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Full Length Research Paper

Fractal Analysis of Coarse-Grained Superplastic 5052-Aluminum Alloy

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Abstract
This study presented the fractal analysis of coarse-grain structure in superplastic aluminum 5052 alloy deformed at temperature 450º C and at the high strain rate of $10^{2}S^{1}$, water quenched at the elongations of 10%, 50% and 130% respectively. The grain sizes resulting from each micrograph were analyzed using weighted average and a measure of dispersion, which is doneby measuring the dispersion of the shapes of the grains from that of a perfect sphere (β = 1). The analysis show that the initial microstructure (undeformed sample) has sphericity0.9433 ± 0.1021 and fractal dimension 1.2825± 0.1215 indicating that the grains had almost attained the regular shapes. However, deformation of the sample above 50% elongation does not favor the growth of the grains within the microstructure.

Keywords: *Fractal analysis, Grain sizes, Superplastic, Sphericity and Fractal dimension.*

Introduction

Ordinary aluminum alloys elongate by less than about 100 % even when deformed at high temperatures (Diao*et al* 2012; Musin et al, 2004), some materials with suitable microstructure exhibit high elongation strain ranging from several hundreds to one thousand percent when deformed under specified conditions. Such a phenomenon is called "super-plasticity".Super-plasticity is the name given to the ability of a material to sustain extremely large deformationsat low flow stresses at a temperature around half the melting point expressed in Kelvin. It is onlyfound in metals and alloys, which have and can maintain during forming a very fine grain structure (Musin *et al.* 2002 and 2004).In addition, a parameter which indicates the degree of super plasticity is the strain rate sensitivity '*m'*, given bythe high temperature flow equation: $\sigma = k\dot{e}^{m}$, 'σ' is the stress for plastic flow, 'ė' is the applied strain rate and 'k' is a constant. Superplastic materials have '*m*' values normally between 0.4 and 0.6, whilemost other metals and alloys at elevated temperatures have '*m*' values of 0.2.On the other hand, viscous materials (e.g.glass) behave like a Newtonian fluid and have '*m*' values of 1.

However, there is a considerable interest in the application ofwrought Al–Mg–Sc alloys in the aerospace industry due to their good weldability, superior corrosion resistance and high strength [1]. The formability of the Al–Mg–Scalloys has been shown to improve significantly insuperplastic states Musin*et al,* (2004). These superplastic alloys arehighly suitable for the industrial applications due to thefact that their optimum superplastic properties areexhibited at exceptionally high strain rates. Therefore, the Al–Mg–Sc alloys can be effectivelyused in the fabrication of airframes, thin-walled andstiffened panels where high workability is required.

Musin *et al.* (2002) revealed that the grain sizes in superplastic 1421-Al alloy (Al-4.1Mg-2.0Li, 0.16Sc-0.07Zr) after subjecting to intense plastic strain by equal-channel angular extrusion (ECAE) was about 0.8 µm with a fraction of high angle boundary of 80%. Highest elongation of 1850% without failure at a temperature of 400º C and strain rate of 1.4 x $10^{-2}S^{-1}$ was observed. In a similar study, Musin *et al.* (2004) recorded a maximum elongation-to-failure of 2000% when a commercial Al–Mg–Sc alloy was subjected to severe plastic deformation through equal-channel angularextrusion (ECAE) at a temperature of 450º C and an initial strain rate of 5.6 x $10^{-2}S^{-1}$.

In addition, Diao*et al.*(2012) affirmed that continuous re-crystallization occurs during hot deformation of the 5052-Alalloy (Al-2.35Mg-0.16Cr-0.03Mn) at the temperature of 425º C and strain rate of $10^{-2}S^{-1}$.Maximumelongation to failure of 181% was observed which is sufficient for manufacturing of extremely complex shapes using superplastic forming technology.In this study, fractal analysis was used to numerically characterize the grain sizes in superplastic 5052-Al alloy.

Methodology

Fractal Analysis of Grain size Characterization

Fractal geometry was firstly developed by Mandelbrot (1983). Itsprinciple is universal in any measurement and has been previouslyused by many researchers to numerically describe complexmicrostructures including graphite flakes, nodules and pores (Lu and Hellawell 1995, Huang and Lu 2002; Hangai and Kitahara 2008; Kong *et al.* 2011; Durowoju and Akintan 2013; Ping *et al.* 2008). The mathematical basis for measuring chaotic objects with the power law isadopted in this work. The basic equation is as follows:

$$P = P_e\, \delta^{D-1} \qquad (1 < D < 2 \text{ and } \delta_m < \delta < \delta_M) \qquad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where "P_e" is the measured perimeter, "P" is the true perimeter, "δ" is the yardstick, "δ_m and δ_M" are the upper and lower limits respectively for any shape and "D" is defined as the fractal dimension. The fractaldimension "D" describe the complexity of the contour of an object which can be more practically called roughness. Sphericity "β", on the other hand is used with fractal dimension "D", todescribe the shape of the grain sizes formed (Durowoju and Akintan 2013; Mandelbrot 1983). It can be expressed as:

$$\beta = 4\pi A_T/P^2 \qquad (0 < \beta < 1 \text{ and } 1 < D < 2) \qquad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

From the above two equations:

$$\beta = (4\pi A_T/P^2)\delta^{2(1-D)} \qquad (0 < \beta < 1 \text{ and } 1 < D < 2) \qquad \ldots\ldots\ldots\ldots\ldots (3)$$

where; "A_T" is the total grain sizearea. When β = 1 and D=1, a perfect circular shape is formed by the grain sizesin the microstructure. As β decreases, the shapes become more elongated showing a departure from perfect sphere.

In this work, an interactive Matlab program was developed to obtain the numerical values of the fractal dimension "D" and the sphericity "β". To develop the program the box counting method wasused with a counter incorporated into the program and the smallboxes or pixels occupied by the platelets outlines were counted. In all,four pixels (2×2 pixels, 4×4 pixels, 8×8 pixels and 16×16 pixels) andfour grid sizes (200×200, 100×100, 50×50 and 25×25) were selected.The selections were made for better resolution and to obtain accurate results. The spatial point pattern method (Figure 1) and the grain size distribution map (Figure 2) (Huang and Lu 2002) were used to describe the patternsdisplayed by the grain sizes after the samples had been deformed at 425º C and $10^{-2}S^{-1}$. The grain size distribution map can further be used to identify the shapes of thegrains and their dispersion from regular shapes.

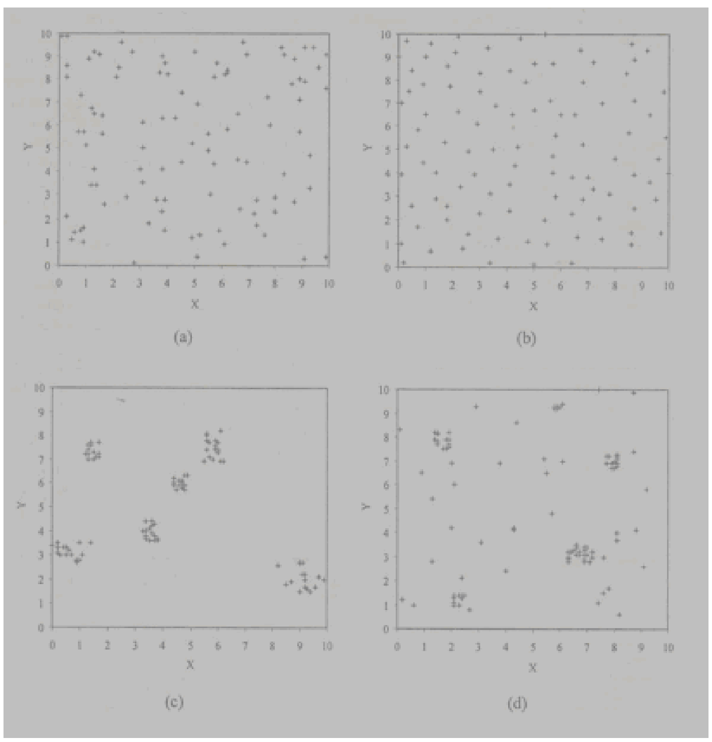

Figure 1: The four common types of spatial point patterns (a) random, (b) regular (c) clustered (d) clustered superimposed on random background.

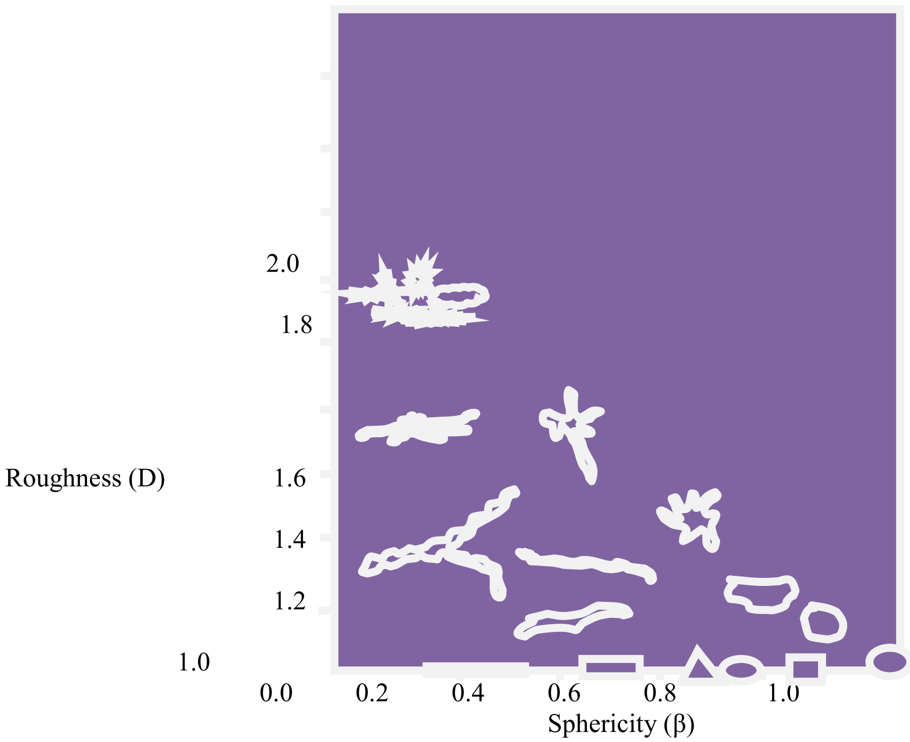

Figure 2: Illustration of development of irregular shapesbased upon Euclidean circle or rectangle.

Figure 3 showthe resulting micrographs of the experimental process that was conducted by Diao *et al.* (2012) on a superplastic 5052-Al alloy (Al-2.35Mg-0.16Cr-0.03Mn).In order to examine the variaton in grain sizes, uniaxial tensile tests were performed on the samples,interrupted and water quenched at the elongations of 10%, 50% and 130% respectively. Samples were prepared for optical microscope (OM) by electrolytic anodizing in Barker's Reagent at 20V for 240s.

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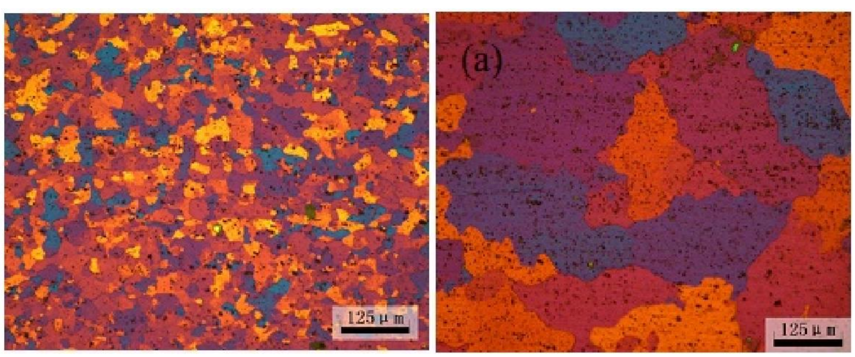

Initial microstructure of the 5052-Al alloy

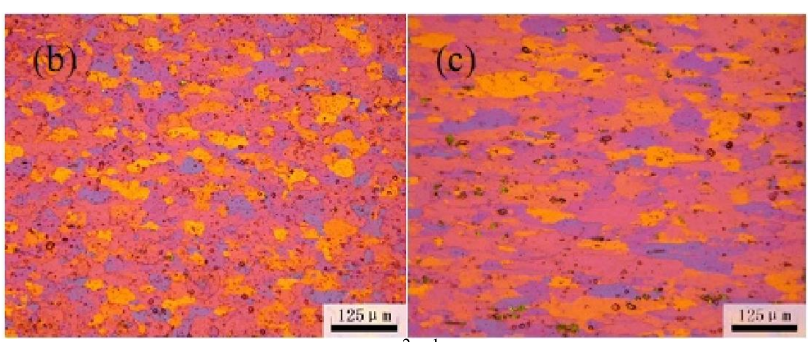

Figure 3: OM images in 5052-Al alloy deformed at 425º C and $10^{-2}S^{-1}$ to (a) 10%, (b) 50% and (c) 130% respectively.

Results and Discussion

Figure 4 show the isolation of the grain sizes in each of the micrograph. Presented in Figure (5a) is the grain size distribution map for un-deformed sample (initial microstructure), the grains were seen to be clustered and approximately of the same geometry. However, weighted average sphericity and fractal dimension $\beta = 0.9433$ and $D = 1.2825$ were obtained, showing that the grains have almost attained the perfect shapes. This is in good agreement with the work of Diao *et al.* (2012) where they observed that the grains in undeformed sample (initial microstructure) are almost equiaxed.

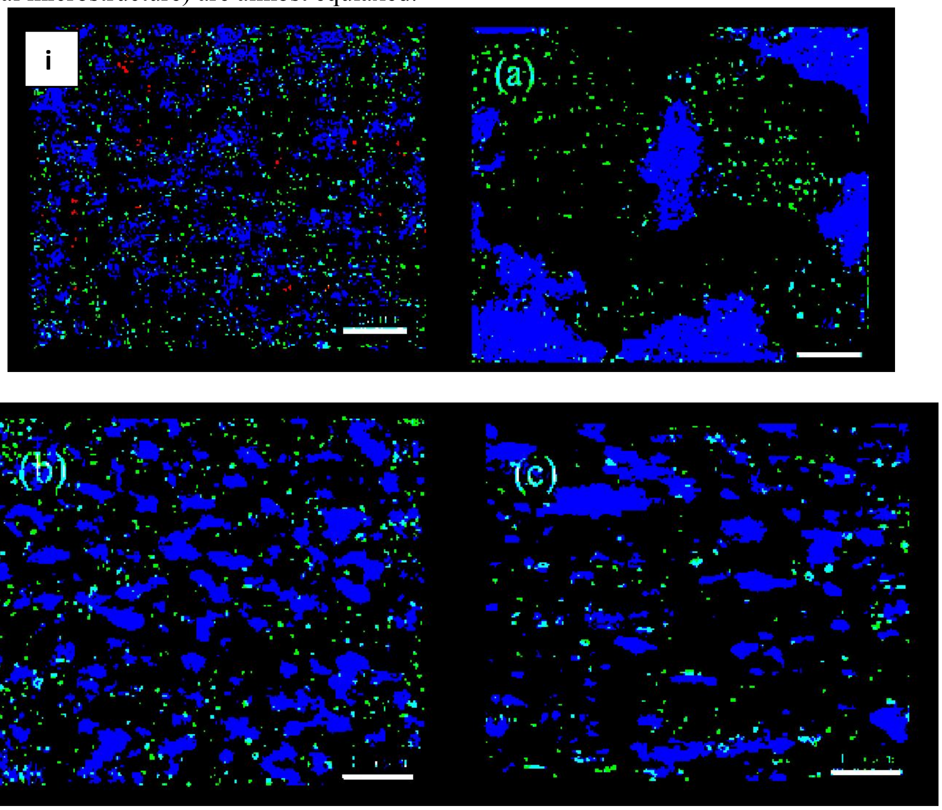

Figure 4: Isolation of the Grain sizes in 5052-Al alloy: (i) Initial microstructure (ii) After deformed at 425º C and $10^{-2}S^{-1}$ to (a) 10%, (b) 50% and (c) 130% respectively.

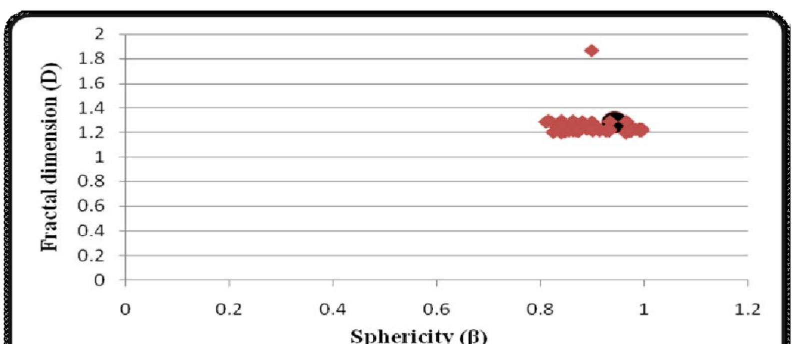

Figure 5a: Grain size distribution map for undeformed 5052-Al

Presented in Figures 5(b – d) are the grain size distribution maps for 5052-Al samplesdeformed at temperature 425º C and at the high strain rate of $10^{-2}S^{-1}$, water quenched at the elongations of 10%, 50% and 130%respectively, as obtained from the fractal analysis of theirmicrograph (Figure 4). Each data point represents an individual grain and the big-data points are the weighted average of the grains' sphericity and fractal dimensions.

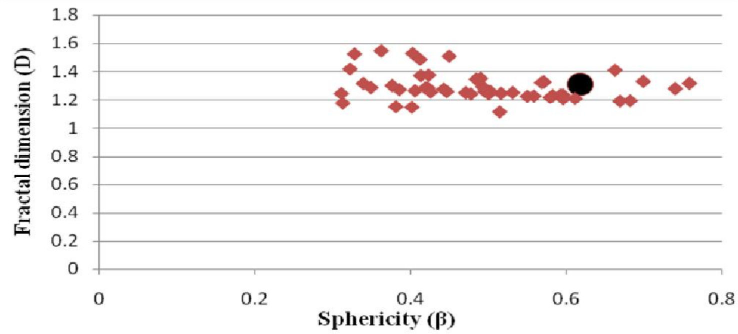

Figure 5b: Grain size distribution map for 5052-Al deformed at 425° C and $10^{-2}S^{-1}$ to 10%

Figure 5b above shows the grain size distribution map for sample deformed at 425º C and$10^{-2}S^{-1}$, water quenched at the elongation of 10%. The weighted average has0.6187 and 1.3085 for sphericity and fractal dimension. The grains are said to be clustered superimposed on random background.

However, in Figure 5c, the grains are seen to be attaining better regular shapes with weighted average sphericity and fractal dimension values (β = 0.9036 and D = 1.1979) when quenched at the elongation of 50% better than the sample quenched at the elongation of 10%. The grains are clustered superimposed on random background.

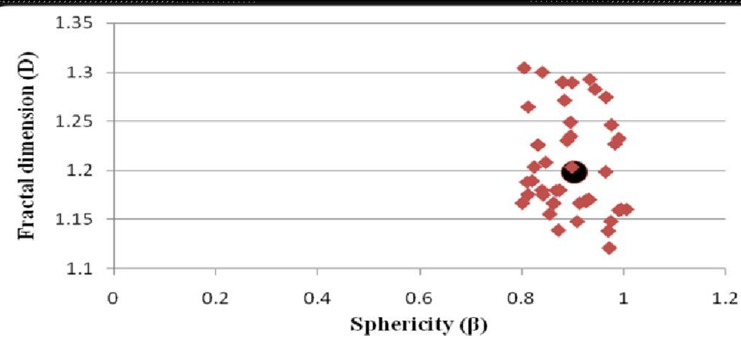

Figure 5c: Grain size distribution map for 5052-Al deformed at 425° C and $10^{-2}S^{-1}$ to 50%

Presented in Figure 5d is the grain size distribution map for sample deformed at 425º C and$10^{-2}S^{-1}$, water quenched at the elongation of 130%. The weighted average sphericity and fractal dimension 0.6829 and 0.9444 were obtained. The grains in the sample have far moreirregularshapesthan grains in initial micrograph.

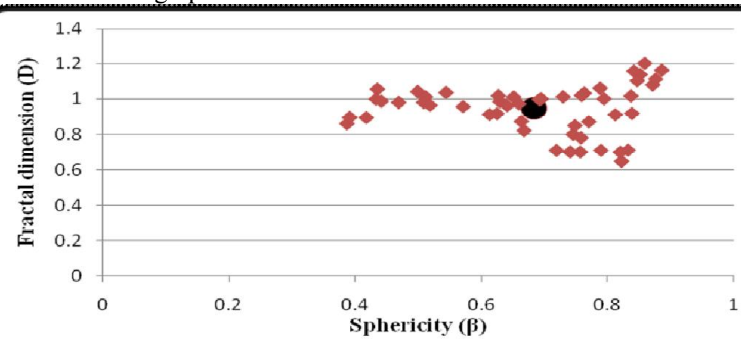

Figure 5d: Grain size distribution map for 5052-Al deformed at 425° C and $10^{-2}S^{-1}$ to 100%

Conclusion

From the grain sizedistribution maps, it can be seen that grains in under-formed sample are concentrated between β = 0.81 and 0.99. However, deformation of 5052-Al at temperature of 425º C and at the high strain rate of $10^{-2}S^{-1}$, water quenched at the elongations of 50% favor the growth and distribution of grains within the microstructure.It can be inferred from this analysis that increases in elongation of the sample above 50% decreases the sphericity values of the grains.Hence, further study can be done on the deformation of aluminum 5052 alloy between 50% to 100% elongation rate to ascertain whether the β values will attain the perfect shapes and sizes (β = 1 and D = 1).

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