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MODIFICATION AND PORE DISTRIBUTION IN CAST AL A356 ALLOY USING WC NANOPARTICLES

Mudashiru, L.O^{1*}, Adeaga O.A², Adegbola, A.A¹ and Sanusi, W.O¹

¹Department of Mechanical Engineering, Ladoke Akintola University of Technology, PMB 4000, Ogbomoso, Nigeria

²First Technical University, Ibadan, Nigeria

Abstract

The rapid growth of Aluminum is as a result of their extensive use in automotive, aerospace and transport industry. Several modifiers have been employed in order to improve the mechanical properties of Al-based alloys. Porosity formation and distribution in eutectic Al-Si alloy A356 modified with Tungsten Carbide (WC) nanoparticles was investigated using fractal analysis. WC nanoparticles added in an amount of 0.1 wt. % to the molting melts yield fine microstructure with porosity level lower than the as-cast sample. As average sphericity value approaches 0.12 %, this is an indication that the porosity level as being reduced to a lesser harmful effect. Shrinkage and gaseous pores are more pronounced in untreated aluminum alloys. The result has demonstrated that Fractal analysis can be applied to the porosity measurement to describe the shapes and sizes of the pores in recycled aluminum alloys.

Keywords: Al 356 alloy, WC nanoparticles, Fractal analysis, Sphericity

*Corresponding Author: lomudashiru@lautech.edu.ng

Introduction

Aluminum due to its excellent mechanical properties such as high power-to-weight ratio, high wear resistance has found application and used in production of many components in aerospace, automotive and transport industry. Modification processes is being used as one of the most effective method for improvement of the mechanical properties of Al-based alloys (Gupta and Ling, 1999; Saleh *et al.*, 2016). Most mechanical properties of castings, especially

the elongation to fracture are determined by eutectic microstructure as Al-Si eutectic, consist of a hard, brittle Si phase in a softer Al matrix. Two different modification methods had been identified to modify flake-like Al-Si eutectic structure to a fine fibrous Si structure; chemical-modification (addition of certain elements) or quench-modification (rapid cooling rate) (Campbell, 2003).

Strontium, sodium, antimony, barium and calcium are among known several modifiers used in modification of alloy. Due to ease of handling and effectiveness, strontium in recent years has been employed as a chemical modifier in Al based industry (Lu and Hellawell, 1994; Konstantin and Michael, 2015). In recent time, nanotechnology has also been used extensively in metal strengthening processes. It has been reported that the addition of TiC, SiC and Al₂O₃ nanoparticles in a concentration of 1 wt. (%) during casting improved the mechanical properties of Al A356 (Lu and Hellawell, 1995; Zhang, *et al.*, 2006). In this study, the influence of ceramic WC nanoparticles on the features, formation and distribution of pores in Al A356 was reported.

Fractal analysis plays a vital role in quantification of self similarity and complexity of natural structures such as the perimeters of clouds, coastlines and various other geometries (Lu and Hellawell, 1994; Huang and Lu, 2002). Many researchers (Lu and Hellawell, 1995; Durowoju, 2013; Durowoju *et al.*, 2013) have used it extensively in engineering field to study the morphological changes in pores found in cast alloys. Similarly, it has been applied in medicine to distinguish cancer tissue from normal tissue (Hangai and Kitahara, 2008). Also, fractal geometry provides a method by which the individual particles or pores, shape and their mode of the distribution in irregular microstructures, can be fully described in a numerical manner (Huang and Lu, 2002). Many researchers have extensively used fractal analysis to study surfaces of different materials and more work is still on-going in the area of the study.

It has been established that there is a link between composition and processing of cast aluminum alloys, when fractal analysis of

the pores in the microstructure was carried out to the crack initiation and the quantitative estimation of the morphology of pores such as their shape, size or distribution which can also be a source of useful information (Hangai and Kitahara, 2008; Durowoju, 2013; Durowoju, *et al.* 2013). The method of Huang and Lu (2002) was used to investigate fractal analysis of perimeter to carry out quantitative study of porosity in aluminum die castings while that of Durowoju (2013) and Durowoju *et al.* (2013) was employed to thoroughly examined the fractal analysis of the platelets in Al-Si eutectic cast alloy. The fractal dimension and microstructure of aggregates of Fe-2%Cu-0.5%C in powder form, compacted and sintered under varying temperature was investigated (Kong *et al.*, 2011). In this study, fractal analysis of porosity formation in Al A356 alloy was determined.

Materials and Methods

Al-Si alloy A356 was used as a bulk material in this study. The modifier employed was WC nanoparticles (Wolfram Bergbau, Austria), with a theoretical density 99.95 %, crystallite size 40 - 70nm. In the first sample, 5 wt. (%) WC nanoparticles was mixed with 20 kg A356 (99 %+, 20-40 mesh), homogenized for four hours in a Retsch planetary ball mill with milling speed and activation time of 400 rpm and 5 min, respectively. The powder mixture obtained was hot extruded using home-made extrusion container with an extrusion ratio equal to 17.4 at 623K. Electric resistance furnace was employed to melt 20 kg of Al-Si alloy A356 ingots, as a control sample. The melt was poured into a prepared green sand mould. Samples for a microstructure investigation were prepared by polishing and etching with Kalling's reagent. Optical

metallurgical microscope (XJL-17 model) was used to carry out microstructure studies.

Determination of Porosity Using Fractal Analysis

Fractal geometry was firstly developed by Mandelbrot (1983). Its principle is universal in any measurement and has been previously used by many researchers to numerically describe complex microstructures including graphite flakes and nodules (Lu and Hellawell, 1995; Huang and Lu, 2002; Lu and Hellawell, 1994).

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 was used with a counter incorporated into the program and the small boxes or pixels occupied by the pores outlines are counted. In all, four pixels (2×2, 4×4, 8×8, and 16×16 pixels) and four grid sizes (200×200, 100×100, 50×50 and 25×25) were selected. The selections were made for better resolution and to obtain accurate values. In this work, the mathematical basis for measuring chaotic objects with the power law was adopted. The basic equation is as follows:

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

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.

The fractal dimension “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”, to describe the shape of the pores formed (Saleh *et al.*, 2016). It can be expressed as:

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

From the above two equations:

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

Where “ A_T ” is the total pore area. When $\beta = 1$ and $D = 1$, a perfect circular shape is formed by the pore in the microstructure. As “ β ” decreases, the shapes become more elongated showing a departure from perfect sphere. Furthermore, Spatial Point Pattern Method (SPP; Figure 1) and the pore distribution maps (Figure 2) were also constructed to identify the shapes of the pores and their dispersion from regular shapes.

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

Results and Discussion

The micrographs of unmodified and the samples treated with WC nanoparticles were shown in Figures 3. From the result, it can be observed that the addition of WC nanoparticle seems to promote the formation of fine equiaxed α -Al grains with distributed eutectic Si particles compared with large,

elongated α -Al grains present in unmodified sample. Pores selected from both micrographs were fed into the computer program to evaluate their fractal dimensions and sphericities. Each data point represents an individual pore and the big-sized data point represents the weighted average of the pores' sphericities and fractal dimensions, respectively.

Figure 2: Illustration of development of irregular shapes based upon Euclidean geometry

Figure 3: Optical micrographs of A356 alloy before^(a) and after^(b) modification process using WC modifier Magnification $\times 100$

Figure 4: Porosity distribution map for AL A356 without modifier

Figure 5: Porosity distribution map for AL A356 with modifier

Figure 4 shows the pore distribution maps for unmodified sample of AL A356. It is evidence from the micrograph that the pores are randomly distributed. Weighted average values of sphericity and fractal dimension of 0.8393 and 1.6060, respectively were obtained.

The pore distribution map for sample modified with WC nanoparticles was presented in Figure 5. It was evidence from the micrograph that the pores are evenly and randomly distributed as the shape of the pores had attained regular domain. Weighted average values of sphericity and fractal dimension of 0.9649 and 1.0019 were obtained. Compared with the unmodified

sample, there is significant improvement in the sphericities of modified samples. In addition, Huang and Lu (2002) observed that shrinkage pores are usually larger in size and of more irregular than gaseous pores. This is in good agreement with $\beta < 0.38$ given by Huang and Lu (2002). Thus, the pores in Figure (3b) are less harmful and perhaps could not pose any detriment to the mechanical properties of the alloy.

Conclusion

This study has shown that fractal analysis can be applied to the porosity measurement to describe the shapes and sizes of the pores in recycled aluminum alloys using two

dimensionless parameters, fractal dimension (D) and sphericity (β). This method may complement with the conventional quantitative examination for porosity measurements. Furthermore, it was observed that both shrinkage and gaseous pores are more pronounced in untreated aluminum alloys. As the average values of Fractal dimension (D) and sphericity (β) for sample modified with WC nanoparticles were closer to 1, the shrinkage pores have been totally eliminated and gaseous pores were also reduce to the barest minimum.

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