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Studies on the Artificial Ageing and Microstructure of the Al-6Si-0.5Mg Alloys with Copper Addition at Various Levels

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Abstract

The influence of Cu content on the artificial age hardening and microstructure of Al-6Si-0.5Mg-xCu (x = 0.5%, 1%, 2% and 4%) was investigated. Different amounts of copper were added to molten Al-Si-Mg master alloy. Molten alloys at 700°C were cast in a metal mold. The solution treatment was performed at 540°C for 2h and then the specimens were quenched in ice salt water. The samples were aged isochronally for 60 minutes at temperatures up to 400°C and isothermally at 225°C for different periods in the range 15 to 360 minutes. Hardness of the alloys was measured to study the age hardening effect due to copper addition. Resistivity changes with annealing time at 225°C were measured to understand the precipitation behaviour of the alloys. The microstructure was examined using an optical microscope and a scanning electron microscope. Maximum hardness of the solution treated alloys increased with an increase in Cu content. However, copper in amounts of more than 2% did not cause significant increase in hardness during artificial ageing at 225°C. The hardness of matrix increases due to precipitation hardening. The microstructural investigations show that the shape of the eutectic Si particles changes to granular type in all alloys after heat treatment.

Keywords: *Al-Si-Mg-alloys, Cu content, Hardness, Age hardening, Resistivity.*

1. Introduction

Aluminium-silicon cast alloys are widely used in the automotive industry due to their outstanding castability, good wear resistance and low thermal expansion, together with their low specific weight. These properties lead to the application of Al-Si alloys in automotive industry, especially for cylinder blocks, cylinder heads, pistons and valve lifters [1-3].

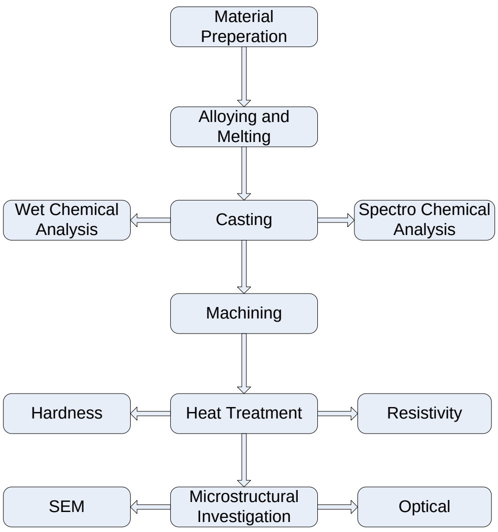
The quality of microstructure of Al-Si alloys depends on chemical composition, alloying elements, melting process, casting process and solidification rate. The mechanical properties of cast Al-Si alloy parts largely depend on grain size and its morphology, dendrite arm spacing (DAS), size and distribution of secondary phases [4]. As DAS decreases, structural refinement takes place which leads to improvement in mechanical properties [5]. Addition of Mg and Cu to Al–Si alloys increases strength and reduces ductility [6, 7]. For Al–Si–Mg and Al–Si–Cu–Mg alloys, a heat treatment consisting of solution treatment, quenching and ageing is often used to increase the strength by precipitating nanometer particles, which provide excellent obstacles for the dislocation movement [8]. For Al–Si–Mg alloys, the age hardening is caused by the precipitation of β'' and/or β' phases (precursor of Mg_2Si phases) [2]. For Al–Si–Mg–Cu alloys, the precipitation behaviors are rather complicated and several phases such as β (Mg_2Si), θ($CuAl_2$), S($CuMgAl_2$) or Q ($Cu_2Mg_8Si_6Al_5$) in metastable situations may exist [9].

Heat treatment is generally carried out to obtain an optimum combination of strength and ductility in Al-Si-Cu-Mg alloys. The steps for the heat treatment consist of solution treatment, quenching and artificial aging [3]. The age-hardening mechanisms responsible for strengthening are based on the formation of intermetallic compounds during decomposition of a metastable supersaturated solid solution obtained by solution treatment and quenching. The mechanical properties of these alloys are significantly influenced by the presence of precipitates. W($Al_xCu_4Mg_5Si_4$) and S(Al_2CuMg) phases coexist with θ(Al_2Cu) and β(Mg_2Si) phases in aged Al-Si-Cu-Mg alloys. θ phase preferentially precipitates on the dislocations introduced around eutectic Si particles in the Al-Si-Cu based alloys, while λ($Al_5Cu_2Mg_8Si_5$) phase homogenously precipitates in the α matrix, regardless the sites of dislocations and therefore these precipitates significantly raise the age-hardening

ability. $Q(Al_5Cu_2Mg_8Si_6)$ phase exhibiting an effect on age-hardening may exist in aged Al-Si-Cu-Mg alloys [7, 10].
In this study, the effect of Cu content at various levels on the age hardening, precipitation behavior and microstructure of Al-6Si-05Mg alloys was studied.

2. Experimental Procedures

Calculated amounts of commercially pure aluminium (99.7% pure) and Al-7.1Si-0.3Mg master alloy were melted in a gas fired clay-graphite crucible under suitable flux cover (degasser, borax etc). Magnesium ribbon (99.7% pure) was added to the molten solution. Copper, in the form of wire (99.98% purity) was then added by plunging. The final temperature of the melt was always maintained at 950±15^oC with the help of an electronic temperature controller. Before casting, the melt was homogenized by stirring at 700^oC. Casting was done in cast iron metal moulds preheated to 200^oC. Mould sizes were 15mm x 150mm x 300mm. All the alloys were analysed by wet chemical and spectrochemical methods simultaneously. The chemical compositions of the alloys are given in Table 1. The cast samples were first ground properly to remove the oxide layer from the surface. All the alloys were then homogenised by heating in an electric muffle furnace for 24 hours at 500^oC. The homogenised samples were solution treated at 540^oC for 120 minutes and quenched in salt iced water solution. As-cast and quenched samples were aged isochronally for 60 minutes at different temperature up to 400^oC. The samples were also isothermally aged at 225^oC for different ageing times ranging from 15 to 360 minutes. Hardness of different alloys processed with different schedules and aged at different temperatures was measured in Rockwell hardness testing machine with 60 kg load and 1/16$^{//}$ steel ball indenter [F scale]. An average of seven consistent readings was accepted as the representative hardness value of an alloy. Electrical conductivity of the heat treated alloys was determined with an Electric Conductivity Meter, type 979. Pieces of the alloy measuring 15 mm x 20 mm x 5 mm were ground and polished prior to the electrical conductivity measurement. Electric resistivity was calculated from the conductivity data. All the samples were observed under an optical microscope. The specimens for metallographic observation were prepared using standard techniques, final polishing was done with very fine alumina. The etching was done in Keller's reagent (HNO_3 – 2.5 cc, HCl – 1.5 cc, HF – 1.0 cc and H_2O – 95.0 cc). The washed and dried samples were observed carefully in an OPTIKA Microscope (Model: B-600 MET) at different magnifications and some selected photomicrographs were taken. Scanning Electron Microscopy of the selected samples was carried out by a Scanning Electron Microscope type Inspect^{TM} S50 FEI Quanta at various magnifications.



Alloy synthesis and production of samples for aging studies

Table 1. Chemical Composition of the Experimental Alloys (wt %)

Alloy	Si	Mg	Cu	Ni	Fe	Zn	Mn	Pb	Cr	Sn	Ti	Sb	Al
1	5.902	0.461	0.007	0.005	0.146	0.004	0.002	0.003	0.001	0.004	0.099	0.008	Bal
2	6.033	0.517	0.558	0.006	0.129	0.006	0.003	0.002	0.001	0.001	0.094	0.005	Bal
3	6.105	0.555	1.185	0.029	0.334	0.005	0.005	0.002	0.004	0.001	0.088	0.005	Bal

4	5.801	0.497	1.980	0.003	0.300	0.004	0.004	0.002	0.005	0.001	0.094	0.005	Bal
5	5.884	0.532	3.800	0.014	0.181	0.003	0.003	0.001	0.010	0.001	0.086	0.007	Bal

Remarks:
Alloy 1 Al-6 wt% Si-0.5 wt% Mg
Alloy 2 Al-6 wt% Si-0.5 wt% Mg-0.5 wt% Cu
Alloy 3 Al-6 wt% Si-0.5% Mg-1 wt% Cu
Alloy 4 Al-6 wt% Si-0.5% Mg-2 wt% Cu
Alloy 5 Al-6 wt% Si-0.5% Mg-4 wt% Cu

3. Results and Discussion

3.1. Optical and SEM micrographs:

Microstructure Al-6Si-0.5Mg alloy in T6 condition is presented in Fig. 1. Analyzing the micrographs of the alloy after solution treatment at 540°C for 2h, it had been found that during solution heat treatment the morphology of primary eutectic Si changes from relatively large needle like structure to the more refined "Chinese script" and spherical in shape particles.

The optical microstructure of solution treated alloy 1 shows dendrites with black second phase particles within inter-dendritic spaces (Fig. 1). Addition of copper to the base alloy by 0.5 wt% shows a diminution in the amount of second phase particles. It further appears that dendrite arm spacing is decreased in Alloy 2 with the consequent refinement of dendrites (Fig. 2).

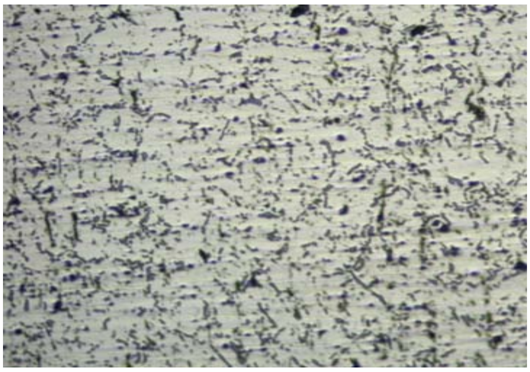


Fig. 1. Optical micrograph of solution treated alloy 1

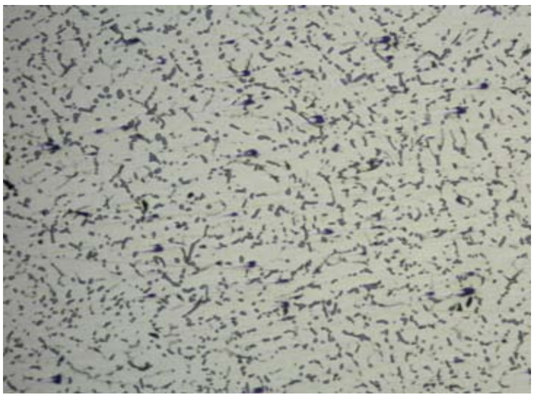


Fig. 2. Optical micrograph of solution treated alloy 2

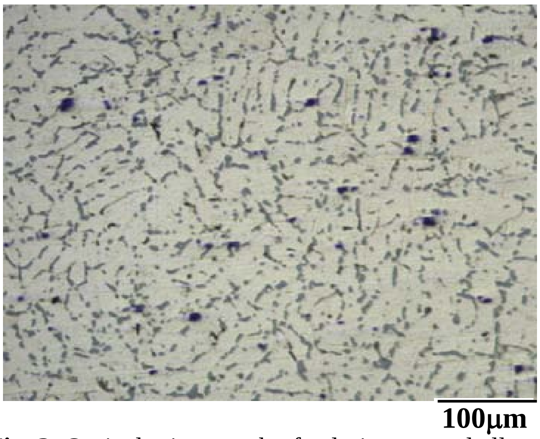


Fig. 3. Optical micrograph of solution treated alloy 4

The structural fineness is seen to increase with increasing copper content. In the alloys with 2 wt% Cu and 4 wt% Cu the amount of second phase particles is reduced to a great extent. The dendrite fragments are seen to have refined remarkably (Figs. 3 and 4).

Where the alloys are aged at 300^{o}C for 1 hour, noticeable change in microstructures results. Alloy 1 shows relatively coarse grain structure with somewhat less amount of second phase constituent (Fig. 5). Alloy with 2 wt% Cu has not been able to refine grain structure to any greater extent (Fig. 6)

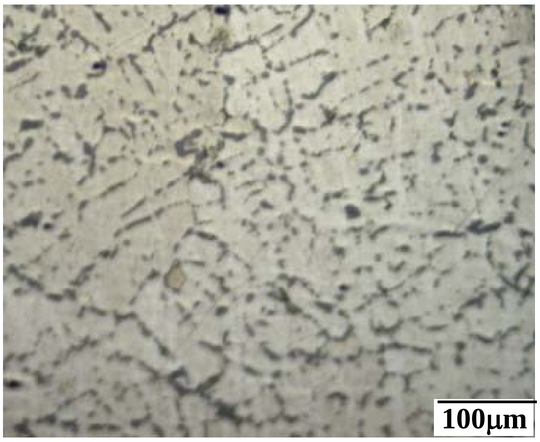


Fig. 4. Optical micrograph of solution treated alloy 5

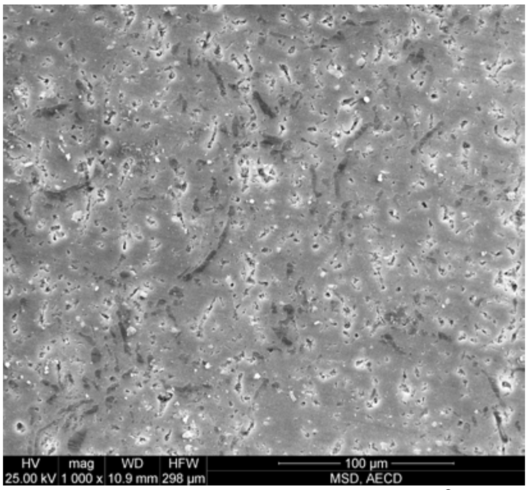


Fig. 5. SEM micrograph of alloy 1 aged at 300^{o}C for 1 hour

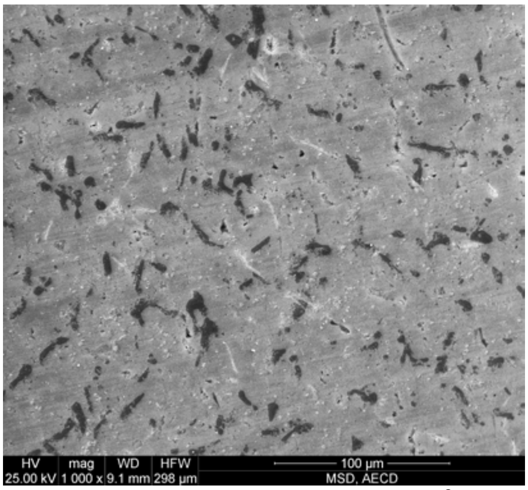


Fig. 6. SEM micrograph of alloy 4 aged at 300°C for 1 hour

3.2. Isochronal Ageing:

Figure 7 shows the isochronal aging behavior of the different alloys. For all the alloys, the peak aging condition is attained at 225°C. Although hardness of the base alloy is lower than the Cu-bearing alloys in the solution treatment. The decrease in hardness became more pronounced with increasing aging temperature beyond 250°C. However, the Cu-bearing alloy exhibits stronger resistance to softening in comparison with the base alloy. Hardness in both of the as quenched conditions and peak-aged conditions increases strongly with increase of Cu content. The increase of hardness in as quenched conditions with increase of Cu content indicates that the solid-solution strengthening of the alloys is enhanced with increase of Cu content. This indicates that addition of Cu increases the age hardening ability slightly; moreover Cu addition decreases the age hardening rate. The strong increase of maximum hardness during ageing with increase of Cu content is mainly the results of solid-solution strengthening of Cu on a (Al) matrix.

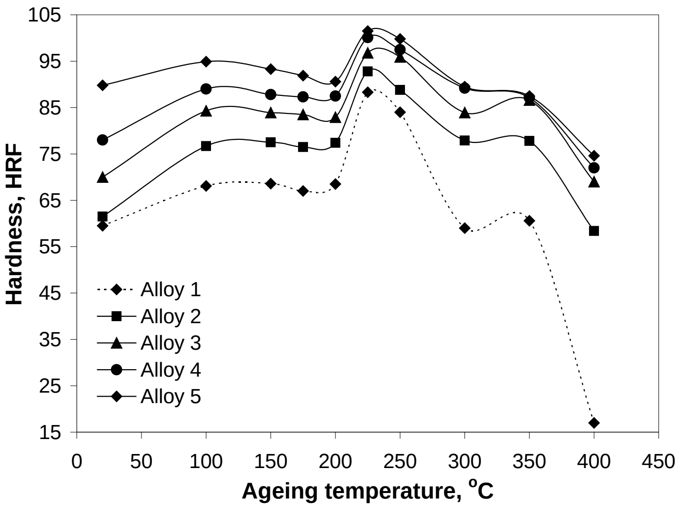


Fig. 7. Isochronal ageing curve of the alloys, aged for one hour

3.3. Isothermal Ageing:

Fig. 8 shows the isothermal aging behavior of different alloys at 225°C, all the alloys attain the peak condition after 60 min. In the case of Cu-bearing alloys the peak hardness is maintained without any appreciable softening duration of aging. Fig. 9 shows the effect of the ageing time on the electrical resistivity of the samples isothermal ageing at 225°C. It is clear that the electrical resistivity of the material decreased with increasing holding time of ageing. It can also be seen that the most significant decrease in the electrical resistivity occurs at the first 2 hours of ageing. The electrical resistivity shows a step decrease and then an increase leading to peak or a plateau followed by a decrease until it reaches a nearly constant value.

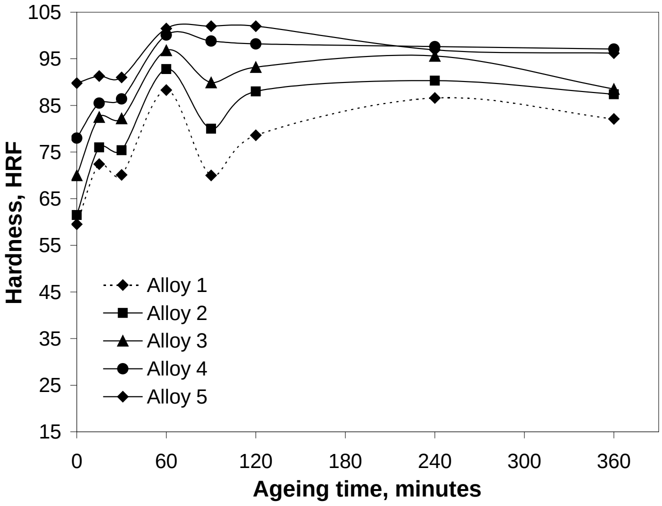


Fig. 8. Isothermal ageing curve of the alloys, aged at 225°C

In the presence of secondary particles, the primary elective parameters on the electrical resistivity are as follows: [8] (1) the volume fraction of fine and coherent particles in the structure, (2) the particle interspacing, and (3) the concentration of elements in solid solution. The formation of dispersoids leads to a decrease in the concentration of the corresponding elements in the matrix. If the elements precipitate out during a thermal process such as homogenization or precipitation hardening, the change in the electrical resistivity of the material depends on the size and the interface of the newly formed particles. If the new particles are small and coherent, the electrical resistivity of the material increases and vice versa. The formation of the plateau in the electrical resistivity curve may be due to the balance of the increase in the concentrations of some elements, namely Si, Mg, and Cu in the matrix. When the rate of the increase in the electrical resistivity due to the dissolution of constitutive particles and therefore, the enrichment of the structure becomes equal to the rate of the decrease in the electrical resistivity due to the formation of dispersoids, a peak or plateau is observed in the electrical resistivity curve.

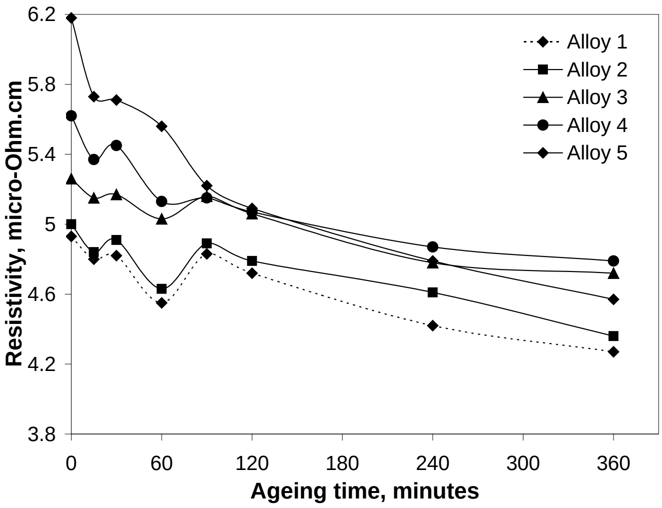


Fig. 9. Variation of resistivity of the alloys, Isothermally aged at 225°C

The effect of grain refinement of the alloys is clearly evident from the resistivity curves, which show a significant difference of resistivity values of the copper added alloy with that of the base alloy. The initial high resistivity of copper treated alloy is indicative of high electron scattering sites viz. grain boundary area to mean that grains in all those alloys are finer. Formation of supersaturated solid solution assures a high precipitation hardening effect upon decomposition of this solid solution with the formation of fine coherent precipitates. The softening of the alloys at higher temperature may be due to particle coarsening effect. The initial drop in resistivity is due to stress relieving in the alloys during ageing. The steeper drop at the initial period of isothermal ageing at 225°C may be attributed to the formation solute atom vacancy complex. Transition metals are known to bind vacancies strongly. For this reason, the number density of scattering centers is reduced. This causes a sharp fall in resistivity. The subsequent increase in resistivity is due to the appearance of fine precipitates. When the ageing temperature is small, the resistivity continues to increase beyond the peak because the precipitation formation and reordering of atoms continues.

4. Conclusions

Addition of Cu to Al–6Si–0.5Mg alloy decreases the age hardening rate. Maximum hardness could be achieved by artificial ageing for 1h at 225°C. With increase of Cu content, the solid-solution strengthening of the alloys is enhanced, but the age hardening ability increases slightly, moreover it decreases a little with addition of 2 wt% Cu. The strong increase of maximum hardness during ageing with increase of Cu content is mainly the results of solid-solution strengthening of Cu on a (Al) matrix. The microstructural investigations show that the shape of the eutectic Si particles changes to granular type in all alloys after heat treatment.

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