STRENGTH DUCTILITY AND FRACTAL CHARACTERISTICS OF AN Al-0.57Si-2.03Ge ALLOY

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ABSTRACT A study has been made on the fractal dimension-mechanical properties relations in an aged Al-0.57Si-2.03Ge (wt %) alloy. By using the vertical section and the slit island method, the corresponding fractal dimensions, Dv and Ds, were determined and correlated with the yield strength, σ_{ys}, the true tensile strength, σ_{ts}, the true fracture strain, ε_f, the critical strain for cavity nucleation, ε_c, the diameter of the incoherent SiGe precipitates, λ, and the dimple size of the tension fracture surfaces, d. The results showed that with increasing aging time; d, λ and ε_c increase. At the same time, its was observed a decrease of σ_{ys}, σ_{ts} and ε_f. Although the values of Dv and Ds were different, both showed similar tendencies: they were higher for higher values of d, λ and ε_c which means that the roughness of the fracture surfaces is an ultimate consequence of the initiation of the void nucleation which depends on the size of the precipitates. This is the reason why σ_{ys}, σ_{ts} and ε_f decrease as Dv and Ds increase.

Keywords: *Aluminium Alloys, Mechanical Properties, Fractal Dimension, Ductile Fracture, Microvoid Coalescence, Slit Island Method, Vertical Section Method.*

1. INTRODUCTION

In recent years a consisted formalized approach has emerged in fractography to search for correlations between morphology descriptors and mechanical properties. The ultimate objective of this approach, called "Fractal Geometry" [1-4], is to use the characteristic descriptor of the surface roughness, D, or "Fractal Dimension", to monitor materials properties in an attempt to improve material strength or resistance to fracture.

Fractal Geometry has been succesfully used to describe many irregular microstructure of materials, for instance, fracture surfaces [5-7], grain boundaries [8-13], dendritic microstructures [14], martensitic microstructure [15, 16], graphite shape and distributions [17], disordered particle composites [18] etc. Several kind af analyses in different materials show that the fractal dimension of the fractured surfaces correlates well with toughness. However, the question of whether this relation is positive or negative remains unknown, since the numerous experimental results are contradictory [19-23].

On the other hand, materials properties of technological importance, different than toughness, have been correlated with fractal dimension. For example, Richards and Dempsey [24] analyzed the relation between the ultimate tensile strength, the elongation, the alpha-volume fraction and the alpha-platelet lengths, and the fractal dimension in a series of Ti-4.5Al-5.0Mo-1.5Cr alloys. Wang et. al. [25], studied the relationship between D and the fatigue threshold value in dual-phase steels and Ling and Tang [26] correlated the fractal dimension of fracture surfaces with the uniaxial tensile strength in ductile polycrystalline CuZnAl alloy. For ductile fracture it is very difficult to interpret the variations in the relationships between D and the mechanical properties, including toughness, as the ductile fracture involves a more complex dissipated energy process during rupture.

Ishikawa [27], pointed out the fractal nature of the dimple patterns observed in ductile fracture and Nagahama [28], proposed a universal relationship between fractal dimension and toughness to define a criterion for brittle and ductile fracture. Based on the observations made by these authors, on some experimental results obtained by Koenigsmann et. al. [29], and Koenigsmann and Starke Jr. [30], as well as on current physical concepts of fracture, the strength, the ductility and some microstructural characteristics of an aged Al-0.57Si-2.03Ge (wt %) alloy, were studied in the present work and correlated with the fractal dimension of the uniaxial tensile fractures.

2. EXPERIMENTAL PROCEDURE

2.1. Materials, Aging Treatments and Tensile Testing.

An Al-0.57Si-2.03Ge (wt %) alloy was obtained from a commercial supplier. The chemical composition corresponding to the as-received material, was checked several times, and as a result, the reported one is a little different than the original. Since some data used in the present work (namely, the values of the critical strain for cavity nucleation, ε_c, and the average diameter of the incoherent SiGe precipitates, λ) were taken from the literarture [29-30]; we used the same general heat treatments as reported elsewhere, i.e. homogenization for 30h at 500 °C, hot rolling, solution heat treating at 490 °C, cold water quenching and aging in an air furnace for up to 16 days at 160°.

Room temperature tensile tests were done by duplicate in an Instron tensile machine at a strain rate of 10^{-3} s^{-1}, for the several aging conditions. The mechanical properties determined after the tensile tests were: the yield strength, σ_{ys}, the true tensile strength, σ_{ts} and the true fracture strain, ε_f.

2.2. Quantitative Fractography

The fracture surfaces of the broken samples were analyzed using a Hitachi S2400 scanning electron microscope operated at 25 kV. The evolution of the dimple size was studied assuming the dimples to be ellipsoids of revolution. According to this assumption, the mean chord in space, $\overline{L}_3$, is a reasonable parameter to characterize the dimple size, d [31].

2.3 Fractal Dimension Measurements

Two fracture surfaces for each experimental condition were mounted in resin. Before the mounting step, one of the fracture surfaces were given an electroless coating, in order to preserve the features of the profile, generated after a cross sectioning operation perpendicular to the surface. After metallographic preparation, the corresponding profiles were analized to evaluate their length, L, with a digitizing software, using rulers of different sizes, η, according to the vertical section method, VSM and the relation [32]:

$$L(\eta) = Lo\,\eta^{-(Dv-1)} \qquad (1)$$

where Lo is a constant with dimensions of length. For this case, the fractal dimension, $1 < Dv < 2$, was obtained from the linear portion of the log L vs log η diagrams.

The second fracture surface in each case, was studied by polishing operations in a series of steps according to the slit island method, SIM. The fractal dimension, Ds, was obtained from full logarithmic scale diagrams of Σ (Pi) vs Σ (Ai), being Pi and Ai, respectively, the perimeter and the area of the ith island, on a particular jth layer containing n such islands. According to the SIM [6]:

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

3. RESULTS AND DISCUSSION

3.1 Fractal Dimension Tendencies

In comparing the fractal dimension values corresponding to Ds and Dv, we found that both showed similar tendencies respect to the mechanical properties and microestructural parameters, which can be seen in Table 1.

Table 1. Mechanical Properties, Microstructural Parameters and Fractal Dimension Data

t (days)	σ_{ys} (MPa)	σ_{ts} (MPa)	ε_f (%)	ε_c* (%)	λ* (nm)	d (μm)	Ds	Dv
1	108	167	18	0.8	5.0	6.2	1.12	1.09
2	105	165	15	1.1	8.8	6.9	1.15	1.11
4	100	159	13	1.2	10.3	9.9	1.16	1.11
8	98	156	10	1.4	11.5	12.4	1.19	1.14
16	93	152	10	1.4	14.4	15.1	1.25	1.16

* After Koenigsmann et. al. [29] and Koenigsmann and Starke Jr. [30].

The values of the fractal dimension corresponding to the VSM and to the SIM, increased from 1.09 to 1.16 in the first case and from 1.12 to 1.25 in the second. Fig.1 shows both tendencies. For the VSM, the curves of the Fig.1-a show reversed sigmoidal behavior, RSB [33], so the values of Dv were evaluated in the central linear portion of each curve. The values of Ds, on the other hand, were derived from the straight lines developed in Fig.1-b.

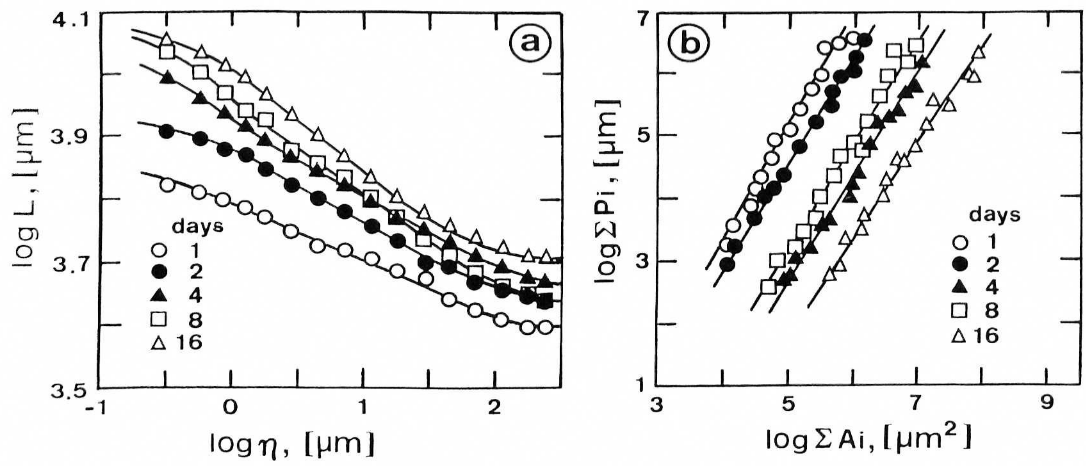

Fig.1 Fractal plots for the aged Al-0.57Si-2.03Ge alloy studied. (a) According to the vertical section method, using the Richardson-Mandelbrot relationship and (b) Using the SIM.

3.2 Fractal Study of the Microstructure

As can be seen in Fig.2-a, the higher the time of aging, the higher the fractal dimensions, Ds and Dv, the average diameter of the SiGe precipitates, λ, and the average dimple size, d. Since the fractal dimension has been considered a measure of the surface roughness, the direct relation between Ds and Dv on one hand, and λ and d, on the other hand, can be explained in terms of the deep of the dimples, which is a consequence of the size of the ligaments between the voids just before the local coalescence event. the higher the time of aging, the higher the average precipitate diameter [29, 30], the size of the intervoid ligaments and the average dimple size. As a result the surface irregularity increases.

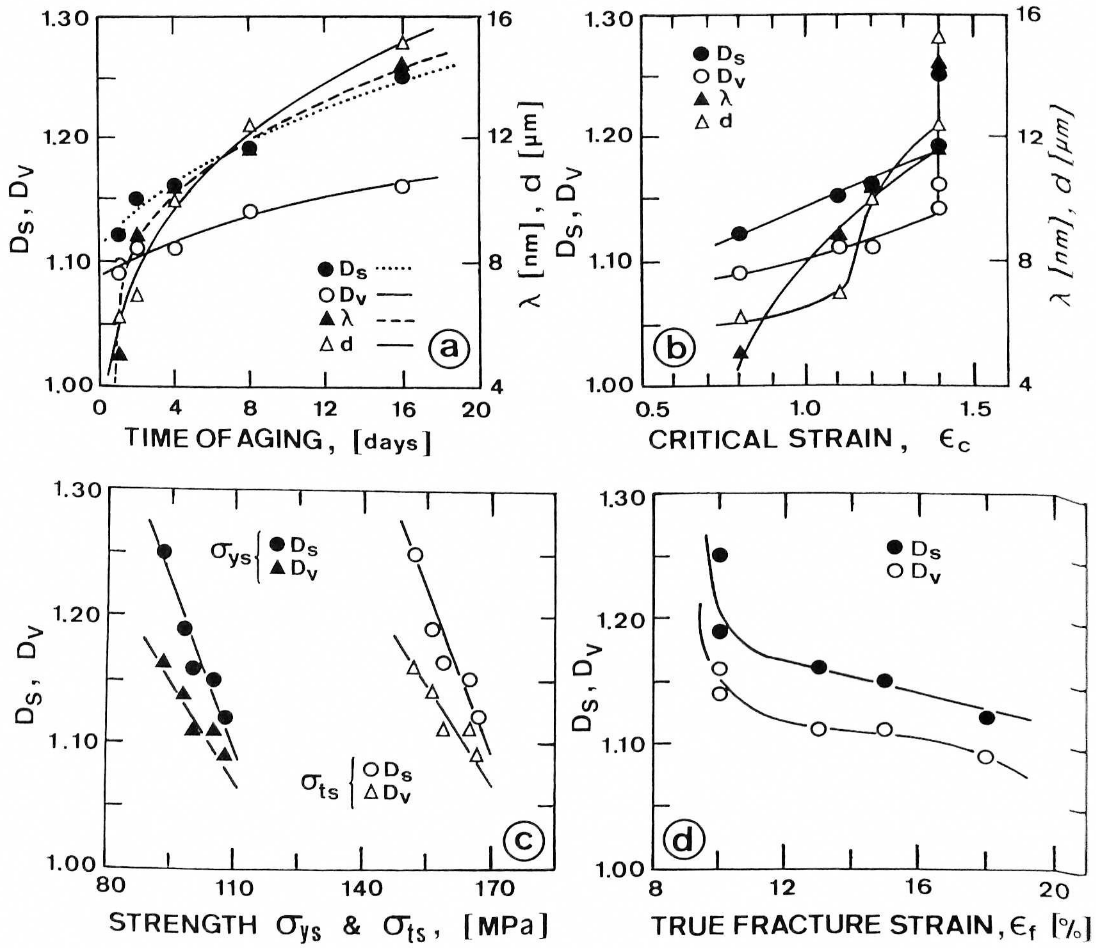

Fig.2 Fractal dimension as measured by the SIM, Ds, and the VSM, Dv; average precipitate diameter, λ, and average dimple size, d, vs: (a) the time of aging at 160 °C and (b) the critical strain ε_c. Dependence of Ds and Dv on: (c) the yield strength, σ_{ys}, and the true tensile strength, σ_{ts}, and (d) the true fracture strain ε_f.

It has been demonstrated that ε_c, in general [34, 35], and for the alloy studied here, increases as the precipitate size increases [29,30]. The Fig.2-b is a summary of all these findings.

3.3 Fractal Dimension-Mechanical Properties Relations

The results obtained for the fractal dimension as a function of the strenght and ductility (Fig.2-c and 2-d) indicate that these relationships are of the negative type. Since the fracture surfaces were of ductile nature for all the aging conditions, this kind of behavior is similar to the one proposed by Nagahama [28], between K_c and D when the fracture surfaces are ductile. This author suggest that the average size of void pits on ductile fracture surfaces is larger than that on brittle fracture surfaces, and normalizing by the average size of void pits on the brittle-ductile transitional fracture surfaces, shows that for small enough values of the average size of void pits, the negative relation between K_c and D changes to a positive one. This change defines the "brittle behavior", although the only mentioned features of the brittle fracture surfaces were those associated to small ductile deformations, i. e., mainly small dimples. We did not obtain brittle fracture surfaces, but the trends show in Figs.2-c and 2-d, support the Nagahama's criterion for ductile fracture.

The increase in dimple size with aging time is evident from Fig.3, which shows the dimple patterns associated to the fracture surfaces obtained after aging for 1 and 8 days. It can be seen that the values for σ_{ys} decrease from 108 to 93 MPa as the time of aging increases from 1 to 16 days. The corresponding values for the true tensile strength are 167 and 152 MPa. These variations represent a relatively small reductions of about 13.9% and 9% respectively. On the other hand, ε_f decreases in 44.44%, from 0.18 to 0.10. This concurrent reduction in strength and ductility is associated to the normal behavior expected from the coarsening of an incoherent precipitate.

Finally, the results obtained in the present work can be generalized by using a statement from Ishikawa [27]: "If a fractal is observed on a fracture surface with the dimple pattern, which is produced through the same process, the dimension of the fractal appears to be associated with the fracture properties".

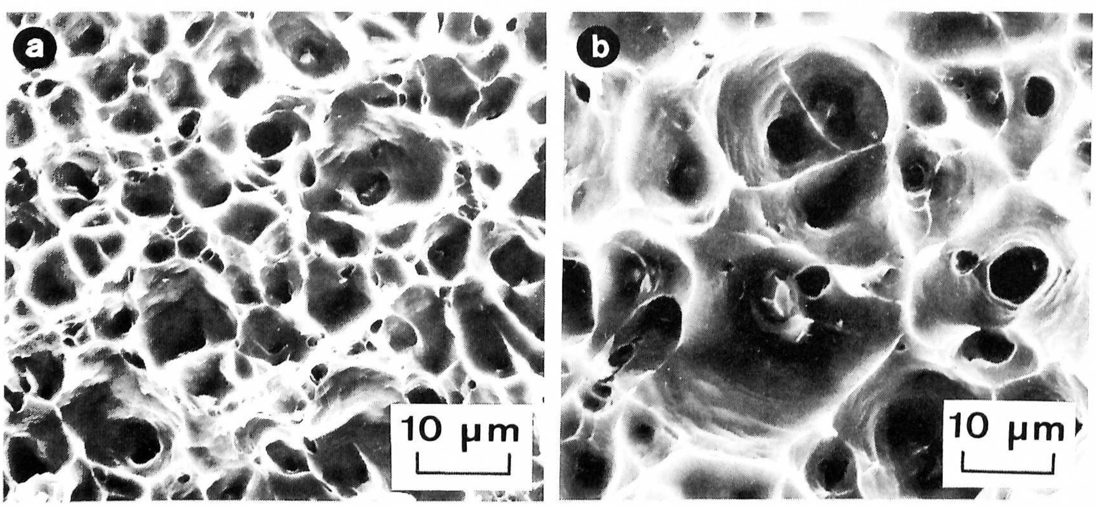

Fig. 3 Scanning electron micrographs showing the dimple characteristics of the tension fracture surfaces, corresponding to the studied alloy: (a) aged for 1 day and (b) aged for 8 days.

4. CONCLUSIONS

The behavior of an aged Al-0.57Si-2.03Ge alloy, based on fractal dimension-mechanical properties relations was studied. The results showed that with increasing aging time and fractal dimension (as measured by the vertical section, Dv, and the slit island method, Ds), the values of the average dimple size of tension fracture surfaces, d, increase; which agree with the concurrent increasing in the diameter of the incoherent SiGe precipitates, λ, and the critical strain for cavity nucleation, ε_c.

A negative relationships were obtained between the fractal dimensions Dv and Ds and the values of the yield strength, σ_{ys}, the true tensile strength, σ_{ts}, and the true fracture strain, ε_f. The values of the fractal dimension increasing from 1.09 to 1.16 and from 1.12 to 1.25 for Dv and Ds. At the same time, σ_{ys}, σ_{ts}, and ε_f decrease from 108 to 93 Mpa, from 167 to 152 Mpa and from 0.18 to 0.10 respectively.

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