Application of Fractal Analysis in Evaluating the Pores in Heat Treated Samples of Al-20%wtMg.

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ABSTRACT

Fractal analysis was used to observe the sizes, shapes, and distribution of pores in samples of Al-20%wtMg heat-treated at 470^0C for a soaking time of 30 minutes. The fractal analysis was done by obtaining the values of fractal dimension D and sphericity β. These values were used to identify the shapes of the pores (best or worst) and the pore distribution pattern in the porosity distribution map.

The best shapes of pores are those with D and β values closest to that of a perfect sphere (i.e., D=1 and β=1) while the worst shapes are those with D and β values farthest away from that of a perfect sphere. The analysis revealed that the pores were either nodule-like or flake-like and of irregular shapes. They were shrinkage pores, with sphericity $\beta<0.3$. In the microstructure of the oil quenched sample, the "worst" of the shapes is the pore with β=0.0102 and D=1.1260, while the "best" shape is the pore with β=0.0662 and D=1.0510. Similarly, in the microstructure of the water quenched sample, the "worst" of the shapes is the pore with β=0.0166 and D=1.0762, while the "best" shape is the pore with β= 0.0740 and D=1.0510.

The β vs D graph shows that there exist critical values of fractal dimensions (1.0360 and 1.0510) above which any increase in the fractal dimension causes a decrease in the sphericity. Similarly, there exists minimum values of fractal dimension and sphericity (D= 1.048 and β= 0.0384), above which the tensile strength and hardness increases. The results largely validate the works of Huang and Lu (2002) for similar Aluminum alloy treated as described above.

(Keywords: Aluminum alloy, quenching, fractal dimensions)

INTRODUCTION

The use of fractal analysis to study surfaces of different materials has been done by different researchers and it is still receiving increasing attention. Scientists who study or try to describe natural phenomena have to consider the use of fractal geometry. From the theory of chaos, to land surface description, from sea surface synthesis, to stock market analyses, fractal concepts are used in more and more research fields (Giuseppe et al., 2006).

Chung-Kung (1998) used fractal analysis and observed the effect of heat treatment on the well-measured nitrogen isotherms on alumina and aluminum borate samples. He observed that heat treatment, for the two methods used, may decrease fractal dimension, D, of the four examined porous samples. From the analysis carried out, fractured surfaces were discovered to be fractal in nature (Alexander, 1990).

For alloys and composite materials containing regular microstructures, a prediction of the mechanical properties can be made by a quantitative measurement of features such as grain size, particle sizes, spacing, etc. This, however, is not the case where an irregular microstructure is involved because of the difficulty in numerical characterization of the structure. For such a microstructure, the application of fractal geometry offers a method by which both the individual particle shapes and the mode of the distribution of the particles can be fully described in a numerical manner (Shu-Zu and Hellawell, 1994).

The measurement of the porosity in cast aluminum alloys using fractal analysis was done by Huang and Lu (2002) and more recently on the pores in annealed Al-V_2O_5 mechanically alloyed composite by Durowoju (2007). They found that fractal analysis can be applied to the porosity measurement to describe the shapes of the pores in cast aluminum alloys using two dimensionless parameters, roughness, D and sphericity, β. They further observed that the tensile strength of the samples is related to the shapes of the pores in the microstructure. The higher the sphericity β, the higher the tensile strength.

Blaz et al. (2004) working on Al-V_2O_5 mechanically alloyed composites, observed that inter-metallic grain coarsening and increased porosity of aged samples result in a reduction of the metallic hardness. However, the term heat-treating is often used in the aluminum to describe the procedures and practices required to achieve maximum strength or hardness in a suitable alloy. Normal practice involves a sequence of solution heat-treating, rapid cooling (quenching), and precipitation hardening (aging).

This work is aimed at studying the effect of water and oil quenching on the shapes of the pores in Al-20%wtMg. The intention is to use fractal analysis to numerically characterize the shape, size and the distribution of the pores in the microstructures of both water and oil quenched Al-20%wtMg. In addition, an empirical equation will be established between the fractal parameters (β and D) and the mechanical properties (Tensile Strength and Hardness)

MATERIALS AND METHODS

One kg (80% by proportion) of commercial aluminum (99.7% pure, by weight) and 250g each (20% by proportion) of Mg, was obtained from the Federal Institute of Industrial Research, Oshodi, and were prepared for the casting.

The molten alloys were poured into the prepared mould after cooling for three minutes. The resulting cast samples, in rod form, were removed from the mould after three hours (to allow for effective cooling) with two of them prepared for the quenching operation. The two samples were put into an electrical furnace preset to a temperature of 470°C. The soaking time for the samples in the furnace after the preset temperature was attained was 30 minutes.

The samples were removed from the furnace and some were quenched in water and while the others were quenched in spent engine oil plus 50 (15W- 40) in line with the work of Evans (1996). The photograph of the resulting microstructure of the aluminum alloy samples were taken with a digital camera attached to the optical microscope set at x100 magnification.

The fractal geometry developed by Mandelbrot (1983) was adopted in this work and its principle is universal in any measurement and has been previously used to numerically describe complex microstructures including graphite flakes and nodules (Lu and Hellawell, 1994, 1995, 1999). The mathematical basis for measuring chaotic objects with the power law modified is adopted in this work. The basic equation is as follows:

$$P = P_E \delta^{D-1} \qquad \textbf{(1)}$$

where P_E is the measured perimeter, P is the true perimeter, δ is the yardstick, δ_m and δ_M are lower and upper limits, respectively, for any shape and D is defined as the fractal dimension (1< D< 2).

From this expression, it can be deduced that the true perimeter is actually a function of the yardstick for measurement. The smaller the yardstick used, the more accurate the measurement. The fractal dimension, D, therefore describes the complexity of the contour of an object. It can be more practically called its roughness (Huang and Lu, 2002).

When $\delta < \delta_m$, the measurement is not sensitive to the yardstick chosen, therefore giving a smaller value of the slope, while when $\delta > \delta_M$, the size of the yardstick exceeds that of the individual feature being measured so that the measurement loses meaning because the object falls below the resolution limit of the yardstick used for measurement (Lu and Hellawell, 1994). Sphericity, β, another dimensionless number, is used together with the fractal dimension, D; to describe the shape of the pores formed. It can be expressed as

$$\beta = 4\pi A_T / P^2 \qquad \textbf{(2)}$$

Substituting equation (1) in eqn. (2) gives:

$$\beta = \left(4\pi A_T / P_E^2\right)\delta^{2(1-D)} \qquad \textbf{(3)}$$

where, A_T is the total area. 0<β<1 and 1<D<2. When β = 1 and D = 1, a perfect circular shape is formed by the pore in the microstructure. For shrinkage pores, β<0.3 and for gaseous pores β>0.3.

As β decreases, the shapes become more elongated showing a departure from perfect sphere (Huang and Lu, 2002).

The locations of $1 < D < 2$ represent less regular shapes.

It can also be deduced from the equations that the larger the roughness the more irregular a pore and thus more stress concentration

Area of a pixel or yardstick = L x B

Area of the total pore A_T = Area of yardstick x Number of yardsticks

To calculate the perimeter P of the pore, the Slit Island Method (SIM) (Bigeralle and Iost, 2006) introduced by Mandelbrot (1983) was used. It is expressed as:

$$\log_e P = 0.5 D \log_e A_T$$

$$\log_e P = \log_e A_T^{D/2}$$

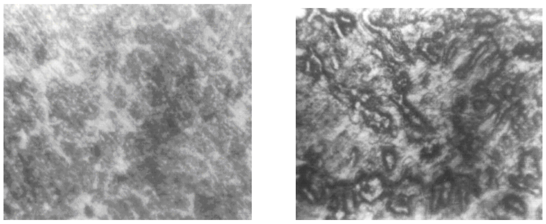
$$P = A_T^{D/2} \qquad \textbf{(5)}$$

Using the Equation (1), (2), and (5) above, an interactive software in MATLAB® programming language is developed to obtain the numerical values of the fractal dimension, D, and the sphericity, β, for the microstructures.

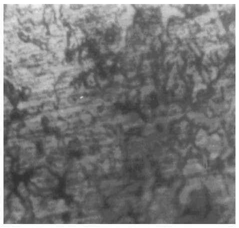
RESULTS AND DISCUSSIONS

Figure 1 shows the microstructures of the quenched Al-20%wtMg alloy samples used in this work. The pores are all-irregular in shape and are either nodule-like or flake-like.

The formation of the nodule-like or flake-like shape is due to the nucleation and growth kinetics usually compounded by composition variations and the concentration of elements such as magnesium, in the samples. Oil quenching preserved the nodule-like pores (i.e. the less harmful pores) as the dominating pores in the oil quenched alloy sample.



(a) As-Cast Sample (b) Oil Quenched Sample



(c) Water Quenched Sample

Figure 1: Microstructures of Quenched Al-20%wtMg

Water quenching on the other hand made the flake-like pores dominant pores in the water quenched cast sample. This observation is due to the fact that water has a high thermal conductivity (0.55-0.70W/mK) and high Grossman number (0.9-1.0) otherwise called the quench severity than oil, with thermal conductivity of 0.15W/mK and Grossman number of 0.25-0.30.

(4)

These shape changes in the quenched samples greatly depend on the soaking time and the cooling rates, with rapidly cooled (water quenched) sample having drastic changes than the intermediately cooled (oil quenched) sample as shown in Figure1.

It was also observed that the inter porosity separation distance decreases from the intermediately cooled to the rapidly cooled sample. Paramo et al. (2000) had observed a similar shape change in morphology of intermetallic phases when working on the spheroidization of the Al-Si eutectic in a cast aluminum alloy quenched in cold water with soaking time ranging from 2-40h. Based on the aforementioned shape considerations, oil quenched sample should have better mechanical properties than the water quenched sample. This implies that, if improved mechanical properties are desired, water quenching should be avoided in Al-20%wtMg.

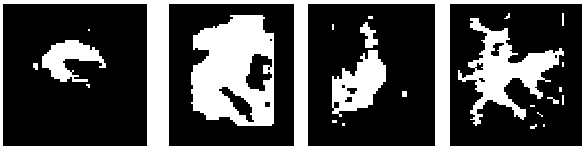


Figure 2: Isolation of Some of the Pores in Oil and Water Quenched Microstructures of Al-20%wtMg.

Crack initiation is likely to commence in samples with more flake-like pores because of the irregular shapes of the pores and their ease of linkages, creating areas of stress concentration leading to failure. Fractal analysis reveals that the pores are of irregular shapes. They were shrinkage pores as shown in Figure 2, with β approaching zero and fractal dimension D approaching 2.0 (note: for a perfect sphere β=1 and D=1 where 0 < β < 1 and 1< D < 2). For shrinkage pores, β< 0.3 and for gaseous pores, β> 0.3 (Huang and Lu, 2002)

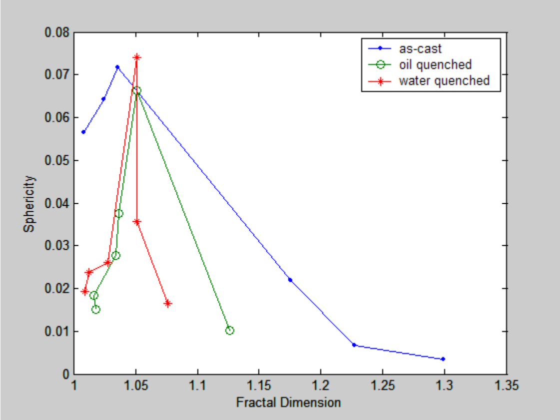


Figure 3: Sphericity against Fractal Dimension.

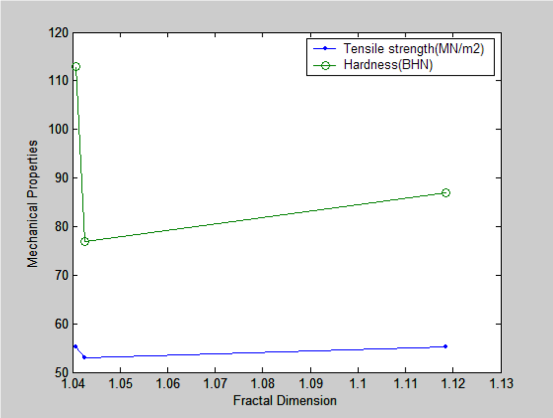


Figure 4: Mechanical Properties against Average Values of Fractal Dimension.

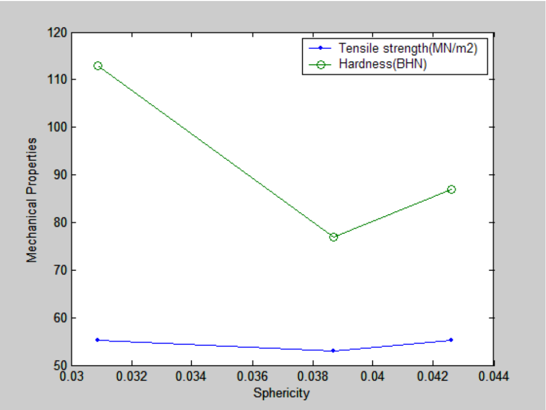


Figure 5: Mechanical Properties against Average Values of Sphericity.

The values of D and β were used to identify the shapes of the pores (best or worst) and the pore distribution pattern in the porosity distribution map. The best shapes of pores are those with D and β values closest to that of a perfect sphere (i.e. D=1 and β=1) while the worst shapes are those with D and β values farthest away from that of a perfect sphere.

In the oil quenched sample the "worst" of the shapes is the pore with β=0.0102 and D=1.1260, while the "best" shape is the pore with β= 0.0662 and D=1.0510. Similarly, in the water quenched sample the "worst" of the shapes is the pore with β=0.0166 and D=1.0762, while the "best" shape is the pore with β= 0.0740 and D=1.0510. In Figure 3, it was observed that there exist critical values of fractal dimension (1.0360 and 1.0510) above which any increase causes a decrease in the sphericity.

Figures 4 and 5 show that as the fractal dimension and sphericity of the shapes approach the minimum point (D= 1.048 and β= 0.0384), the tensile strength and hardness decreases. Any increase in the fractal dimension and sphericity above the minimum points causes a corresponding increase in the tensile strength and hardness.

This result implies that as the shapes approaches a perfect shape the tensile strength and hardness increases. Similarly, as the surface of the pores becomes rougher the tensile strength and hardness also increases.

CONCLUSIONS

- The pores in the microstructures of Al-20%wtMg after heat treatment were either nodule-like or flake-like.
- Water quenching caused a change in pore shapes from the predominant nodule-like shapes in the as-cast sample to flake-like shapes in the water-quenched sample.
- There exist minimum values of fractal dimension above which any increase causes a decrease in sphericity.
- In addition, there exist minimum values of fractal dimension and sphericity above which any increase causes a corresponding increase in tensile strength and hardness.

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