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Effect of Age Hardening on Fractal Behavior of a Li-Containing Al-Mg-Si Alloys

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Abstract

Three Al-Mg-Si alloys with a Lithium content of 1.52, 1.75 and 2.09 (wt. %), were aged at 433 and 453 K and broken in tension at room temperature. The observed mechanisms of fracture were the classical “micro-void coalescence” (MVC), and the “quasi- micro-void coalescence” (QMVC). It has been shown that two alloys with different Li content associated to different aging temperatures and broken at the peak aged condition but with the very same mechanism of fracture, can be discriminated through the fractal geometry approach. The fractal dimension value for each alloy aged at 433 K was higher that the corresponding to the same alloy aged at 453 K. In general, the higher the ductility at each aging temperature, the higher the fractal dimension.

1. Introduction

The deformation and fracture of real materials are related to a class of processes in which the macroscopic effects are predetermined by microscopic behavior. Current theories of deformation and fracture based on continuum approximation are often unsatisfactory as they do not take into account the interrelation of different processes at different levels.

On the other hand, *fractal geometry*, developed by Mandelbrot [1-2] to describe irregular phenomena in nature, allows the description of complex structures such as fracture surfaces and cracks, based on the fact that they are statistically invariant over a wide range of scale transformation, i.e. they have a similar appearance regardless of the scale on which they are being observed. Then, each portion of a self-similar object is considered a reduced-scale image of the whole [3-4], and its tortuosity or roughness can be described by the *factal dimension* D, an intensive property [5-9] which is used to evaluate the variation of the length or area with changes in the scale of measurement.

The fractal dimension of fractured surfaces has recently been attracting substantial interest [10-19], since, as is well known, the area of a fractured surface can be related to the dissipated energy during rupture and then to the mechanical properties of materials.

Since the tension test can be used quickly and reproducibly to determine many mechanical properties and is the single most informative test available, we intend to clarify whether tension fracture surfaces of three different Al-Mg-Si(-Li) alloys aged at 433 and 453 K can be characterized by *fractal geometry* and to confirm the close relationship between topography, strength and ductility.

2. Experimental Procedure

Three types of Al-Mg-Si alloys with different amounts of Li (wt. %) were used in this study. The corresponding chemical compositions are given in Table 1. The as-received materials consisted of 25 x 75 mm plates of 3 mm thickness, prepared from hot forged and cold rolled ingots for a commercial supplier. Tensile samples of cross section 2.5 x 10 mm, gauge length 25 mm and the tensile axis parallel to the rolling direction were taken from the as-received plates, solution heat treated at 810 K for 1 h in a salt baths, cold water quenched and aged in oil baths at 433 and 453 K. Room temperature tensile tests were done by duplicate in an Instron type machine at a strain rate of 2.8×10^{-4} s^{-1}. The reported tensile properties were the yield strength σ_{ys} (0.2%),the true tensile strength σ_{ts} and the true fracture strain ε_f. Hardness measurements were performed on aged 10×30 mm as-polished plates of 3 mm thickness, using a Vickers hardness tester with a 5 kg load. Each measurement was repeated ten times in order to obtain the corresponding average.

Table 1 Chemical Composition (wt. %) of the Al-Mg-Si(-Li) Alloys.

Alloy Designation	Li	Mg	Si	Cr	Fe	Al
1	1.52	0.65	0.82	0.20	0.072	Bal.
2	1.75	0.65	0.79	0.20	0.080	Bal.
3	2.09	0.64	0.84	0.21	0.025	Bal.

The fractography was conducted using a Hitachi S2400 scanning electron microscope (SEM), operated at 25 Kv. In order to determine the fractal dimension D, The “slit island method” developed by Mandelbrot [2] was used. The fracture surfaces were mounted in an epoxy resin base down. Then, they were ground and polish until the fractured surface showed in the form of small metallic islands. After each ground-polish operation the islands growth and the corresponding areas and perimeters were measured with a digitizing software. The fractal dimension is obtained from a full logarithmic scale diagram of $\sum(Pi)$ vs $\sum(Ai)$, being Pi and Ai the perimeter and the area of the ith island on a particular jth layer containing n such islands. According to the slit island method:

$$D = 2\left\{ d\left[\log \sum_{i=1}^{n}(Pi)\right] \Big/ d\left[\log \sum_{i=1}^{n}(Ai)\right] \right\} \quad (1)$$

where 1<D<2, being 1 and 2 the euclidean dimensions corresponding to a smooth line and a flat surface respectively. Then, the fractal dimension increment is D-1, and as it increases from 0 to 1, the irregularities become increasingly predominant.

3. Results and Discussion

The isothermal hardening response for the studied alloys aged at 433 and 453 K are shown in Figs. 1-a and 1-b respectively. Both the 1.52 and 1.75 Li alloys aged at 433 K do not reached the peak aged condition even after 100h, being the corresponding hardness values after this maximum aging time of 105 VHN and 93 VHN respectively. This effect probably arises because of the slow precipitation and limited amount of the Li-rich δ' phase. On the other hand, the hardness of the 2.09 Li alloy aged at 433 K, rapidly increases from 67 VHN in the as-quenched condition to 122 VHN (peak age condition) after 30 h. It is believed that the enrichment of δ' promotes and increased aged response as compared to the 1.52 and 1.75 Li alloys. The results for the aging treatments at 453 K shows that the hardening response decreased significantly and that the peak age condition was achieved almost at the same aging time of 25 h for the three alloys. The corresponding maximum hardness values were 83, 68 and 106 VHN for the 1.52; 1.75 and 2.09 Li alloys respectively. Yield strength, true tensile strength and true fracture strain were measured for the maximum aging time of 100 h or the peak age conditions of 30 or 25 h correspondingly.

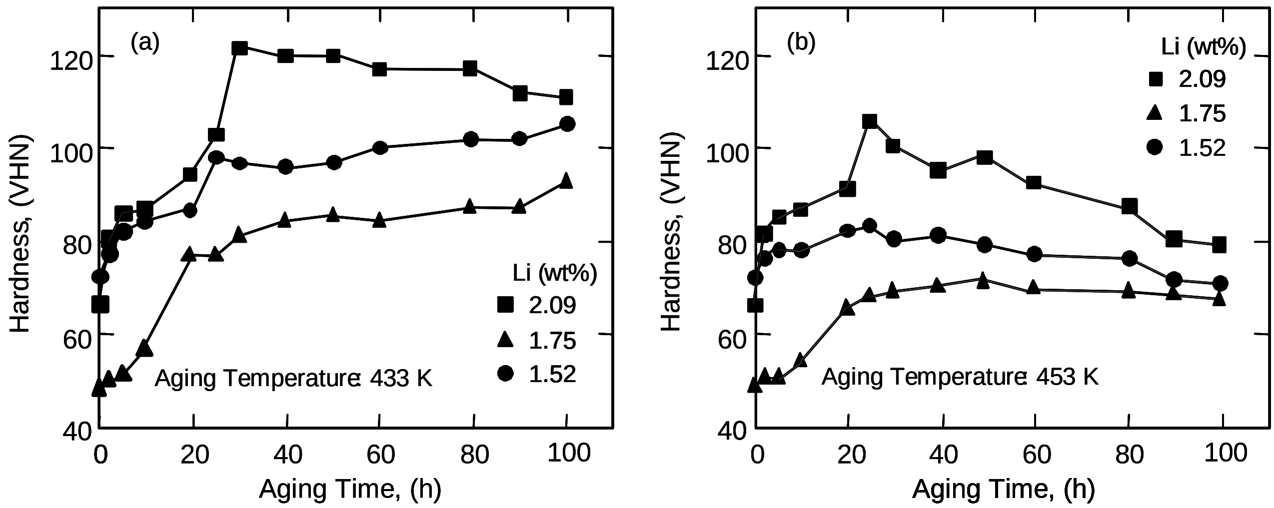

Figure 1: Isothermal hardening response for the AlMgSi(-Li) Alloys aged at (a) 433 K, (b) 453 K.

Figure 2 shows the fractal plots for the fracture surface of specimens aged at 433 K (Figure 2-a), and 453 K (Figure 2-b). The slope of a straight line fitted to the corresponding data points by a linear least square method was used to calculate D. The fractographic analysis reveals two kind of fracture mechanisms which can be seen in Figure 3: "micro-void coalescence" (MVC) and "quasi-micro-void coalescence" (QMVC). The rupture of the 1.52 Li alloy aged at 433 K (Figure 3-a) shows the QMVC pattern, as the micro dimples do not show a good definition characteristic of the regular network commonly observed in ductile alloys [20-23]. Besides, the general fracture appearance resembles a transition between intergranular separation and MVC, but without exhibiting grain facets. Instead, deformed dimples covered the fracture surface, which has a fractal dimension of 1.23. On the other hand, the fractured surface of the 1.75 Li alloy aged at 433 K (Figure 3-b), shows a well defined MVC mechanism and a fractal dimension of 1.19. The fracture surface for the 2.09 Li alloy aged at 433 K (Figure 3-c), shows the same QMVC mechanism of fracture as the 1.52 Li alloy, and a fractal dimension value of 1.16.

This alloy showed a clear increase in strength and decrease in ductility (Table 2) as compared to the former two alloys, being these changes promoted by the enrichment of δ'.

As the aging temperature was increased to 453 K, just the 1.52 Li alloy changed the mechanism of fracture, showing a regular MVC pattern (Figure 3-d). The values of the fractal dimension were somewhat smaller than the corresponding to the alloys aged at 433 K (Table 2). As expected for the high temperature aged alloys, the overall ductility was higher and the general strength much lower compared with that obtained after aging at 433 K.

Table 2: Mechanical Properties and Fractal Dimension.

Aging Temperature (K)	Li Content (wt. %)	σys (0.2%) (MPa)	σts (MPa)	ε_f (%)	D
433	1.52	185	259	28.0	1.23
	1.75	179	242	28.4	1.19
	2.09	243	358	20.0	1.16
453	1.52	142	231	29.1	1.22
	1.75	145	220	26.0	1.17
	2.09	160	255	24.3	1.15

Although it seems obvious that the deeper the dimples the higher the roughness and the fractal dimension of a fracture surface [24], it is not always the case, since in addition to dimples many other complex features are frequently present, some of them almost undetectable, as the overlaps or re-entrant zones [25]. If several similar fracture surfaces are studied by conventional fractographic methods, the final results become meaningless if our attempts concern to find a relation between fracture morphology and mechanical properties. Nevertheless, from the point of view of the fractal geometry, several fracture surfaces with similar morphologies can be discriminated since there is a high probability that the corresponding fractal dimensions could be different. This is the case for the 1.52 Li alloy aged at 433 K and the 2.09 Li alloy aged at both, 433 and 453 K, (Figure 3-a, D = 1.23; Figure 3-c, D = 1.16 and Figure 3-f, D = 1.15), which showed the same QMVC mechanism of fracture. A similar result holds for the 1.52 Li alloy aged at 453 K and the 1.75 Li alloy aged at both, 433 and 453K, (Figure 3-d, D = 1.22; Figure 3-b, D = 1.19 and Figure 3-e, D = 1.17), which showed a MVC mechanism of fracture. The fractal dimension correlates well with the tensile ductility but if seems that there is not correlation at all when D is related with the yield strength or the true tensile strength as can be seen in Table 2. The higher the ductility at each aging temperature, the higher the fractal dimension, which agree with some previous results for other aluminum alloy systems [26-27].

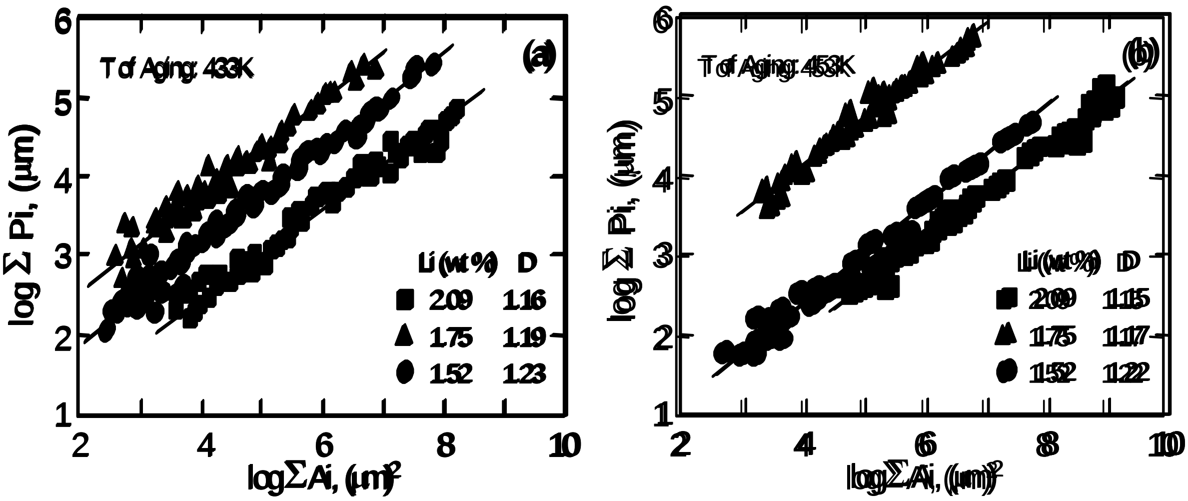

Figure 2: Fractal plots for the AlMgSi(-Li) alloys. (a) Aged at 433 K. (b) Aged at 453 K.

4. Conclusions

A quantitative fractographic study has revealed the fractal nature of tension fracture surfaces of three Al-Mg-Si alloys with a Lithium content of 1.52, 1.75 and 2.09 (wt. %), aged at 433 and 453 K. The true fracture strain measured at the peak aged condition correlated well with the fractal dimension. The higher the ductility at each aging temperature, the higher the corresponding fractal dimension. Very similar morphologies of fractured surfaces showing the same mechanism of separation but with different Li contents and aged at different temperatures, can be discriminated through fractal geometry examination

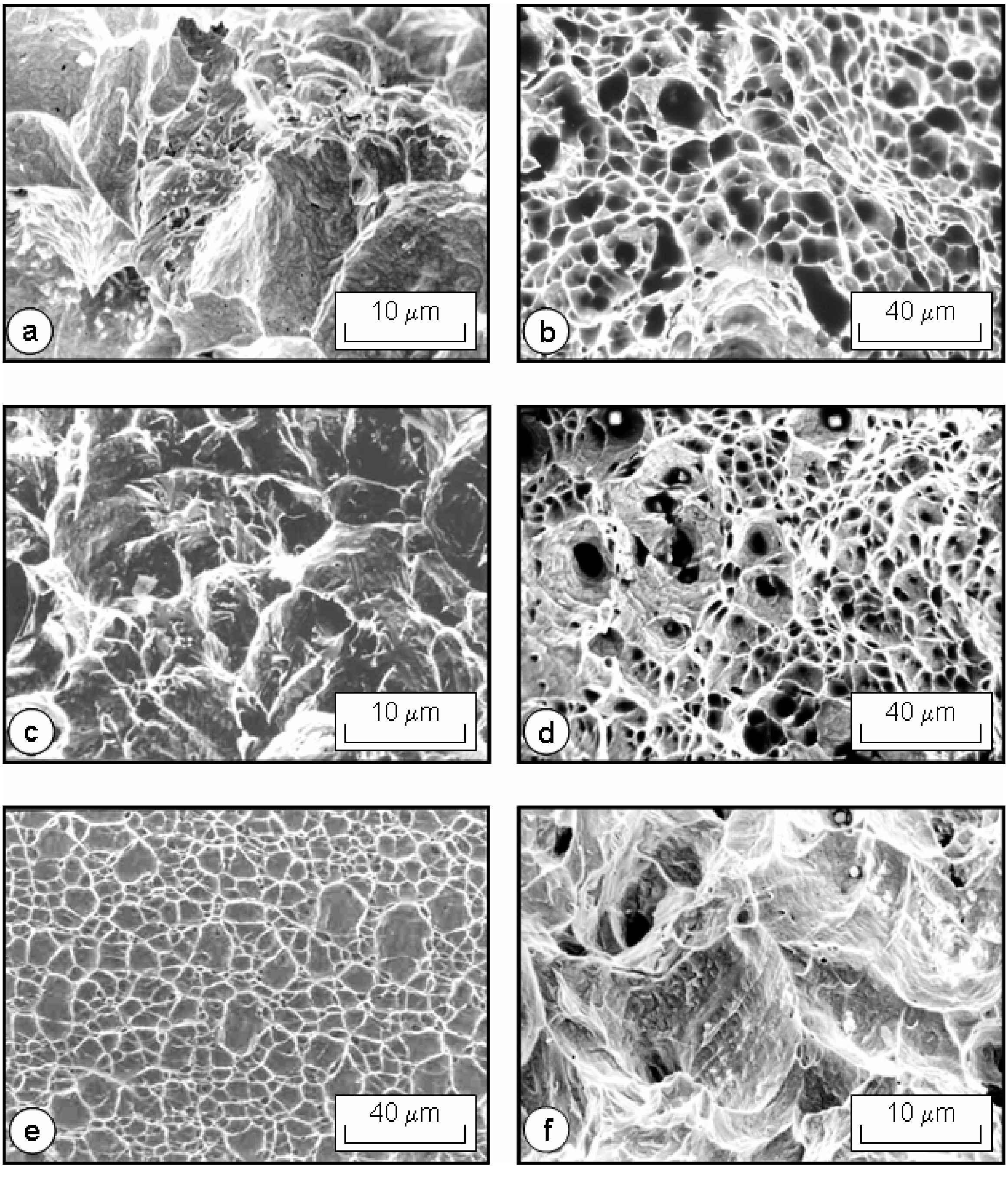

Figure 3: SEM fractographs for the Al-Mg-Si (-Li) alloys. (a) 1.52 Li, aged at 433K for 100h; (b) 1.75 Li, aged at 433K for 100h; (c) 2.09 Li, aged at 433K for 30h; (d) 1.52 Li, aged at 453K for 25h; (e) 1.75 Li, aged at 453K for 25h and (f) 2.09 Li, aged at 453K for 25h.

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