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# A Comparative Study of Macro-Grain Silicon Contents in Aluminium Alloy Produced by Electrolysis

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***ABSTRACT:*** *Fractal analysis of macro-grain size distributions in pure-Al and Al-Ti based alloys produced by electrolysis process were comparatively studied. The macro-grain sizes resulting from each macrograph treated with 0.04, 0.5, 1, 2, 3, 5, 7, 10 and 12 (mass%) silicon contents were analyzed using weighted average and a measure of dispersion (variance), which is done by measuring the dispersion of the shapes of the grains from that of a perfect sphere (β = 1). Spherical grain size results were obtained in pure-Al with 12% silicon contents and Al-Ti based alloy with 1% silicon contents having sphericity's value of 0.9952 ± 0.0043 and 0.9989 ± 0.0011 respectively. The analysis revealed that high percentage of silicon contents in pure-Al produced by electrolysis method favour the growth of macro-grain sizes. On the other hand, low percentage of silicon contents in Al-Ti based alloy promotes the formation and distribution of macro-grain sizes.*

***Keyword:*** *Macro-grain size, Electrolysis, Silicon contents, Sphericity.*

## I. Introduction

Cast aluminium-silicon alloys are being increasingly used in marine, electrical, automotive, defence and aerospace industries for critical structure applications because of their excellent castability, low density, acceptable mechanical properties and low cost (Kaufman and Rooy 2004; Brown 1999). Mechanical properties of this family of cast alloys are strongly affected by the shape, size and distribution of the silicon eutectic and different intermetallics present in the microstructure. Chemical composition of the alloy, solidification conditions and modification are the most important casting parameters which are able to change the mentioned features of the silicon eutectics and intermetallics.

Silicon is one of the most frequent alloying elements in commercial pure aluminium. The master alloys containing titanium contents are usually used as the refiners in Al-Si alloys to ensure the mechanical properties, to improve feeding and surface finish, to reduce hot tearing and to evenly distribute porosities within the molten metal (Kaufman and Rooy 2004; Sadrossadat and Johansson 2009). Among the commercial Al-Si modifiers, Al-10Sr master alloy is the most commonly used one. It improves the mechanical properties considerably by changing the morphology of silicon eutectic from coarse plate like to a fine fibrous structure. Several research findings have shown that iron rich phases are the most effective intermetallics in altering the mechanical properties of the aluminium silicon base alloys depending on their type, size and shape (Sadrossadat and Johansson 2009).

However, the development of new processing techniques has becomes an inevitable task for both the materials community and the automobile industry. Different casting parameters change the microstructure and residual stresses in cast Al-Si alloy. The microstructure of Al-Si cast alloys is influenced by the morphology of silicon particles (shape, size and distribution), aluminium grain size and dendrite parameters (Hurtalová *et al.* 2001).

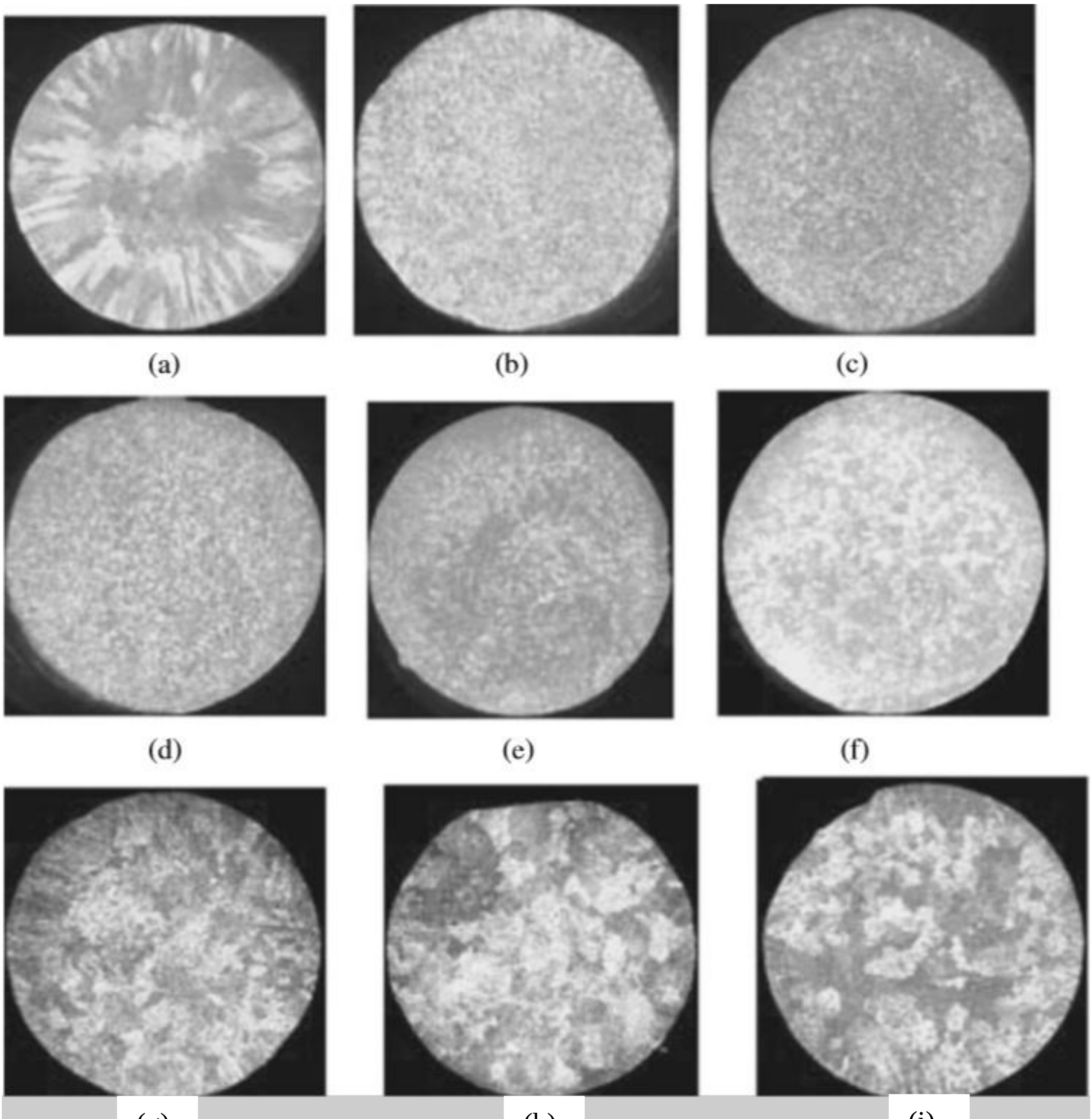
The secondary cast alloys also possessed a complex as-cast microstructure. By using various instruments (light microscopy, SEM) and techniques (black-white, colour etching, differential interference contrast and deep etching, EDX analysis) a wide range of intermetallic phases have been identified. Microstructural analyses also revealed that some alloying elements can form intermetallic compounds. Fe enters the intermetallic phases regardless of its concentration in the alloy. Mn usually presents in the Fe-containing phases. Cu on the other hand makes the intermetallic phases form in Al-Si alloys more compact. Mg forms intermetallic phases with Si or Cu (Taylor 1995).

Additions of Mn to neutralise the effects of iron are common, at Mn:Fe ratios of ≈0.5, however, the benefits of this treatment are not always apparent. Excess Mn may reduce β-phase and promote α-phase formation, and this may improve ductility but it can lead to hard spots and difficulties in machining. Mn additions do not always improve castability and reduce porosity in high Fe alloys. Its affect is sensitive to alloy composition (Liu *et al.* 2003). The effect of the processing temperature on the microstructural and mechanical properties of Al-Si (hypoeutectic) alloy solidified from intensively sheared liquid metal has been investigated. Intensive shearing gives a significant refinement in grain size and intermetallic particle size (Kotadia *et al.* 2005).

## II. Materials and Method

The effect of various silicon contents on the grain refinement and crystal morphology of pure aluminium and the Al-based alloy with low titanium content produced by electrolysis has been investigated (Liu *et al.* 2003). The starting materials used in their study were commercial pure aluminium (Si: 0.04mass%, Fe: 0.087mass %), Al-based alloys produced by electrolysis (Ti: 0.178mass%, Si: 0.047mass%, Fe: 0.085mass %) and crystal silicon (99.90mass %). After pure aluminium and Al-Ti-based alloy had been melted in two different graphite crucibles, varying silicon contents were added to the molten metal.

In this study, fractal analysis was used to evaluate the variation in grain sizes and shapes of the crystal morphology of the grain refinement after the addition of silicon contents to pure-Al and Al-Ti melts. Figure 1 and 2 show the macrographs of pure-Al and Al-Ti alloys with 0.04, 0.50, 1.00, 2.00, 3.00, 5.00, 7.00, 10.00 and 12.00% silicon respectively.




(g) **1:** Macrographs of pure alumini (h) us (a) 0.04, (b) 0.50, (c) 1.00, (d (i)
(e) 3.00, (f) 5.00, (g) 7.00, (h) 10.00 and (i) 12.00% Silicon

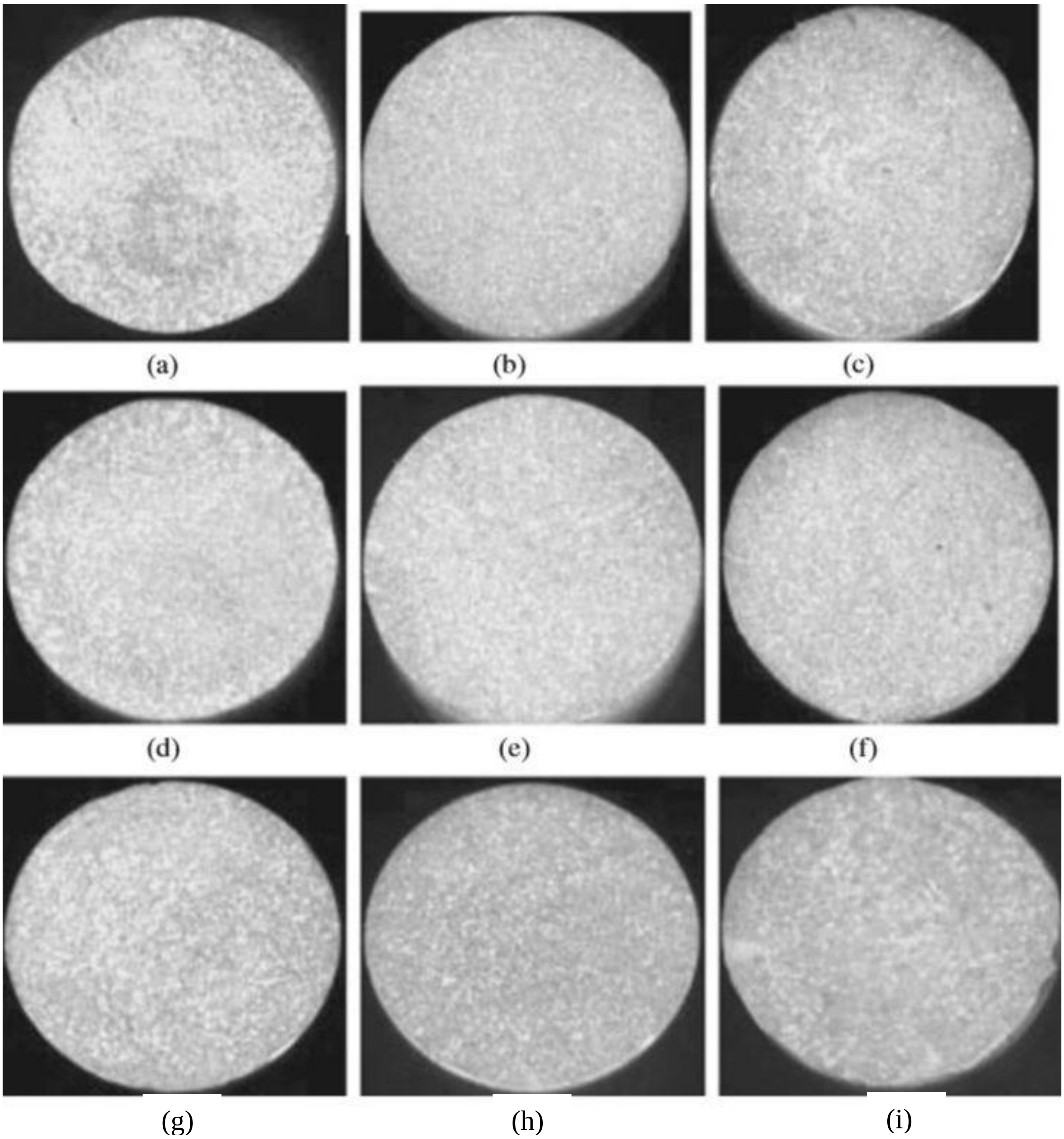



**Figure 2:** Macrographs of Al based alloy with low titanium content versus 0.04, (b) 0.50, (c) 1.00, (d) 2.00, (e) 3.00, (f) 5.00, (g) 7.00, (h) 10.00 and (i) 12.00% silicon.

## III. Macro-Grain Size Characterization Approach

Fractal analysis (Mandelbrot 1982; Peitgen *et al.*1992; Buchníček 2000) is a useful tool to quantify the inherent irregularity of nature. Fractals are self-similar and infinitely detailed, and the related fractal dimension (D), sphericity (β) and lacuranity parameter (Γ) are index of its morphometric variability and complexity. Moreover fractal analysis has been applied to a variety of natural objects (Peitgen *et al.*1992; Buchníček 2000; Durowoju and Akintan 2013; Lu and Hellawell 1995) and the "D and β" may be obtained even if the object is not a fractal. Thus, among the different methods of fractal analysis calculation, the box-counting method is one of the most appropriate in landscape structural estimation because it can be apply to fractal patterns with or without self-similarity.

In this work, the mathematical basis for measuring chaotic objects with the power law is adopted. The basic equation is as follows:

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

where "$P_e$" is the measured perimeter, "P" is the true perimeter, "δ" is the yardstick, "$\delta_m$ and $\delta_M$" are the upper and lower limits respectively for any shape and "D" is defined as the fractal dimension. 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 grains formed (Mandelbrot 1982; Durowoju and Akintan 2013). It can be expressed as:

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

From the equations above:

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

where "$A_T$" is the total grain area. When β = 1 and D = 1, a perfect circular shape is formed by the grain sizes in 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 was used with a counter incorporated into the program and the small boxes 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) 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 results. The spatial point pattern method (Figure 3) and the grain size distribution map (Figure 4) (Huang and Lu 2000) were used to describe the patterns displayed by the grains after the addition of different percentage of silicon contents to pure aluminuim melt. The grain size distribution map can further be used to identify the shapes of the grains and their dispersion from regular shapes.

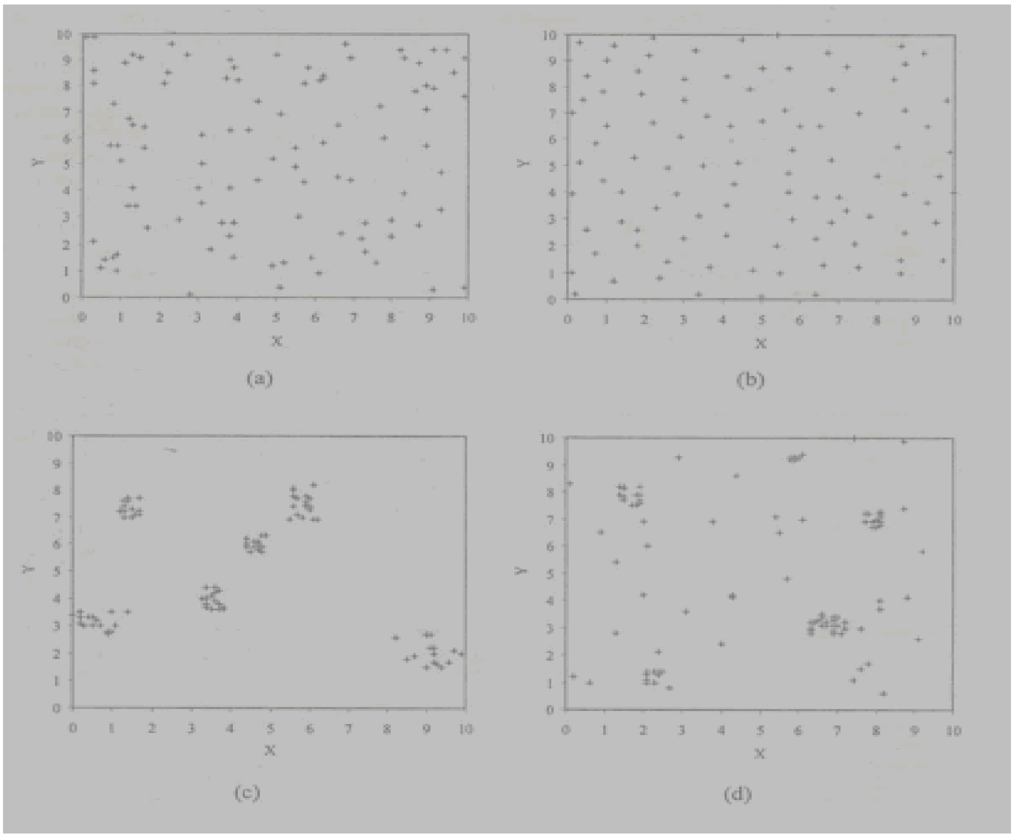



**Figure 3:** The four common types of spatial point patterns (a) random, (b) regular (c) clustered, (d) clustered superimposed on random background.

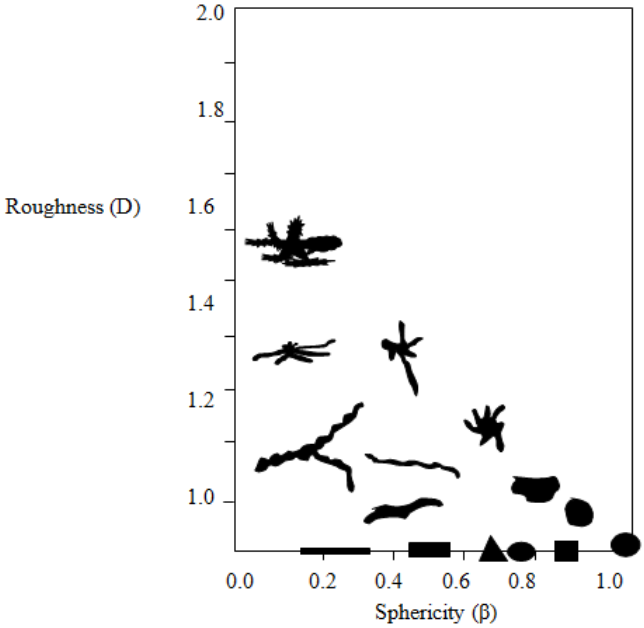



**Figure 4:** Illustration of development of irregular shapes based upon Euclidean circle or rectangle.

## IV. Result and Analysis

Typical results of such a fractal analysis for the macro-grain sizes in the view field shown in Figure 1 are listed in Table 1a. Each data point represents the weighted average values of the grains' sphericities and fractal dimensions respectively. However, pure-Al sample with 0.04% silicon content has "the worst" shape and is represented by low values of β. On the other hand, above 5% silicon content, the β values had almost attained the perfect shape with relatively high values of D. The best of the grains were found in the samples modified with 7 to 12% Si contents. This is in agreement with the work of Liu *et al.* (2003). From the grain size distribution map, it was found that the grains are clustered superimposed on random background.

Presented in Table 1b and Figure 5b are the measured sphericity's and fractal dimension for Al-Ti based alloy modified with 0.04 – 12% Silicon contents. In Table 1b, it was found that addition of silicon to Al-Ti alloy above 2% does not favour the growth of grain size formations. This may be attributed to iron and silicon crystal present in molten alloy. However, the grain size distribution map in Figure 5b are more regular and evenly distributed when compared with grain size distribution in Figure 5a.

**Table 1a**: Measured Result for the view field in Figure 1

| % Silicon content | Fractal dimension (D) | Sphericity (β) |
|---|---|---|
| 0.04 | 1.0568 | 0.5110 |
| 0.50 | 0.8751 | 0.6023 |
| 1.00 | 0.9715 | 0.6301 |
| 2.00 | 0.8749 | 0.6536 |
| 3.00 | 1.1003 | 0.7249 |
| 5.00 | 1.0427 | 0.7242 |
| 7.00 | 1.0882 | 0.9868 |
| 10.00 | 1.1024 | 0.9532 |
| 12.00 | 1.0063 | 0.9952 |

**Table 1b**: Measured Result for the view field in Figure 2

| % Silicon content | Fractal dimension (D) | Sphericity (β) |
|---|---|---|
| 0.04 | 1.0123 | 0.9867 |
| 0.50 | 1.0375 | 0.9877 |
| 1.00 | 1.0059 | 0.9989 |
| 2.00 | 1.2501 | 0.7132 |
| 3.00 | 1.3206 | 0.6024 |
| 5.00 | 1.4073 | 0.5705 |
| 7.00 | 1.4970 | 0.5087 |
| 10.00 | 1.6991 | 0.4789 |
| 12.00 | 1.7043 | 0.4168 |

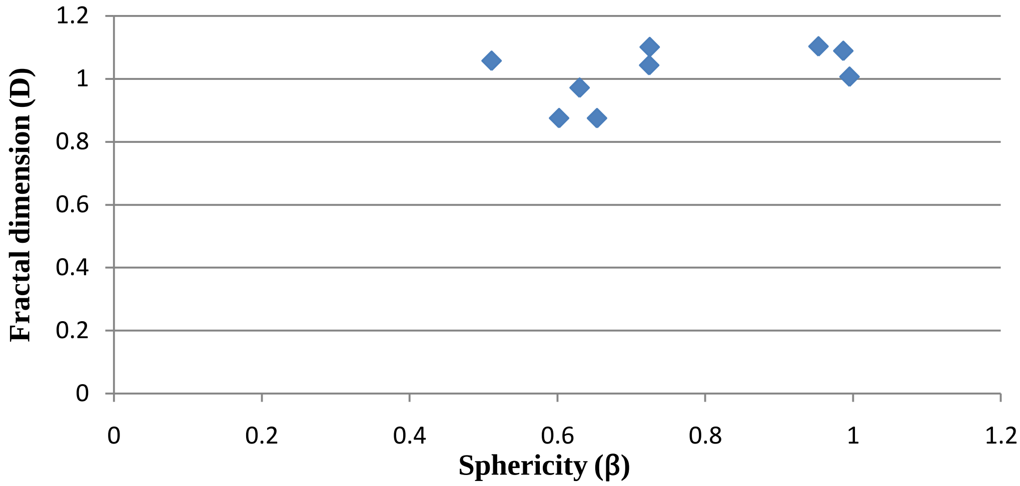



**Figure 5a: Grain size distribution map for Al-based alloy in response to Si content**

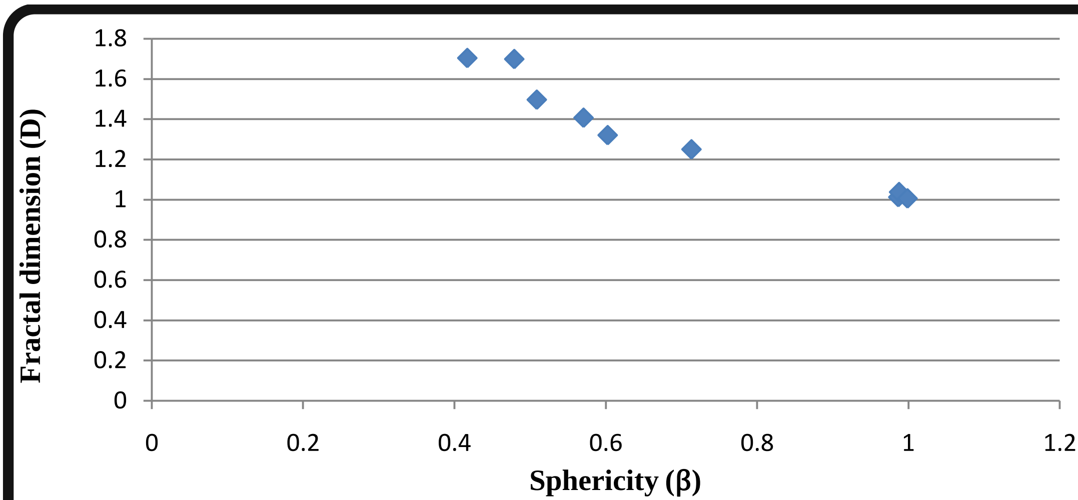



**Figure 5b: Grain size distribution map for Al-based alloy with low titanium contents in response to Si content**

## V. Conclusion

Fractal analysis of macro-grain sizes in pure-Al and Al-Ti based alloys were comparatively investigated. The macro-grain sizes of pure aluminium took the peak at 7% silicon content. Thus, the grain sizes might have been grown from macro-level to micro-level upto 12% silicon contents. Hence, Al-based alloy with low titanium contents show better grain refinement response to silicon contents, especially to low silicon contents.

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