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Effect of 2wt% Cu Addition on the Tensile Properties and Fracture Behavior of Peak Aged Al-6Si-0.5Mg-2Ni Alloy at Various Strain Rates

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Abstract**—**Effect of 2wt% Cu addition on tensile properties and fracture behavior of Al-6Si-0.5Mg-2Ni alloy at various strain rates were studied. The solution treated Al-6Si-0.5Mg-2Ni (-2Cu) alloys, were aged isochronally for 1 hour at temperatures up to 300°C. The uniaxial tension test was carried out at strain rate ranging from $10^{-4}s^{-1}$ to $10^{-2}s^{-1}$ in order to investigate the strain rate dependence of tensile properties. Tensile strengths were found to increase with ageing temperature and the maximum being attained ageing for 1 hr at 225°C (peak aged condition). Addition of 2wt% Cu resulted in an increase in tensile properties at all strain rates. Evaluation of tensile properties at three different strain rates (10^{-4}, 10^{-3} and 10^{-2} s^{-1}) showed that strain rates affected the tensile properties significantly. At higher strain rates the strength was better but ductility was poor. Microstructures of broken specimens showed that both the void coalescence and the interface debonding affect the fracture behavior of the alloys.

Keywords**—**Al-Si-Mg-Ni-Cu alloy, tensile properties, strain rate, SEM.

I. Introduction

EXCELLENT aptitude to casting and forging processes, machinability, corrosion resistance and high strength-to-weight ratio, which increases performance and fuels economy, make heat treatable aluminium alloys suitable materials for various crucial applications in the automotive industry, such as engine blocks, pistons and cylinder heads. The mechanical properties of Al alloys containing Si, Cu, Mg has been found to depend on distribution and shape of the silicon particles. The strengthening of these alloys during age-hardening has been attributed to the precipitation of Mg and Cu-rich phases [1]-[3].

Addition of Cu to Al-Si alloys leads to the formation of Al2Cu phases and other intermetallic compounds, which influences the strength and ductility [4]. In high copper content alloys, complete dissolution of the Al_2Cu phase is sluggish and a longer time must be chosen to allow maximum dissolution of this intermetallic phase. However, solution treating the alloy for a long time is expensive and may not be necessary to achieve the optimum strength. Moreover, prolonged annealing can lead to the formation of porosity and it has been shown that porosity deleteriously affect the mechanical properties [5]. 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 [6], [7].

A lot of works on the microstructure, heat treatment and mechanical behavior of Al-Si-Mg-Cu alloys have been done. The major advantages of Cu addition are increase in strength and hardness, both in the as-cast and in the heat-treated condition. Addition of Cu also affects corrosion resistance and ductility. Addition of Ni leads to the formation of Al3Ni in the aluminum matrix through eutectic reaction during solidification. In previous works 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 continuity of the eutectic network by increasing the volume fraction of rigid phases (Si + Al_3Ni) in the eutectic [8]-[10].

Results of tests on aluminium alloys at different strain-rate levels have been reported by a number of investigators. At room temperature, a very low, yet slightly positive, increase in flow stress with strain rate was reported by Oosterkamp et al. [11]. Similar observations regarding rate sensitivity of AA7003-T79 and AA7108-T6 alloys in tension have been reported [12]. Flow stress and fracture strain of AA6005-T6 alloys were shown to have rather strong positive strain-rate sensitivity [13].

The aim of this paper is to evaluate the effects of 2wt% Cu addition on the tensile properties and fracture of Al-6Si-0.5Mg-2Ni alloy and to establish data on the stress–strain behaviour of the Al-6Si-0.5Mg-2Ni(-2Cu) alloys with applications in automotive engineering.

II. Experimental Procedure

Al, Ni chips and A356 master alloy, contained in a clay-graphite crucible, was melted in a gas-fired pot furnace. Copper, in the form of sheet (99.98% purity), was then added by plunging. Magnesium (99.7% purity) in the form of ribbon and packed in an Al-foil was added to the melt. The final temperature of the melt was maintained at 900±15°C. Before casting, the melt was degassed with solid hexachloroethane (C_2H_6) and homogenized by stirring at 700°C. Casting was done in a metal mould measuring 15mm x 150mm x 300mm and preheated to 200°C.The spectrochemical analysis were shown in Table I.

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The cast samples were ground to remove the oxide layer from the surface and were homogenised for 24 hours 500°C. Samples for tension tests were prepared from the homogenised plates according to ASTM standard (Sub-size standard ASTM E8 M-04). The tension test samples were solution treated at 540°C for 120 minutes and quenched in ice-salt-water solution. Tensile testing was carried out in an Instron testing machine at three different cross-head speeds: 0.15, 1.5 and 15mm/minute which are equal to the nominal strain rates of 10^{-4}, 10^{-3} and $10^{-2}s^{-1}$ respectively for each alloys. The averages of three consistent test results were accepted as the tensile value for the corresponding sample. Fractographic observations of the fractured surfaces of selected samples were carried out in a Scanning Electron Microscope.

TABLE I
CHEMICAL COMPOSITIONS OF THE EXPERIMENTAL ALLOYS

Alloy	Si	Mg	Ni	Cu	Fe	Ti
Al-6Si-0.5Mg-2Ni	5.97	0.45	2.20	0.01	0.14	0.09
Al-6Si-0.5Mg-2Ni-2Cu	5.76	0.50	2.00	1.97	0.27	0.08

III. RESULTS AND DISCUSSION

A. Effect 2wt% Cu on Tensile Strength with Ageing Temperatures

The results of the variation of ultimate tensile strength (fracture strength) under various aging conditions of the Al-6Si-0.5Mg-2Ni (-2Cu) alloys are shown in Fig. 1.

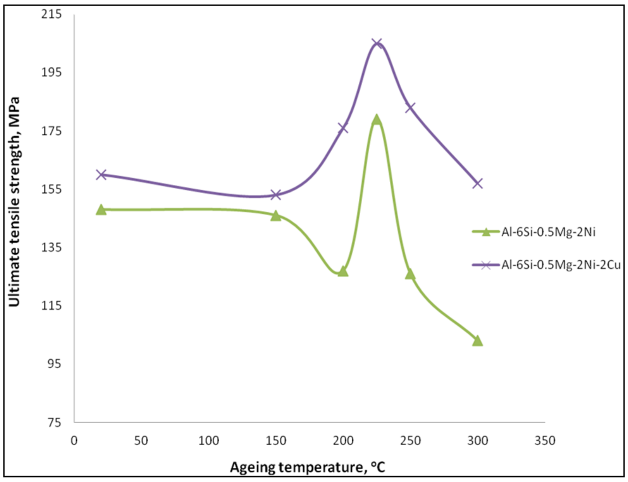


Fig. 1 Ultimate tensile strength of the investigated alloys at different ageing temperatures

The test values obtained at a strain rate of testing $10^{-3}s^{-1}$ are used to plot the graph. From the nature of variation in tensile strength with aging temperature of the alloys, the tensile strength is an average of three tensile specimens. It can be seen that a maximum ultimate tensile strength is 205 MPa for Al-6Si-0.5Mg-2Ni-2Cu alloy, which was obtained at 225°C and Al-6Si-0.5Mg-2Ni alloy shows 179 MPa. Al-6Si-0.5Mg-2Ni-2Cu alloy shows higher strength than the Al-6Si-0.5Mg-2Ni alloy all over ageing temperatures. The UTS of the alloys decreases gradually when the test temperature is beyond 225°C.

B. Effect 2wt% Cu on Ultimate Tensile Strength at Various Strain Rates

The ultimate tensile stress - strain rates curves of Al-6Si-0.5Mg-2Ni (-2Cu) alloys (aged at 225°C for 1 hour) are plotted in Fig. 2. The tensile test experiments are conducted at three different strain rates (10^{-4}, 10^{-3} & $10^{-2}s^{-1}$) for evaluation their effects on tensile properties. Enhancing strain rates results in an obvious increase in fracture strength. When the strain rates are below $10^{-3}s^{-1}$, work hardening decreases strongly for the alloys. In the case of Al-6Si-0.5Mg-2Ni-2Cu alloy work hardening decreases strongly during the plastic deformation of sample and sometimes necking phenomenon is observed in this strain rate before fracture. The tensile strength increases more pronounced with the increase of strain rates and 2wt% Cu content Al-6Si-0.5Mg-2Ni alloy. Al-6Si-0.5Mg-2Ni-2Cu alloy shows the highest ultimate tensile strength all over the strain rates. The ultimate tensile strength of reference alloy (Al-6Si-0.5Mg-2Ni) does not show significant change with the increase of strain rates.

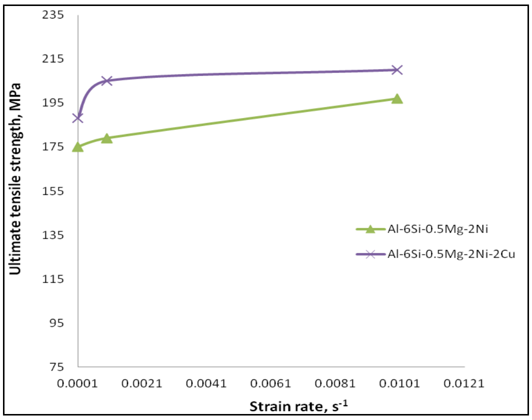


Fig. 2 Ultimate tensile strength- strain rate curves of the peakaged alloys

C. Effect 2wt% Cu on Yield Strength at Various Strain Rates

Fig. 3 indicates that the yield strength (0.2% proof strength) vs. strain rates of Al-6Si-0.5Mg-2Ni (-2Cu) alloys. The increasing in proof strengths with strain rates of the alloys is very similar to the ultimate tensile strengths. Al-6Si-0.5Mg-2Ni-2Cu alloy , was found to be higher yield strength than the reference Al-6Si-0.5Mg-2Ni alloy all over the strain rates. The higher yield strength is due to the effect of Cu addition, precipitation hardening and higher strain hardening.

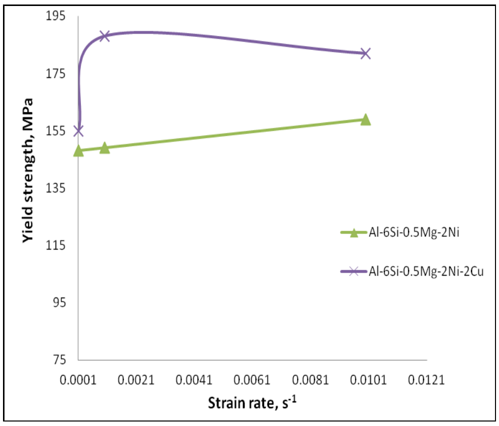


Fig. 3 Yield strength- strain rate curves of the peakaged alloys

D.Effect 2wt% Cu on Ductility at Various Strain Rates

Fig. 4 demonstrates the variation of ductility (% elongation) with strain rates of Al-6Si-0.5Mg-2Ni (-2Cu) alloys. It is observed that at the strain rate for which strength is maximum (10-2s-1), the ductility values of the alloys pass through minima. The ductility value of the reference aged Al-6Si-0.5Mg-2Ni alloy is found to be less than the Al-6Si-0.5Mg-2Ni-2Cu alloy at higher strain rates. It was recorded maximum ductility at the strain rate of 10-4s-1.So 2wt% Cu addition has a significant effect on ductility of Al-6Si-0.5Mg-2Ni alloy.

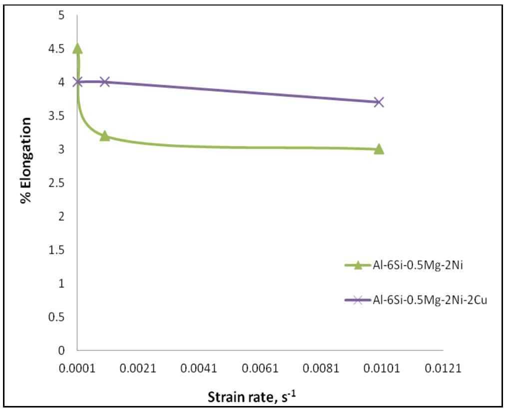
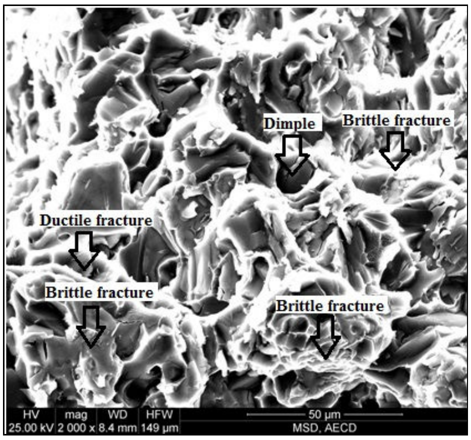


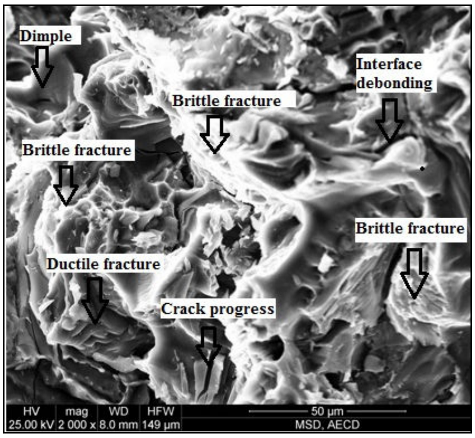
Fig. 4 Ductility (% elongation) - strain rates curves of the peakaged alloys

E. Fracture Behavior

Typical fracture morphologies of (a) Al-6Si-0.5Mg-2Ni and (b) Al-6Si-0.5Mg-2Ni-2Cu alloy tested at a strain rate of $10^{-4}s^{-1}$ shown in Fig. 5. The precipitate particle fracture, interface debonding and matrix crack are main failure modes of aluminum based alloys. The tensile behaviors of the alloys are controlled by particle strength, particle matrix interface strength, and matrix strength and also affected by the strain rates. On a microscopic scale, the fracture surfaces appear to contain many microvoids in the matrix. The void coalescence occurs when the void elongates to the initial intervoid spacing. This leads to the dimpled appearance on the fractured surfaces.



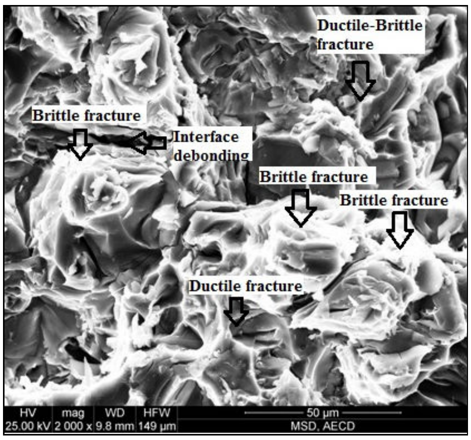
(a) Al-6Si-0.5Mg-2Ni



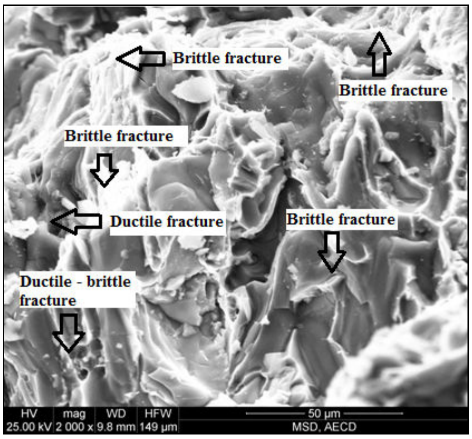
(b) Al-6Si-0.5Mg-2Ni-2Cu

Fig. 5 Tensile fracture SEM micrographs of the alloys at a strain rate of 10^{-4} s^{-1}

Fig. 6 shows the fracture surfaces of Al-6S-0.5Mg-2Ni-2Cu alloy at three different strain rates of $10^{-4}s^{-1}$, $10^{-3}s^{-1}$ & $10^{-2}s^{-1}$.



(a) Strain rate$10^{-3}s^{-1}$



(b) Strain rate $10^{-2}s^{-1}$

Fig. 6 Tensile fracture SEM micrographs of Al-6Si-0.5Mg-2Ni-2Cu alloy at (a) strain rate$10^{-3}s^{-1}$ and (b) strain rate$10^{-2}s^{-1}$

The fracture surfaces are perpendicular to tensile direction and show broken primary Si particles. With the increase of strain rates the void coalescence occurs more rapidly and the load cannot be transferred from the matrix to the particles & precipitates, as a result the ductility of the materials decrease at higher strain rate.

IV. Conclusions

The addition of 2wt% Cu to the thermal treated Al-6Si-0.5Mg-2Ni alloy resulted in improved tensile properties. Strain rate affects the ultimate tensile strength, yield strength, ductility and fracture behavior of the Al-6Si-0.5Mg-2Ni (-2Cu) alloys during tensile testing. Ultimate tensile strength and yield strength increase with decreasing strain rate but ductility reduces. The alloys show the ductile or ductile-brittle mixed fracture behavior at various strain rates.

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