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Effects of Composition on the Mechanical Properties and Microstructural Development of Dilute 6000 Series Alloys

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Abstract: The aim of the present investigation is to study the effect of composition on the mechanical properties and microstructural development during thermal treatment of some dilute 6000 aluminium alloys. The alloys were based on 6000 series dilute aluminium alloys containing different levels of magnesium (Mg) and silicon (Si) contents. The effects of artificial ageing (T6) on the precipitation hardening behaviour were studied in the four dilute alloys. The solution treated alloys samples were quenched at 530°C for 5 min and then immediately subjected to ageing at 185 and 300°C. The ageing response and mechanical properties of the alloys were investigated by hardness and tensile test, respectively. The microstructures of the alloys were monitored using Transmission Electron Microscopy (TEM). The results from this study showed a correlation between the Mg and Si contents on the mechanical properties and microstructures of the alloys after ageing treatment. It is apparent that an increasing solute content of Mg_2Si and ExSi has marked effect in increasing hardness and tensile properties of the alloys. It was found that Mg_2Si is more effective than ExSi in hardening and strengthen the alloys. The precipitates formed during artificial ageing were needle-shaped with their major axes parallel to (100) directions of the matrix. The number density of precipitates increased as their solute contents of Mg_2Si and ExSi increased. Overall results of TEM observation are in agreement with the results of hardness and tensile test.

Key words: Al-Mg-Si, ageing response, tensile test, precipitation hardening, TEM

INTRODUCTION

Aluminium alloys of the 6000 series containing Mg and Si as the major elements have found increased application in automotive industry recently. These alloys have good combination of low weight, excellent formability and resistant to corrosion (Marioara *et al*., 2003; Demir and Gunduz, 2009). The type of these alloys is very important due to their strong ageing response and normally they obtain their strength by precipitation of the Mg_2Si precipitates during heat treatment (Marioara *et al*., 2006). The precipitation hardening response of the alloys is very significant and hence control of precipitation during heat treatment is critical for attaining optimum alloy performance (Edwards *et al*., 1998).

It is well known that the ageing responses and mechanical properties of the alloys are highly dependent on alloys composition. Many of the studies had focussed on alloys in 6000 series whose Mg and Si contents were balanced to produce Mg_2Si (Miao and Laughlin, 1998). The presence of Si in excess (ExSi) of that required to form Mg_2Si is known to give large response to the precipitation hardening (Kang *et al*., 1996; Vanmousse *et al*., 2002). Addition of Copper (Cu) to the Al-Mg-Si alloy give beneficial effect on strength by refinement Mg_2Si precipitates which leads to increase the distribution of precipitates (Barry, 1984; Dutkiewicz and Litynska, 2002; Gaber *et al*., 2006). It has been reported that the precipitation sequence of Al-Mg-Si alloys is (Thomas, 1961; Dutta and Allen, 1991; Edwards *et al*., 1998):

$$\alpha_{ssss} \rightarrow \text{GP-zones} \rightarrow \beta\text{''-phases} \rightarrow \beta\text{'-phases} \rightarrow \beta\text{-phase } (Mg_2Si)$$

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where, α_{ssss} refers to the supersaturated solid solution, GP-zones are generally considered spherical clusters with unknown structure and the zones are fully coherent with the matrix (Yassar *et al.*, 2005). β' and β''phases are intermediate phases, a precursors of the β phase (Miao and Laughlin, 1999). The most effective hardening phase in Al-Mg-Si alloy system is β'' phases (Eskin and Kharakterova, 2001). The β'' phases is the fine needle-shaped precipitates extended along $[100]_{Al}$ matrix. In 6000 series alloys, artificial ageing via heat treatment is used to promote the formation of needle-shaped precipitates from the supersaturated solid solution of Mg and Si in aluminium matrix in order to improve mechanical properties of the alloys (Yao *et al.*, 2001).

Precipitation hardening process in dilute 6000 series alloys is still new and not many researches have been reported. By virtue of less amount of alloying addition used in these alloys, they become good in corrosion resistances (Ekuma *et al.*, 2007) and more economical to produce and have a potential to be used in the automotive industry. In this present investigation, the effect of composition on the mechanical properties and microstructural development after ageing treatment of four dilute 6000 series alloys are described.

MATERIALS AND METHODS

The chemical compositions of the dilute 6000 series alloys are given in Table 1. The alloys were obtained in extruded form of 40 mm wide and 3 mm thick.

The alloys samples were solution treated at 530±5°C for 3 min in an electrical muffle furnace and then water quenched into ice water. The samples were then intermediately aged in an oil bath at 185°C and in an electrical muffle furnace at 300°C. Hardness measurements were performed using Vickers hardness tester. The test samples used for hardness measurements were 2×2 cm in size. Hardness data were determined using 5 kg load from the average of six readings from each sample. Tensile testing was carried out at 185°C for 10, 30 and 100 h using an Instron 1185 Testing Machine operating at a constant crosshead speed of 1.0 mm min^{-1}. In this study, ageing at 185°C was chosen as the main temperature for the mechanical properties due to its relevance to commercial applications.

Table 1: Chemical compositions of the dilute 6000 series alloys (wt.%)

Alloys	Si	Fe	Cu	Mn	Mg	Mg_2Si	ExSi
A	0.22	0.17	0.1	0.03	0.20	0.32	0.1
B	0.62	0.17	0.1	0.03	0.21	0.33	0.5
C	0.37	0.17	0.1	0.03	0.49	0.77	0.09
D	0.79	0.17	0.1	0.03	0.51	0.80	0.5

For the microstructure analysis, alloys samples for both ageing temperatures with specific ageing time have been selected for investigation by TEM. Thin foil TEM specimens were prepared by electropolishing at 12 V in a solution of 70% analar methanol and 30% nitric acid cooled to –30±1°C. A Philips TEM 400 and CM 200 operating at 120 and 200 kV, respectively were used for all the TEM investigations. TEM micrographs were taken in the (100) direction of the matrix to observe the precipitates.

RESULTS AND DISCUSSION

The effect of composition on hardness: Figure 1 and 2 show the typical ageing curves for the alloys that aged at 185 and 300°C, respectively. It is clear from Fig. 1 and 2 that the strongest ageing response with highest hardness value is attained in alloy D for both ageing temperatures. This alloy has the highest solute content of Mg_2Si (0.8 wt.%) and ExSi (0.5 wt.%) compared to other alloys. Alloy C (similar content of Mg_2Si with alloy D but lower ExSi (0.09 wt.%) shows a lower ageing response than that of alloy D but a higher hardness increase than that of alloys B and A. Alloy B which contain the same amount of ExSi content with alloy D but lower solute content of Mg_2Si (0.33 wt.%) shows a lower hardness values than that of alloy C. Alloy A shows the lowest hardness values and ageing responses in line with the low solute contents of Mg_2Si and ExSi.

Based on hardness results, it is noticeable that the alloys which possess higher solute contents of Mg_2Si and ExSi have the strongest ageing response as well as the biggest increase in hardness values for both ageing temperatures. The above-mentioned results also indicate that Mg_2Si is more effective in hardening the alloys compared to ExSi.

The results in Table 2 also show that the peak hardness values considerably increase as the solute content of Mg_2Si and ExSi increase. The increase in the solute content in alloy D is responsible for a higher peak hardness values as compared to the other dilute alloys for both ageing temperatures. At higher solute content, the peak hardness values will be attained in a shorter ageing time (Fig. 1, 2). This is related to the

Table 2: Peak hardness values of alloys A, B, C and D at different ageing temperatures

	Peak hardness values (VHN)			
Ageing temperature	A	B	C	D
185°C	-	60±1	79±2	118±1
300°C	29±1	40±1	51±1	65±1

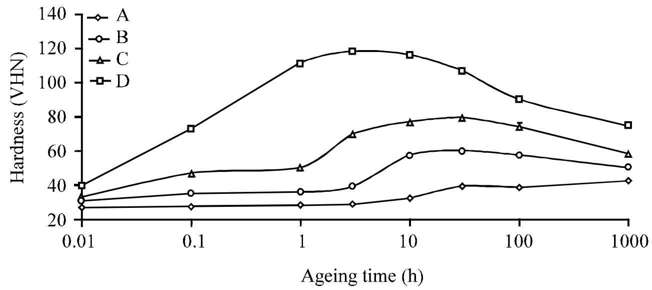

Fig. 1: Ageing curves of alloys A, B, C and D for ageing at 185°C

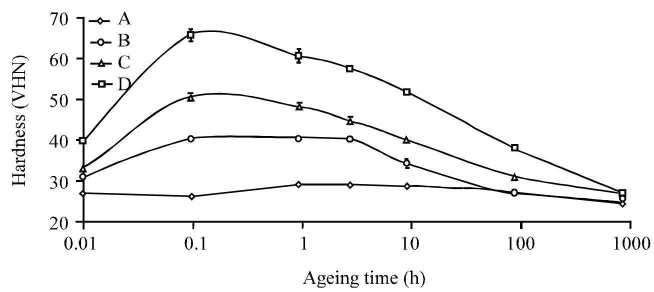

Fig. 2: Ageing curves of alloys A, B, C and D for ageing at 300°C

increase in the nucleation and growth rate of precipitates during artificial ageing resulting in the greater amount of solute available for the precipitates formation (Reed-Hill and Abbaschian, 1992).

In 6000 series alloys, as a result of the nucleation and growing of the precipitates, there is an increase in hardness value due to effect of strengthening. The strengthening effect of the alloys could be explained as a result of interference with the motion of dislocation due to the presence of second phase particles (Mg_2Si precipitates) in the alloys during ageing treatment (Eskin and Kharakterova, 2001; Eiuani and Taheri, 2008; Demir and Gunduz, 2009). Prolong ageing time at given temperature decrease the hardness of the alloys. The reduction in hardness can be attributed to the fact that coalescence of the precipitates into larger precipitates which will cause fewer obstacles to the movement of dislocation (Demir and Gunduz, 2009). A decrease in the hardness of the alloys is referred as over-ageing conditions (Eiuani and Taheri, 2008).

The effect of composition on tensile properties: Figure 3, 4 and 5 show the tensile properties of the four dilute alloys after ageing at 185°C for 10, 30 and 100 h, respectively. It is found from the results that the strongest alloys with highest UTS and YS values is attained in alloy D followed by alloys C, B and A in the all ageing time at 185°C. It is apparent that alloy D showed the highest UTS and YS values due to their high solute contents of Mg_2Si and ExSi. The presence of lower solute content in alloy A resulted in decrease in the tensile properties.

According to the tensile results, it can be proposed that the more Mg_2Si and ExSi contents present in the alloy, the more precipitates will be formed. The presence of the high number solute contents in the alloys may provides a number of sites for the heterogeneous nucleation of precipitates which in turn accelerates the precipitation process during ageing treatment and thus the tensile properties of the alloys are increased. The results of the tensile properties are similar to those results of hardness after ageing at 185°C (Fig. 1).

As expected, the alloys with the lowest UTS and YS values (alloy A) show the highest ductility although the elongation values do not exactly mirror the YS and UTS data (Fig. 3-5). For the artificially aged alloys, it can be concluded that Mg_2Si and ExSi have a high effect on elongation. Elongation is inversely related to strength and the strongest alloy has the lowest ductility.

Microstructural observations: For TEM observations, alloys A and D were selected to study the effect of composition on microstructural development after ageing

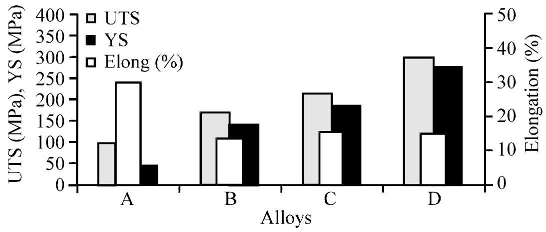

Fig. 3: Tensile properties of dilute alloys after ageing at 185°C for 10 h

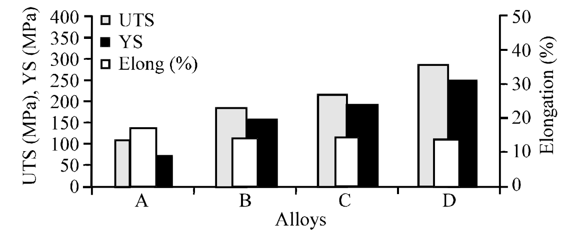

Fig. 4: Tensile properties of dilute alloys after ageing at 185°C for 30 h

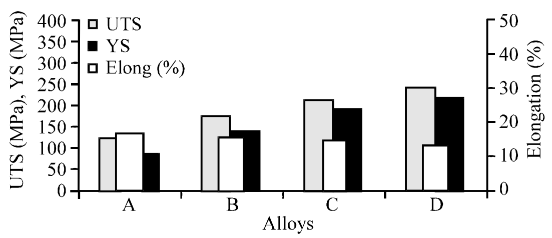

Fig. 5: Tensile properties of dilute alloys after ageing at 185°C for 100 h

at 185 and 300°C. Figure 6 shows the microstructure of alloys A and D that aged at 185°C for 30 h (close to peak-aged). All the TEM micrographs are with the incident electron beam in the (100) matrix direction. In both alloys, the precipitates are in the form of needle-shaped which produces the strengthening effect in T6 condition. The presence of these precipitates has influenced the mechanical properties of the alloys by increasing the strength and reduces the ductility (Garrett *et al*., 2005).

As can be seen in Fig. 6, the distribution of the precipitates in alloy D is finer and denser than in the alloy A. Therefore, the densities of the needle-shaped precipitates in alloy D are much higher than that of alloy A. From TEM results, it can be concluded that alloy D which contains the highest amount of Mg_2Si and ExSi contents somehow cause a higher density of nucleation

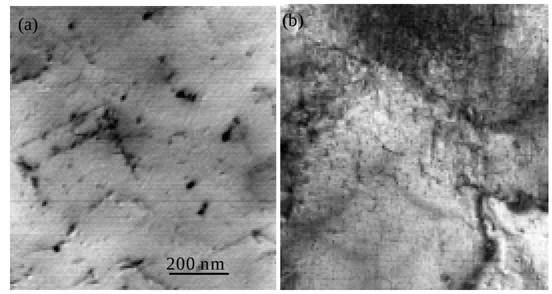

Fig. 6(a-b): TEM micrographs of the (a) Alloy A and (b) Alloy D aged for 30 h at 185°C (close to peak-aged), Electron beam is in the (100) matrix direction

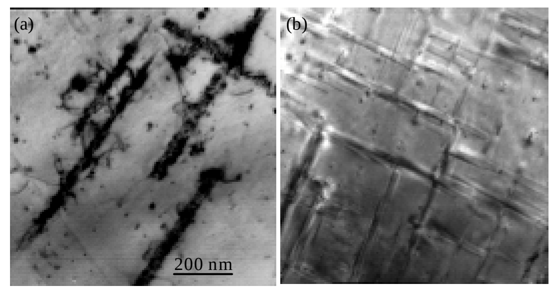

Fig. 7(a-b): TEM micrographs of the (a) Alloy A and (b) Alloy D aged for 1 h at 300°C (close to peak-aged), Electron beam is in the (100) matrix direction

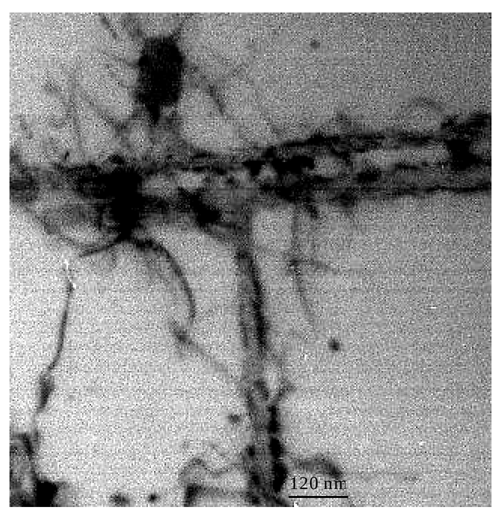

Fig. 8: TEM micrograph of the alloy D aged for 1000 h at 300°C (close to peak-aged), Electron beam is in the (100) matrix direction

sites for the precipitates formation during artificial ageing. These results are supported by the finding of Gupta *et al*. (2001) who found that the distribution and volume fraction of precipitates increased with increasing Mg_2Si and ExSi contents. The obtained results of TEM are in agreement with the results of the hardness tests which showed that the peak hardness value of alloy D was higher than that of alloy A (Fig. 1).

Figure 7 shows TEM micrographs of alloys A and D aged at 300°C for 1 h (close to peak aged). It is observed from the TEM micrographs that the length of precipitates increases with increasing ageing temperature. This is caused by the fact that precipitates formation is accelerated and the growth rate of precipitates is increased. Similar observation was also noted that the density of the needle-shaped precipitates in alloy D is much higher than that of alloy A. Alloy D which contains the highest amount of Mg_2Si and ExSi contents can cause the hardness of alloy D is higher than that of alloy A.

Figure 8 shows TEM micrographs of alloy D that aged at 300°C for 1000 h. Prolong ageing time up to 1000 h have increased the size of precipitates and the precipitates density being reduced. The larger precipitates size will adversely affect the hardness and strength of alloys as a result the mechanical properties of the alloy are lowered (Polmear, 1996; Demir and Gunduz, 2009). Overall TEM results revealed that alloy that aged at 185°C shows precipitates more densely formed than that of alloys aged at 300°C. This supports that the alloy that aged at lower ageing temperatures have higher hardness value than that of the alloy aged at high ageing temperature (Reed-Hill and Abbaschian, 1992).

CONCLUSION

The effect of composition on the mechanical properties and microstructural development of dilute 6000 series alloys was investigated by means of hardness measurements, tensile test and TEM. Based on this work, the Mg_2Si and ExSi contents affect the precipitation hardening behaviour of the alloys. It was found that the alloys that possess higher solute contents of Mg_2Si and ExSi have the strongest ageing response and the biggest increase in hardness and tensile properties. However, it can be concluded that Mg_2Si is more effective than ExSi in hardening and strengthen the alloys. The TEM results show higher solute contents in the alloys produced a higher density of needle-shaped precipitates and consequently the mechanical properties of the alloys is increased. The TEM results are in good agreement with the results of the hardness measurements and tensile test.

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