Effect of Ageing Temperature on the Mechanical Properties of Al-6Si-0.5Mg Cast Alloys with Cu Additions Treated by T6 Heat Treatment

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Abstract Effect of artificial ageing temperature on the mechanical properties of Al-6Si-0.5Mg alloy containing 0.5 – 4 wt% Cu was studied. The solution treated alloys containing different amounts of Cu were aged isochronally for 1 hour at temperatures up to 300°C. The precipitation stages during ageing were monitored by hardness measurements. Tensile and impact properties were determined by standard tests. During artificial ageing, the yield and ultimate tensile strengths were found to increase with ageing temperature; the maximum being attained at peak aged condition. Ductility and impact toughness of the alloys, on the other hand decreased with ageing temperature reaching the minimum at the highest hardness. The addition of Cu resulted in an increase in hardness and tensile strength and substantial reduction of ductility and fracture toughness.

Keywords Al-6Si-0.5Mg Alloy, Age hardening, Tensile properties, Fracture toughness, SEM

1. Introduction

Due to high strength-to weight ratio, besides other desirable properties like appearance, high corrosion resistance, high electrical and thermal conductivities and ease of fabrication, aluminum and its alloys are used in a wide range of industrial applications, particularly in aircraft and space vehicles, construction and building, containers and packaging and in electrical transmission lines [1]. Controlled thermo mechanical treatments can induce considerable improvements in yield strength and hardness of age hardenable Al-alloys. Micro mechanisms governing fracture characteristics of such alloys depend on coherency and distribution of precipitates, grain size and shape, grain boundary precipitates and presence of other second phase particles that result from impurities. The unstable fast fracture, even if it is ductile, becomes frequent because the strengthening lowers the level of toughness, and this

becomes a problem with large scale structures. Since the fracture of many engineering components is promoted under dynamic conditions, there is a need to understand the fracture behaviour of materials under dynamic loads. Moreover, fracture characteristics under the impact load seem to become important, because the application to transportation vehicles is likely to increase [2].

Precipitation hardening is the most common method to increase the strength of the heat treatable aluminum alloys. This method includes a solution heat treatment at high temperature to maximize solubility, followed by rapid cooling or quenching in water to obtain a solid solution super saturated with the solute elements (Mg and Si), followed by aging heat treatment (which may include either natural aging or artificial aging) to produce finely dispersed precipitates. Solution heat treatment is designed to maximize the solubility of solute elements which are precipitated during subsequent aging. It is most effective when carried out at temperatures near the solidus, where maximum solubility exists and diffusion rates are rapid.

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 super-saturated 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]. Therefore, during fracture mechanics tests; it may be advantageous to include Charpy impact tests so that empirical correlations between the various fracture parameters can be developed. Numerous studies have been undertaken on evolution of microstructure, tensile properties and fracture toughness of precipitation hardened Al-alloys [6-15].

The successive precipitation sequence in Al-Si alloys to

which Mg has been added is $\beta_{SSS} \rightarrow \beta'' \rightarrow \beta' \rightarrow \beta$ (Mg_2Si) and in Al-Si-Mg alloys with Cu addition is $\alpha_{SSS} \rightarrow \theta'' \rightarrow \theta' \rightarrow \theta$ ($CuAl_2$) where; β_{SSS} and α_{SSS} is the supersaturated solid solution. The complete precipitation sequence can only occur when the alloy is aged at temperatures below the GP zone solvus. The mechanism of the transformation sequence usually involves heterogeneous nucleation at the sites of earlier products, resulting in fine and uniform precipitate dispersions [16, 17].

The present work focuses on how the changes of artificial ageing temperature influence the mechanical properties of cast Al-6Si-0.5Mg alloys containing different amounts of Cu.

2. Materials and Methods

Melting was carried out in a natural gas heating pot furnace under the suitable flux cover (degasser, borax etc.). Several heats were taken for developing base Aluminium-Silicon-Magnesium alloy, Aluminium-Silicon-Magnesium alloy containing Copper at various levels. In the process of preparation of the alloys the commercially pure aluminium (99.7% purity) was taken as the starting material. First the aluminium and aluminium-silicon master alloy melted in a clay-graphite crucible, Copper, in the form of sheet (99.98% purity), was then added by plunging. Magnesium ribbon (99.7% purity) was added into solution duly packed in an Al foil. The final temperature of the melt was always maintained at $900 \pm 15^\circ C$ with the help of an electronic controller. Before casting, the melt was degassed with solid hexachloroethane (C_2H_6) and homogenized by stirring at $690^\circ C$. Casting was done in cast iron metal moulds measuring 15 x 150 x 300 in millimetre and preheated to $200^\circ C$. 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 for 24 hours at a temperature of $500^\circ C$. The homogenised cast samples were solution treated at $540^\circ C$ for 120 minutes in ice cooled salt-water solution.

Prior to artificial ageing, the solution treated samples were kept at room temperature for 1 day. Artificial ageing was conducted in an electrical furnace. All the samples (only slices) were isochronally aged at room temperature, 100, 150, 175, 200, 225, 250, 300, 350 and $400^\circ C$ for 1 hour. Subsequently, the samples were taken out from the furnace and cooled in still air. The hardness of all the artificially aged samples was determined on a Rockwell hardness testing machine using the F scale with a dwell time of 15 s. Hardness measurements were performed on polished slices measuring 20 mm x 20 mm x 8 mm. An average of seven consistent readings was accepted as the representative hardness value of an alloy.

Sub-size standard tensile (ASTM E8 M-04) and impact test specimens (10mm x 10mm x 55mm in size, a $45^\circ V$ notch

of 2 mm depth and 0.25 mm root radius) were prepared from the homogenised samples. The tensile and impact test specimens were subjected to solution treatment at $540^\circ C$ for 2 hours and then artificially aged at room temperature, 150, 200, 225, 250 and $300^\circ C$ for 1 hour. Tensile testing was carried out in an Instron testing machine at a strain rate of $10^{-3}/s$ and the Charpy impact testing was performed using an impact testing machine (JB-500B). The averages of three consistent test results were accepted as the tensile and impact value for the corresponding sample. Fractographic observation of the selected fractured tensile sample was carried out in a Scanning Electron Microscope (InspectTM S50 FEI Quanta).

Table 1. Chemical composition of the experimental alloys (wt %)

Alloy Name	Si	Mg	Cu	Al
Alloy-1	5.902	0.461	0.007	Bal.
Alloy-2	6.033	0.517	0.558	Bal.
Alloy-3	6.105	0.555	1.185	Bal.
Alloy-4	5.801	0.497	1.980	Bal.
Alloy-5	5.884	0.532	3.800	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 wt% Mg-1 wt% Cu

Alloy 4: Al-6 wt% Si-0.5 wt% Mg-2 wt% Cu

Alloy 5: Al-6 wt% Si-0.5 wt% Mg-4 wt% Cu

3. Results and Discussion

3.1. Effect of Artificial Ageing Temperature on Hardness

Figure 1. Variation of hardness of the alloys as a function of artificial ageing temperature isochronally aged for 1 hour.

Fig.1 shows the isochronal aging behavior of the different alloys. For all alloys, the peak aging condition was attained by ageing for 1 hour at 225°C. The hardness of the base alloy (alloy 1) was always found to be lower than the Cu-bearing alloys (alloys 2-5). The hardness decreased significantly with increasing aging temperature beyond 250°C. The Cu-bearing alloys, on the other hand, exhibited a stronger resistance to softening in comparison with the base alloy. Hardness in both as-quenched sample and in sample aged at 225°C increases strongly with increase of Cu content. The increase of hardness in as-quenched condition (25°C) with increase of Cu content indicates that the solid-solution strengthening of the alloys is enhanced with increase of Cu content. Overageing decreases the hardness value of the alloys.

3.2. Effect of Artificial Ageing Temperature on Yield Strength

The variation in yield strength (0.2% proof strength) of the alloys 1-5 under various aging conditions is shown in Fig.2. Test values obtained at a strain rate of 10^{-3}s^{-1} were used to plot the graph. Fig. 2 shows that the yield strength of the alloys increases to a peak value at an aging temperature of 225°C. Aging at temperatures beyond 225°C was found to lower the yield strength of the alloys. In the base alloy (Al-6Si-0.5Mg alloy) the variation in yield strength with aging temperature is not very significant. When the alloys are aged at 150 to 225°C, the yield strength increases with increasing copper content up to 2 wt. % copper. With addition of copper beyond this level, a marginal fall in yield strength was observed. Further ageing (250°C and 300°C) beyond the peak-aged condition, the yield strength of the alloys decreased due to overage.

Figure 2. Variation of yield strength of the alloys as a function of artificial ageing temperature isochronally aged for 1 hour.

3.3. Effect of Artificial Ageing Temperature on the Tensile Strength

Fig.3 shows that the copper-containing alloys experience extra strengthening due to age-hardening effect and the maximum in tensile strength value is achieved by aging for one hour at a temperature of 225°C. It is further observed that increasing ageing temperature up to 225°C increases the tensile strength of the alloys. Increase in copper content beyond 2 wt% Cu causes a drop in the tensile strength value under all aging conditions.

Figure 3. Variation of ultimate tensile strength of the alloys as a function of artificial ageing temperature isochronally aged for 1 hour.

3.4. Effect of artificial ageing temperature on percent elongation

Fig. 4 demonstrates the variation in percent-elongation with aging temperatures of alloys 1-5. It can be seen that at the aging temperature for which strength is maximum (225°C), the ductility values of the alloys (except alloys 1 and 2) pass through a minimum. The ductility of alloy 1 was found to be a minimum at 200°C, and that of alloy 2 at 250°C. The ductility value of the aged alloy 5 (containing 4 wt% Cu) was found to be less than all the other alloys for all aging conditions.

Figure 4. Variation of percent elongation of the alloys as a function of artificial ageing temperature isochronally aged for 1 hour.

3.5. Effect of Artificial Ageing Temperature on Fracture Toughness

Fig.5 shows the energy absorbed during fracture as a

function of artificial ageing temperature. Heat treatment, especially solution treatment and ageing, greatly influenced the capacity of absorbed energy. In the as-quenched condition, the alloys have shown higher toughness than in the peak-aged (1hr at 225°C) condition. The toughness of the base alloy is higher than the Cu-bearing alloys. As the ageing temperature increases from room temperature (25°C) to 225°C, the absorbed energy decreases for all the alloys. The decrease in absorbed energy is due to the brittleness caused by precipitation of intermediate phases. The maximum decrease in absorbed energy was observed in the peak aged condition. Further ageing from 225 to 300°C the absorbed energy increases slightly and this was due to overage.

Figure 5. Variation of impact absorbed energy of the alloys as a function of artificial ageing temperature isochronally aged for 1 hour.

3.6. Fracture Surface Analysis

Treated specimens were more brittle and showed higher tensile strength than the specimens without T6 heat treatment. Fig.6 shows the appearance of the fractured surface of the samples in the T6 treated condition. The figure shows large and small dimple structure and broken or cracked primary Si particles. This indicates that the fracture was ductile fracture in the Al matrix and brittle in the primary Si particles. It may thus be assumed that the fracture of the primary Si particles is responsible for the relatively low ductility of the T6 treated specimens. In fig.6 the presence of microvoid (shrinkage porosity) on the fracture surface is shown. The void formed at the interfaces between the Si particles and Al matrix enhanced the crack propagation through their centre. On the fracture surface and in micro voids, the presence of secondary phase precipitates (Al_2Cu , Mg_2Si) also contribute to mechanical properties by increasing the bonding of the matrix and reduced the ductility.

Figure 6. SEM fractograph of alloy 4, aged at 225°C for 1 hour and tensile tested at strain rate of 10^{-3}s^{-1}

4. Conclusions

Addition of Cu to Al-6Si-0.5Mg alloy decreases the age hardening rate. An increase in Cu content enhances the solid-solution strengthening of Al-6Si-0.5Mg alloys. The strong increase of maximum hardness during ageing with increase of Cu content is mainly the results of precipitation strengthening. Addition of Cu to the Al-6Si-0.5Mg cast alloy resulted in improved strength and reduced ductility. The Ageing temperatures have a great effect on the properties. The maximum strength is observed after ageing at 225°C for 1 hour (peakaged). The alloys with the lowest fracture toughness and ductility correspond to those that show the highest value of strength and hardness.

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