4, 5].

Additions of Ni lead to the formation of Al_3Ni in the aluminum matrix through eutectic reaction during solidification. In previous work Ni was identified to significantly enhance the high-temperature performance of Al-Si foundry alloys, though just to a certain level, depending on the fraction of eutectic phase in the alloy. Ni stabilizes the contiguity of the eutectic network by increasing the volume fraction of rigid phases (Si + Al_3Ni) in the eutectic [6-9]. Heat treatment (HT) is a commonly used technique to enhance the mechanical properties of the respective alloys, such as strength (HT: T6) or ductility (HT: T4, T7). However, during a solution treatment the eutectic Si spheroidizes and its aspect ratio decreases, which results in a loss of the contiguity of the eutectic platelets [6, 10].

The objective of this research work was to study the effects of Ni on tensile properties of Al-6Si-0.5Mg cast alloy under various ageing conditions.

2. Materials and Methods

The Ni free Al-6Si-0.5Mg and Ni added Al-6Si-0.5Mg-2Ni alloys were used in this study. The alloys were prepared in a natural gas heating clay-graphite crucible furnace. In the process of preparation of the alloys the commercially Al-Si binary alloy and pure aluminium (99.7% purity) were taken as the starting material. The Ni chips were charged into the bottom of furnace. Then the aluminium and aluminium-silicon binary alloy melted into the clay-graphite crucible, and then magnesium ribbon (99.7% purity) was added into solution. The final temperature of the melt was

always maintained at $910 \pm 15^\circ\text{C}$ with the help of the electronic controller. The melt was degassing with solid hexachloroethane (C_2Cl_6) and homogenized by stirring at 690°C before casting. Casting was done in metal moulds preheated to 200°C . Mould sizes were $15\text{mm} \times 150\text{mm} \times 300\text{mm}$. All the alloys were analysed by wet chemical and spectrochemical methods simultaneously. The compositions of the samples are shown in Table 1.

The cast samples were first ground properly to remove the oxide layer from the surface. All the alloys were homogenized at 500°C for 24 hours. The tensile and impact specimens were prepared from the homogenized alloys according to ASTM standard of aluminum alloys. The homogenized samples were solution treated at 540°C for 2 hours and quenched into salt iced water solution. The solutionized samples were aged isochronally for 1 hour at different temperatures up to 300°C . Tensile testing was carried out in an Instron testing machine at strain rates of $10^{-3}/\text{s}$. The averages of three consistent test results were accepted as the tensile test values for the corresponding sample. The Charpy impact test sample has $10\text{mm} \times 10\text{mm} \times 55\text{mm}$ dimensions, a 45°V notch of 2 mm depth and a 0.25 mm root radius was hit by a pendulum at the opposite end of the notch. The pendulum was set at a certain height was released and stuck the specimen at the opposite end of the notch to produce a fractured sample. The absorbed energy required to produce two fresh fracture surfaces were recorded in the unit of Joule. Scanning Electron Microscopy (SEM) with Energy Dispersive Spectroscopy (EDS) of selected sample was observed in a Scanning Electron Microscope.

3. Results and Discussion

3.1. Effects of Ni on Yield strength

Fig.1 illustrates the effect of Ni on the yield strength (0.2% proof strength) of Al-6Si-0.5Mg cast alloy at various ageing temperatures. The graph indicates that the yield strength of Ni containing alloy (Al-6Si-0.5Mg-2Ni) higher than Ni free alloy (Al-6Si-0.5Mg) all over the ageing conditions except aged at 200°C . With increase of ageing temperature, more intermetallic reinforcement particles are in stable form. The Al-6Si-0.5Mg-2Ni alloy shows 47.73% higher yield strength

than the Al-6Si-0.5Mg alloy over the solution treated condition. At peak aged condition (1 hr at 225°C) Al-6Si-0.5Mg-2Ni alloy shows 27.35% higher yield strength than Al-6Si-0.5Mg alloy and 14.62% over the solutionized condition. The intermetallic particles could contribute as a reinforcement effect in the Al-alloy matrix. The higher yield strength is due to the effect of precipitation hardening.

Figure 1. Effects of Ni addition on the yield strength of Al-6Si-0.5Mg cast alloys at various ageing conditions

3.2. Effects of Ni on Fracture strength

The ultimate tensile strength (Fig.2) follows the same trend as the yield strength of Al-6Si-0.5Mg and Al-6Si-0.5Mg-2Ni alloys. There is an increase of 34.55% fracture strength of Ni containing Al-6Si-0.5Mg-2Ni alloy than the Al-6Si-0.5Mg alloy over the solution treated condition. At peak aged condition (1 hr at 225°C) Al-6Si-0.5Mg-2Ni metal alloy is 20.95% higher fracture strength over the solution treated condition and 25.17% higher over the peakaged Al-6Si-0.5Mg alloy. Further ageing (250°C and 300°C) beyond the peakaged condition, the fracture strength and yield strength for both the alloys decrease due to overage.

Table1. Chemical composition of the experimental alloys (wt %)

Alloy	%Si	%Mg	%Cu	%Ni	%Fe	%Mn	%Ti	%Al
Al-6Si-0.5Mg	5.802	0.441	0.006	0.006	0.146	0.002	0.099	Bal
Al-6Si-0.5Mg-2Ni	5.935	0.440	0.007	2.220	0.141	0.003	0.088	Bal

Figure 2. Effects of Ni addition on the fracture strength of Al-6Si-0.5Mg cast alloys at various ageing conditions.

3.3. Effects of Ni on ductility (% elongation)

The effect of Ni addition on ductility (% elongation) of Al-6Si-0.5Mg alloy at various ageing temperatures is shown in fig.3. The Ni containing Al-6Si-0.5Mg-2Ni alloy shows lower ductility than the Ni free Al-6Si-0.5Mg alloy at all ageing conditions. The % elongation of Al-6Si-0.5Mg-2Ni alloy is 30.77 % lower than the Al-6Si-0.5Mg alloy at the peakaged condition. Beyond the 225°C the ductility increases with ageing temperature for both alloys.

Figure 3. Effects of Ni addition on the ductility (% elongation) of Al-6Si-0.5Mg cast alloys at various ageing conditions.

3.4. Effects of Ni on Impact toughness

Fig. 4 shows the Ni free and Ni content Al-6Si-0.5Mg alloys absorbed energy as a function of the artificial ageing temperature. At solution treated condition, the Ni containing Al-6Si-0.5Mg-2Ni alloy has shown lower toughness than the Ni free Al-6Si-0.5Mg alloy at all ageing conditions. The toughness of the Al-6Si-0.5Mg-2Ni alloy has reduced maximum at peakaged condition and minimum at solution treated condition. With the ageing temperature increases from room temperature to 225°C, the absorbed energy decreases for the alloys. The absorbed energy decreased a

maximum due to the precipitation of intermetallic phases at peakaged condition. Further ageing (225 & 300°C) the absorbed energy increases due to overage.

3.5. Tensile and impact Fracture Surfaces Analysis

Fig. 5, 6 and 7 shows the fracture surface of Al-6Si-0.5Mg and Al-6Si-0.5Mg-2Ni alloys at peakaged condition. The fracture surfaces appear to be rough and normal to the axis of loading. On a microscopic scale, the fracture surfaces appear to contain many microvoids in the matrix. The void coalescence occurs when the voids elongate to the initial inter void spacing. This leads to the dimpled appearance on the fracture surfaces. The dimples are neither uniform nor circular in shape. The matrix-intermetallic particles decohesion is also observed for these alloys. The fracture mechanism is ductile, involving the nucleation, growth, and coalescence of voids in the matrix around the intermetallic particles. The voids grow under both the applied load and the influence of local plastic constrain until a coalescence mechanism is activated, and this followed by the total failure of the alloys.

Figure 4. Effects of Ni addition on the impact absorbed energy of Al-6Si-0.5Mg cast alloys at various ageing conditions

Figure 5. SEM tensile fracture surface of Al-6Si-0.5Mg alloy at peak aged condition.

Figure 6. SEM tensile fracture surface of Al-6Si-0.5Mg-2Ni alloy at peak aged condition.

b. EDS analysis of spot1

Figure 7. Fracture surface of impact Al-6Si-0.5Mg-2Ni alloy at peak aged condition (1 hr at 225°C)

c. EDS analysis of spot2

a. SEM image of Al-6Si-0.5Mg-2Ni cast alloy.

d. EDS analysis of spot3

e. EDS analysis of spot4

Figure 8. SEM image (a) and EDS spot analysis (b, c, d & e) of Al-6Si-0.5Mg-2Ni alloy at peakaged condition.

3.6. SEM with EDS Spot Analysis

The Fig.8 illustrating the scanning electron image with EDS spot analysis of the peakaged Al-6Si-0.5Mg-2Ni alloy. Al is present both in solid solution with the matrix and precipitates. Mg and Si combine to form a compound of Mg_2Si , which in turn forms a simple eutectic system. The microstructure of peakaged Al-6Si-0.5Mg-2Ni composite reveals particles of intermetallic and precipitated during the heat treatment. The EDS analysis (spot4) indicates the presence of Ni containing compound Al_3Ni .

4. Conclusions

Addition of 2 wt.% Ni to the Al-6Si-0.5Mg cast alloy resulted in improved strength and reduced ductility. The

yield and fracture strength of Ni containing Al-6Si-0.5Mg-2Ni alloy were higher than the Ni free Al-6Si-0.5Mg alloy over the solution treated and peakaged condition. At peakaged condition, 2wt. % Ni addition to Al-6Si-0.5Mg improved the strength maximum but reduced the ductility and impact toughness significantly. The SEM with EDS spot analysis reports confirm the presence of Al, Ni, Si and Mg containing precipitates in the Al-6Si-0.5Mg-2Ni alloy.

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