

Effects of Strain Rate on Tensile Properties and Fracture Behavior of Al-Si-Mg Cast Alloys with Cu Contents

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Abstract Effects of strain rates on tensile properties and fracture behavior of Al-6Si-0.5Mg alloy containing 0.5 – 4 wt% Cu were studied. The solution treated alloys, containing different amounts of Cu, were aged isochronally for 1 hour at temperatures up to 300°C. Tensile strengths were found to increase with ageing temperature, the maximum being attained at peak aged condition (1 hr at 225°C). Addition of Cu resulted in an increase in tensile strength and 2 wt% Cu addition showed the maximum strength. 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.

Keywords: Al-6Si-0.5Mg alloy, precipitation hardening, tensile properties, strain rate

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1. Introduction

Age hardened Al-alloys are widely used in engineering applications due to the considerable improvements in their yield strength and hardness by controlled thermo-mechanical treatments. 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 will increase [1].

Addition of Cu to Al-Si alloys leads to the formation of Al₂Cu phases and other intermetallic compounds, which influences the strength and ductility [2,3,4]. In high copper content alloys, complete dissolution of the Al₂Cu 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 alloys, the age hardening is caused by the precipitation of β'' and/or β' phases (precursor of Mg₂Si phases) [6,7]. For Al-Si-Mg-Cu alloys, the precipitation behaviors are rather complicated and several

phases such as β (Mg₂Si), θ (CuAl₂), S(CuMgAl₂) or Q (Cu₂Mg₈Si₆Al₅) in metastable situations may exist [8,9,10].

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 various strain rates on the tensile properties of Al-6Si-0.5Mg cast alloys at various Cu contents and to establish data on the stress-strain behaviour of the alloys with applications in automotive engineering.

2. Materials and Methods

2.1. Materials

Aluminium and aluminium-silicon 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 $900 \pm 15^\circ\text{C}$. Before casting, the melt was degassed with solid hexachloroethane (C₂H₆) 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. All the alloys were analysed by wet chemical and spectrochemical methods simultaneously.

2.2. Heat Treatment

The cast samples were ground to remove the oxide layer from the surface and were homogenised for 24 hours at 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.

2.3. Tension Tests

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 observation of the fractured surfaces of selected samples were carried out in a Scanning Electron Microscope.

3. Results and Discussion

The chemical compositions of the alloys are given in Table 1.

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

Alloy	Si	Mg	Cu	Ni	Ti	Al
Alloy-1	5.902	0.461	0.007	0.005	0.099	Bal
Alloy-2	6.033	0.517	0.558	0.006	0.094	Bal
Alloy-3	6.105	0.555	1.185	0.029	0.088	Bal
Alloy-4	5.801	0.497	1.980	0.003	0.094	Bal
Alloy-5	5.884	0.532	3.800	0.014	0.086	Bal

Table 2. Tensile properties at different strain rates

Alloy name	Ageing treatment	Strain Rate (s $^{-1}$)	Tensile Properties		
			UTS (MPa)	YS (MPa)	Elongation (%)
Alloy-1 0 wt% Cu	1 hr at 225°C	10^{-2}	166	127	3.2
		10^{-3}	143	117	3.6
		10^{-4}	140	112	3.9
Alloy-2 0.5 wt% Cu	1 hr at 225°C	10^{-2}	202	170	3.7
		10^{-3}	179	151	4.2
		10^{-4}	162	136	4.3
Alloy-3 1.0 wt% Cu	1 hr at 225°C	10^{-2}	193	165	3.8
		10^{-3}	188	161	4.3
		10^{-4}	186	160	4.6
Alloy-4 2.0 wt% Cu	1 hr at 225°C	10^{-2}	249	226	4.4
		10^{-3}	212	190	4.8
		10^{-4}	183	159	5.2
Alloy-5 4.0 wt% Cu	1 hr at 225°C	10^{-2}	136	123	1.2
		10^{-3}	129	113	1.6
		10^{-4}	90	79	1.6

3.1. Effect of Ageing Temperatures on Tensile Strength

The variation of ultimate tensile strength (fracture strength) of alloys 1-5 under various aging conditions are shown in Figure 1. The test values obtained at a strain rate of 10^{-3} s $^{-1}$ were used to plot the graphs. It can be seen that a maximum ultimate tensile strength of 249 MPa was

obtained after ageing for 1 hour at 225°C for alloy 4 (2 wt.% Cu). A fall in tensile strength was observed in alloy 5 containing a higher amount of Cu (4 wt% Cu). The UTS decreased gradually in samples aged at temperatures above 225°C. The base alloy (alloy-1) showed lower variation in tensile strength at all aging temperatures.

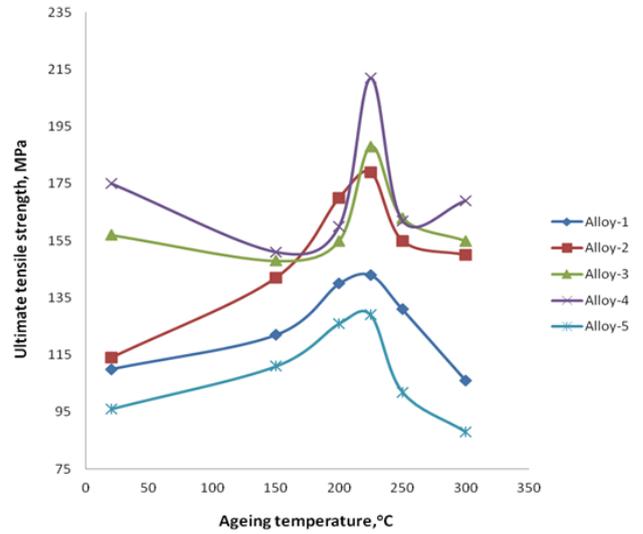


Figure 1. Ultimate tensile strength of investigated alloys at different ageing temperatures

3.2. Effect of Strain Rate on Ultimate Tensile Strength

The tensile strength-strain rates curves of the alloys at 225°C are plotted in Figure 2. The tensile tests were conducted at three different strain rates (10^{-4} , 10^{-3} & 10^{-2} s $^{-1}$). Enhanced strain rates resulted in an obvious increase in fracture strength. Work hardening decreased strongly during plastic deformation of sample at 10^{-4} s $^{-1}$, and necking phenomenon was observed in this strain rate before fracture. The tensile strength increased significantly with increase of strain rates and Cu contents (up to optimum addition of Cu). 2 wt% Cu containing alloy (Alloy-4) showed the highest ultimate tensile strength all over the strain rates. But Alloy-5 (4wt% Cu) showed the lowest ultimate tensile strength at all the strain rates.

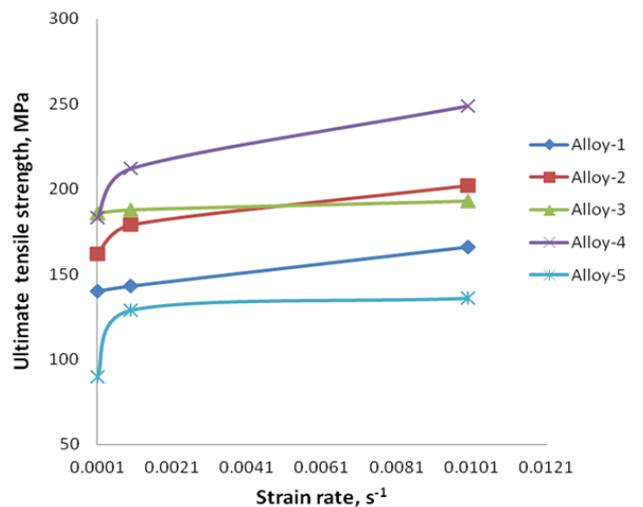


Figure 2. Ultimate tensile strength- strain rate curves of investigated alloys aged at 225°C for 1 hr

3.3. Effect of Strain Rate on Yield Strength

Figure 3 shows the increase in yield strength (2% proof strengths) with strain rates of the alloys. The trend is very similar to that of ultimate tensile strengths. The maximum yield strength in all the alloys was attained at a strain rate of 10^{-2} s^{-1} . At any strain rate the yield strength increased with the amount of Cu in the alloy and the alloy containing 2 wt% Cu (alloy-4) was found to have the highest yield strength of all the alloys. The higher yield strength is due to precipitation hardening and higher strain hardening.

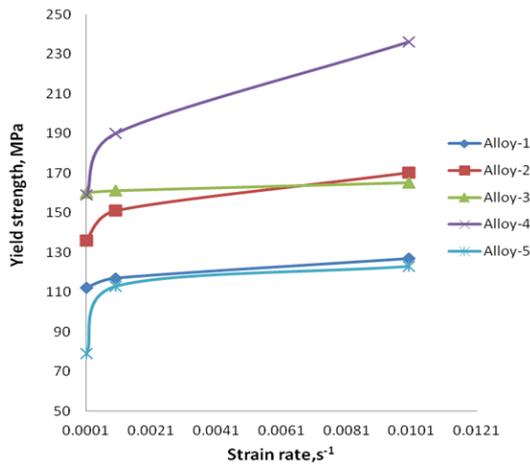


Figure 3. Yield strength-strain rate curves of investigated alloys aged at 225°C for 1 hr

3.4. Effect of Strain Rate on Ductility

Figure 4 demonstrates the variation of % elongation with strain rates of the alloys. It was observed that at the

strain rate for which strength is maximum (10^{-2} s^{-1}), the ductility values of the alloys pass through the minimum. For all strain rates, the ductility value of the aged alloy 5 (4wt % Cu) was found to be less than all other alloys.

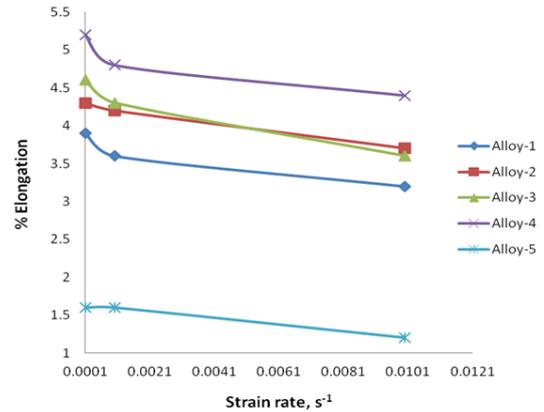


Figure 4. Ductility (%elongation) - strain rates curves of investigated alloys aged at 225°C for 1 hr

At all strain rates investigated, the tensile properties (UTS and YS) of the alloys in the peak aged condition was found to increase with an increase in Cu-content of the alloy up to 2.0 wt% Cu. Tensile strength decreased in alloy having more than 2 wt% Cu. This is in good agreement with the results reported earlier [2,16]. The increase in ultimate tensile strength in alloys containing up to about 2 wt% Cu has been attributed to the precipitation of increasing amount of copper rich precipitates. On the other hand, porosity volume percent increase with an increase in Cu-content [2]. Porosities act as sites for stress concentration and cause decrease in ductility in alloys containing Cu.

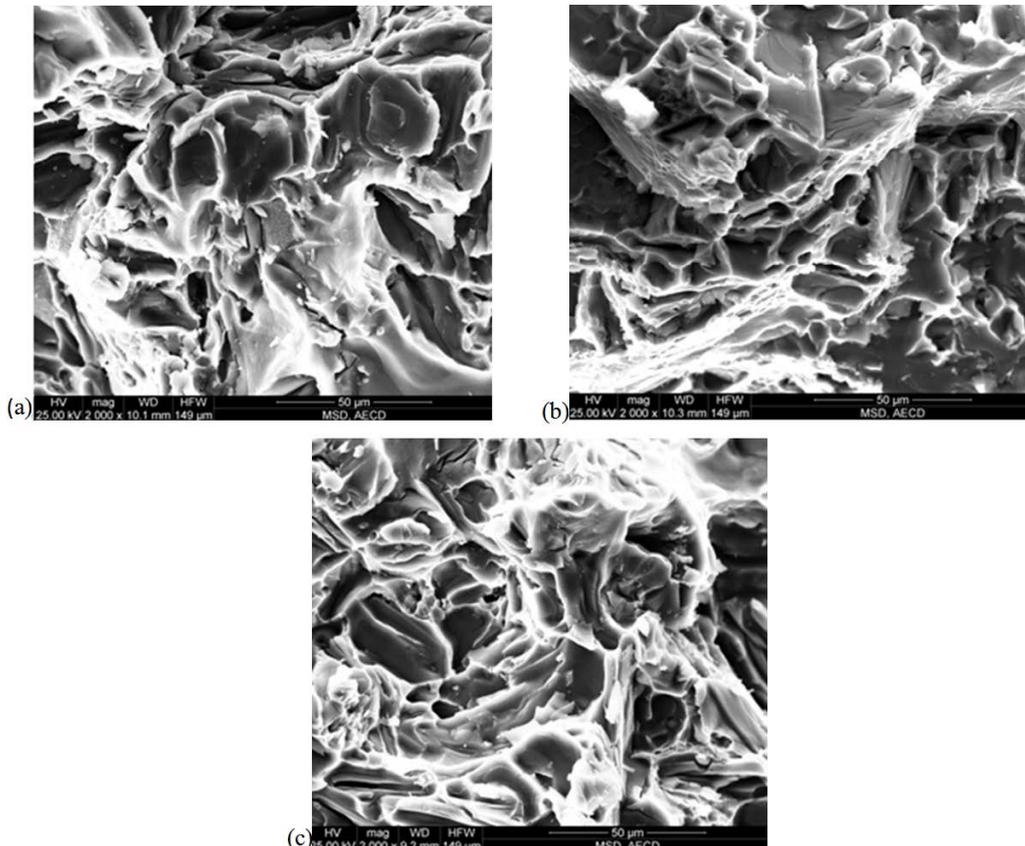


Figure 5. Fracture surfaces of alloy-1 at different strain rates (a) 10^{-4} s^{-1} (b) 10^{-3} s^{-1} (c) 10^{-2} s^{-1}

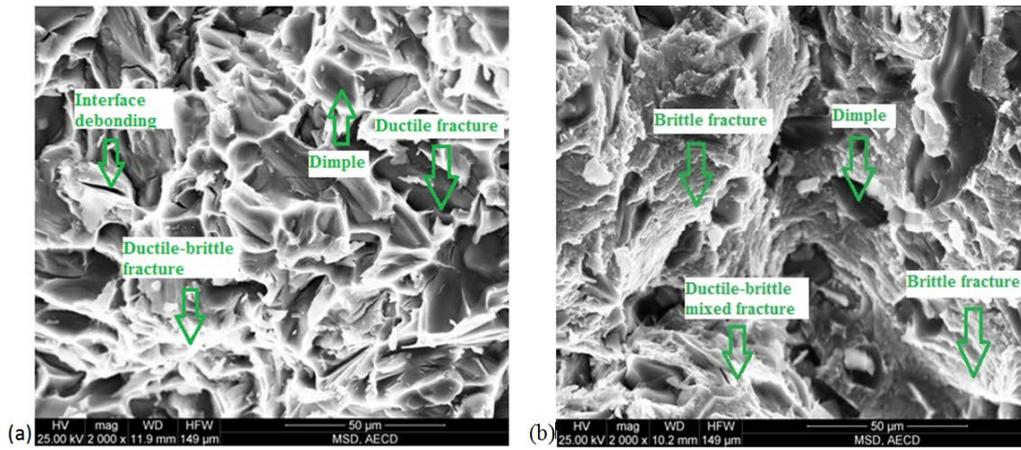


Figure 6. Tensile fracture surfaces of (a) alloy-2 and (b) alloy-5 at a strain rate of 10^{-3} s^{-1}

3.5. Effect of Strain Rate on Fracture Behavior

Figure 5 shows fracture surfaces of Cu free Al-6Si-0.5Mg alloy (Alloy-1) at three different strain rates 10^{-4} s^{-1} , 10^{-3} s^{-1} & 10^{-2} s^{-1} . The fracture surfaces are perpendicular to tensile direction and show broken primary Si particles. As the strain rate increased to 10^{-2} s^{-1} the void coalescence occurred rapidly and the material shows gradually decreasing ductility. Figure 6 shows typical fracture morphologies of (a) alloy - 2 (0.5 wt% Cu) and (b) alloy - 5 (4 wt% Cu) tested at a strain rate of 10^{-3} s^{-1} . The precipitate particle fracture, interface debonding and matrix crack are the main failure modes. Therefore, the tensile behaviors of the alloys are controlled by particle strength, particle matrix interface strength, and matrix strength. In addition, the tensile behavior is also affected by strain rates. On a microscopic scale, the fractures appear to contain many microvoids in the matrix. The matrix-particles decohesion is also observed for these alloys. The void coalescence occurs when the void elongates to the initial intervoid spacing. This leads to the dimple appearance of the fractured surfaces. Brittle fracture of these alloys indicates that void growth and coalescence occurred rapidly and at higher strain rates, the load could not be transferred from the matrix to the precipitates.

4. Conclusions

Al-6Si-0.5Mg alloys with 2 wt.% Cu addition and aged at 225°C for 1hour show excellent tensile properties. During tensile testing, strain rate was found to affect the ultimate tensile strength, yield strength, ductility and fracture behavior of the alloys. Ultimate tensile strength and yield strength increased with increasing strain rate but ductility decreased. The investigated alloys show a ductile or ductile-brittle mixed fracture at various strain rates. Particles and some precipitates fracture are the main damage behavior at relatively low strain rates, while

precipitates/matrix interface debonding is the dominant fracture behavior at relatively high strain rates.

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