Effects of Copper and Magnesium on Microstructure and Hardness of Al-Cu-Mg Alloys

N. Nafsin, H. M. M. A. Rashed

Abstract*—Aluminum alloys with a wide range of properties are used in engineering structures. Selecting the right alloy for a given application entails considerations of its tensile strength, density, ductility, formability, workability, weldability, and corrosion resistance, to name a few. Aluminum alloys are used extensively in aircraft due to their high strength-to-weight ratio. On the other hand, pure aluminum metal is much too soft for such uses, and it does not have the high tensile strength that is needed for airplanes and helicopters. Thus various alloying elements are added to aluminum to enhance the mechanical properties of aluminum. Copper has been the most common alloying element almost since the beginning of the aluminum industry, and a variety of alloys in which copper is the major addition were developed. Magnesium (Mg) used to strengthen and harden aluminum castings. The current research emphasizes establishment of relationship between microstructure and cold deformation behavior of aluminum-copper -magnesium alloys. Aluminum-copper-magnesium alloys with varying Cu% and Mg% were casted and their chemical compositions were determined using Optical Emission Spectroscopy (OES). These alloys undergone cold deformation after homogenization and their microstructures were examined using optical microscope. Finally the effects of deformations were studied by measuring the hardness of those alloys.

***Index Terms*— Aluminum alloy, microstructure, cold deformation, hardness.**

I. INTRODUCTION

Aluminum alloys are alloys in which aluminum is the predominant metal. The typical alloying elements are copper, magnesium, manganese, silicon and zinc. There are two principal classifications, namely casting alloys and wrought alloys, both of which are further subdivided into the categories heat-treatable and non-heat-treatable. About 85% of aluminum is used for wrought products, for example rolled plate, foils and extrusions. Cast aluminum alloys yield cost effective products due to the low melting point, although they generally have lower tensile strengths than wrought alloys. Aluminum alloys are widely used in engineering structures and components where light weight or corrosion resistance is required [1].

The most important cast aluminum alloy system is Al-Cu. The addition of copper as main alloying element (mostly range 3–6 wt. %, but can be much higher), with or without magnesium as alloying constituent (range 0–2 %), allows material strengthening by precipitation hardening, resulting in very strong alloys. Also the fatigue properties are very good for this series. The presence of copper is however very bad for the corrosion resistance. Copper tends to precipitate at grain boundaries, making the metal very susceptible to pitting, intergranular corrosion and stress corrosion [2]. These copper rich zones are more noble/cathodic than the surrounding aluminum matrix and act as preferred sites for corrosion through galvanic coupling. Copper is also very bad for anodizing. Copper precipitates dissolve in the anodizing electrolytes (acid electrolytes for porous film formation) leaving holes in the oxide, and solute copper migrates under the high electric field towards the aluminum/oxide interface compromising the anodic film properties.

Up to 12 wt. % copper the strength of the alloy can increase through precipitation hardening, with or without the presence of Mg; Hardening is achieved through the precipitation of Al_2Cu or Al_2CuMg intermetallic phases during ageing which leads to strengths second only to the highest strength 7xxx series alloys [2]. Above 12 wt. % Cu the alloy becomes brittle. Copper also improves the fatigue properties, the high-temperature properties and the machinability of the alloy. These alloys are used for high strength structural applications such as aircraft fittings and wheels, military vehicles and bridges, forgings for trucks, etc [2, 3]. The main benefit of adding magnesium to aluminum-copper alloys is the increased strength and hardness possible following solution heat treatment and quenching [2]. Environmental legislation to reduce emission of greenhouse gases is forcing transportation industries to find out substitutes of steels – currently profoundly used in vehicle production. Aluminum, being lighter than steel, is considered as an exciting alternative material in such applications. Different aluminum alloys are being prototyped by varying composition and by developing suitable microstructure with different heat treatment schedules. The current work is focused on microstructural effects on deformation of aluminum alloys. Aluminum alloys of different compositions were casted and homogenized at 400 ºC for four hours.

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Then microstructures of as cast and homogenized alloys were observed. Alloys were compression up to different levels.

II. EXPERIMENTAL PROCEDURE

Alloys were prepared by casting pure aluminum (99.8%) with electrolytic copper (99.9%) and magnesium ribbons in a pit furnace at predetermined weight percentages followed by pouring into a permanent metal mold (preheated to 200 ^{o}C) to make bars of size 200x50x80 cm. The compositions of the alloys were determined using Optical Emission Spectrometer (Shimadzu PDA 700). CALPHAD method was used to predict the phases developed in these alloys [4-9].

The samples were cut into small pieces for homogenization treatment at 400 ^{o}C for four hours in a BlueM Electric furnace.

For microstructural observation, specimens were cut into 25 mm^3 size and ground and polished using conventional metallographic techniques. The microstructures were observed in un-etched condition using Optica B-600 MET trinocular upright metallurgical microscope and images of same resolution were acquired using OpticaTM Vision Pro software package.

The casted alloys were deformed by compression to different levels: 10%, 20% and 50% in a Universal Testing Machine. Hardness values were measured by using a standard Rockwell Hardness testing machine in HRF scale with a 60 kg load and using 1/16" diamond indenter.

III. RESULTS AND DISCUSSION

The chemical composition of as cast alloys was determined by Optical Emission Spectroscopy (OES). Table 1 shows the chemical composition of alloys used in current work.

Table 1: Chemical composition of as cast aluminum alloys

Alloy	Fe	Si	Cu	Mg
Al-4%Cu	0.07	0.08	3.69	0.06
Al-4%Cu-1%Mg	0.10	0.05	3.51	0.30
Al-4%Cu-2%Mg	0.08	0.13	4.03	0.59
Al-6%Cu	0.06	0.12	6.16	0.06
Al-6%Cu-1%Mg	0.02	0.09	5.45	0.55
Al-6%Cu-2%Mg	0.09	0.12	6.45	0.76

Each alloy was homogenized at 400 ^{o}C for 4 hours. After holding for 1 hour, samples were quenched in water to retain the precipitates.

A. Relationship between heat treatment and microstructure

Fig. 1 shows hardness of as cast and homogenized aluminum alloys containing 4%Cu-2%Mg. It clearly reveals that, there is little decrease in hardness values after homogenization treatment. This may be due to the fact that after homogenization at 400 ^{o}C some of the magnesium bearing phases (Mg_2Si and Al_2CuMg) goes into solution in the matrix as obtained from CALPHAD analysis, shown in Fig. 2. Since magnesium improves hardness and strength in aluminum alloys [2], such a decrease in magnesium containing phase reduces the hardness than that of as cast condition.

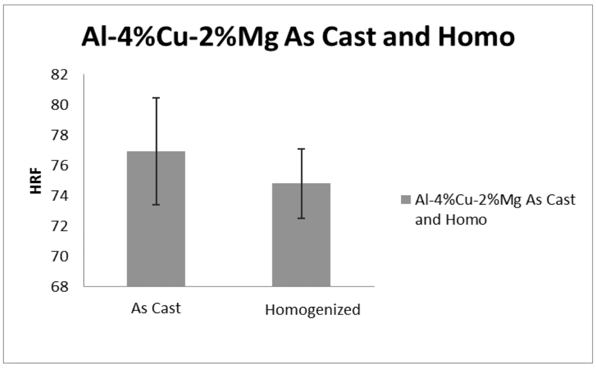

Figure 1: Effect of heat treatment on hardness of Al-Cu-Mg alloy

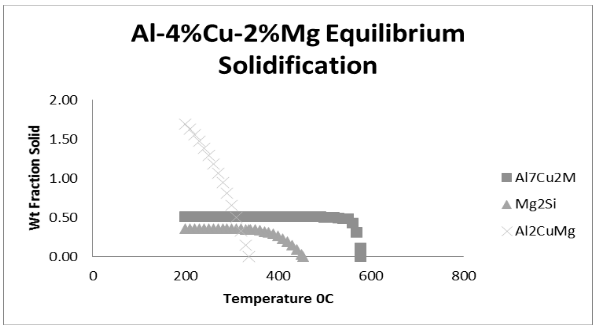

Figure 2: Change in fraction solid wt % with temperature of Al-4%Cu-2%Mg

B. Relationship between alloying elements and hardness

In order to observe the effect of copper in aluminum alloy, two alloys (Al-4%Cu and Al-6%Cu both in as cast and homogenized condition) were compared. It was found that hardness of aluminum alloys increases with Cu% in both as cast and homogenized condition due to the increase of Cu bearing phase Al2Cu (obtained from CALPHAD analysis as shown in Fig. 3) in the microstructure. This increase in hardness is shown in figure 5. The effect of homogenization is also revealed for both alloys from Fig. 4. There is little decrease in hardness values after homogenization treatment. This is due to the same reason described above.

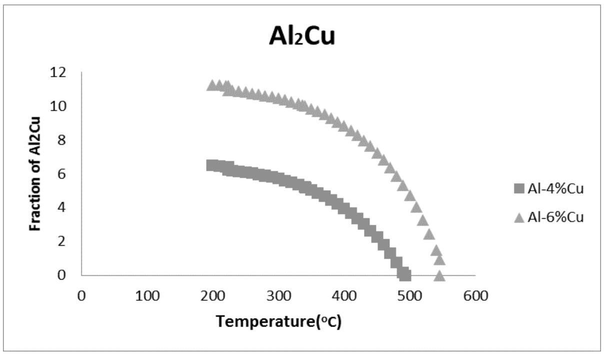

Figure 3: Fraction of Al_2Cu in aluminum copper alloy with temperature

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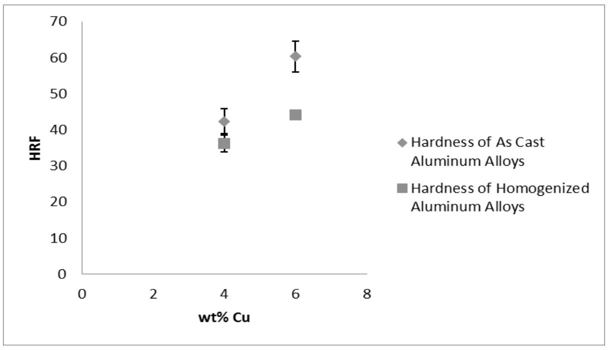

Figure 4: Effect of Cu % and heat treatment on hardness of aluminum copper alloys

Magnesium tends to increase hardness in aluminum alloys. This effect was also observed in the present study. Magnesium content was varied from 0, 1 and 2 % in Al-6%Cu alloy. It was found that with increasing Mg%, magnesium containing phases continues to increase (from CALPHAD analysis in Fig. 5) and thus results a change in microstructure and hardness.

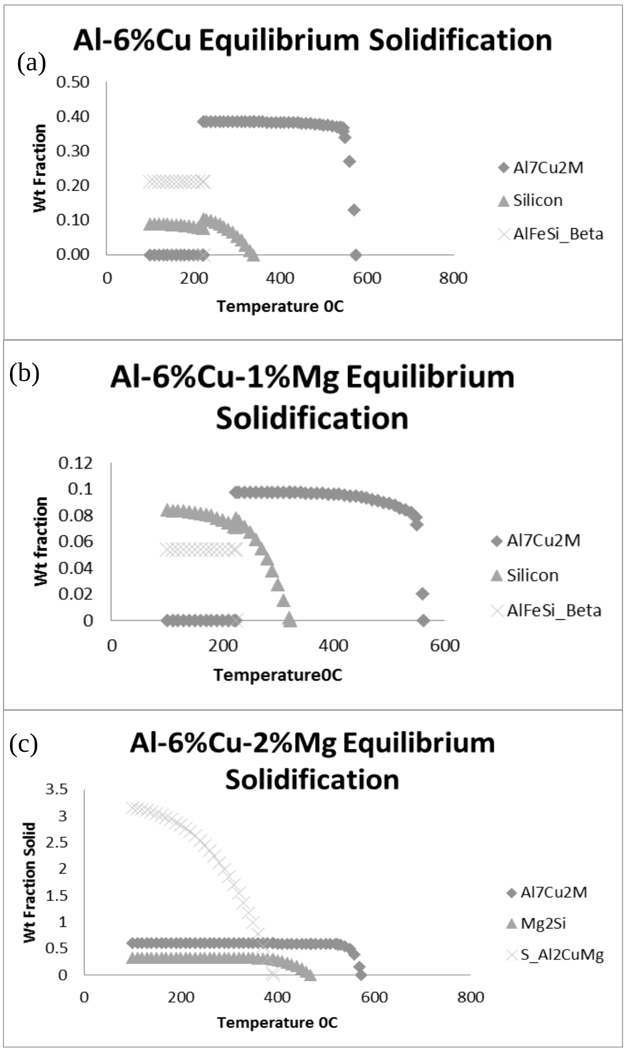

Figure 5: Formation of Mg containing phases with increasing Mg content in (a) Al-6%Cu (b) Al-6%Cu-1%Mg (c) Al-6%Cu-2%Mg

This increase in Mg content results formation of new phases in microstructure (Fig. 6) as indicated by some black phases present on copper bearing phase in Al-6% Cu alloys.

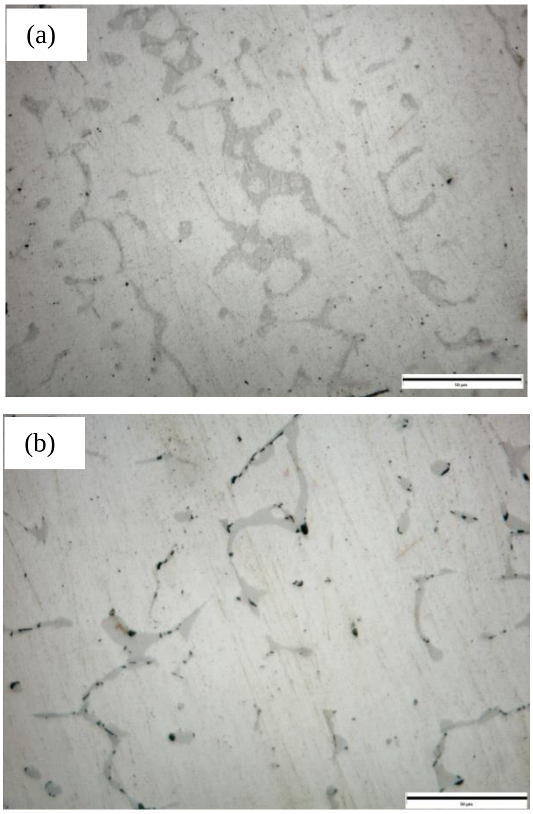

Figure 6: Microstructure of Al-6%Cu with (a) 0%Mg (b) 2%Mg

Thus addition of magnesium results in an increase in magnesium containing phase and therefore increases hardness (Fig. 7). This behavior was also observed earlier [2, 14].

After deformation of the homogenized alloys to 10%, 20% and 50%, a large increase in hardness was evident. For each alloy, hardness was increased with increasing the amount of total deformation. Fig. 8 shows the effect of deformation on hardness. This increase in hardness is due to the presence of stored energy in the microstructure due to increase of dislocation density. Deformation increases the number of dislocations by interactions of dislocation during deformation and other defects, which cause an enhancement of hardness values [9-13]. Deformation also attributes a change in microstructure. It was observed that for each alloy the initial necklace like phases (Al_2Cu and Al_7Cu_2M) were destructed with the extent of deformation. As the amount of deformation increases, phases those provide an increase in hardness are no longer being in a continuous form, thereby have little significance in increasing hardness.

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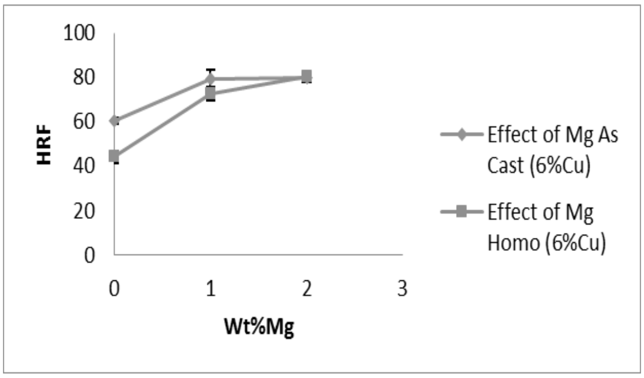

Figure 7: Effect of magnesium content on hardness of Al-Cu alloy

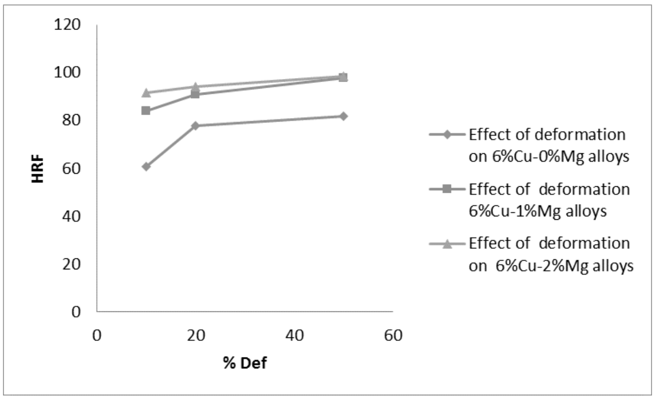

Figure 8: Effect of deformation on hardness of aluminum copper magnesium alloys

IV. CONCLUSION

(i) With increasing amount of deformation, hardness continues to increase for different magnesium addition. Also, the higher the magnesium content, the greater the hardness.

(ii) Deformation causes an increase in hardness than non-deformed homogenized alloy due to changes in dislocation density. Deformation increases the number of dislocations by interactions of dislocation during deformation and other defects, which cause an enhancement of hardness values. High dislocation density results in a large number of dislocation interactions which results in high strength and hardness.

(iii) Deformation also changes the microstructure by destroying the necklace like shape of Al-Cu-Mg phases. For this reason, with larger amount of deformation, the increment of hardness may not be very significant.

(iv) Addition of copper and magnesium results an increase in hardness of homogenized aluminum-copper-magnesium alloy.

(v) Homogenization causes dissolution of low melting point phases in the matrix and thus reduces hardness of aluminum alloys.

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