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DETECTION OF THE POINT OF CRACK INITIATION USING MULTI-STAGE RANDOM SAMPLING (MRS) AND SPATIAL POINT PATTERN (SPP)

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ABSTRACT

Porosity is a major defect in cast aluminum alloys affecting in particular, the fatigue strength. The pores serve as points of stress concentration and points of crack initiation for eventual failure. In this work, Fractal analysis was used to numerically characterize the pores in uni-directionally solidified Al 4.5 wt % Cu alloy micrographs, transverse section at a distance of 14mm from the metal/chill mold interface. The Spatial Point Pattern (SPP) and the Multi-stage random sampling (MRS) methods were used to determine the distribution of the pores and the point of crack initiation leading to eventual failure. The MRS method reveals that all the pores considered are of irregular shapes, i.e shrinkage pores, with sphericity $\beta < 0.3$. The "worst" of the shapes is the pore in the upper left region with $\beta = 5.3078e\text{-}010$ and $D = 1.8949$. The SPP method confirms the result of the MRS method because crack initiation will commence in a region with clustered pores.

Keywords: Fractal Analysis, Pores, Regions, Roughness, Sphericity and Failure.

INTRODUCTION

One of the major defects to which Aluminum alloys is susceptible is porosity. Producing aluminum alloy casting free from defects is difficult because of the wide freezing ranges of the alloying constituents and various modes of their solidification (1). Molten aluminum will dissolve considerable amounts of hydrogen, if present in the furnace atmosphere, damp flux, crucibles and green sand moulds (2). Huang and Lu (3) Concluded that if pores cannot be avoided, they should be small and preferably round in shape to decrease the stress concentration in the finished product. They further observed that shrinkage pores appears to be more irregular (rough contours) while gaseous pores have smooth shapes. It is generally observed that shrinkage pores are more harmful to castings. It is known that the quantity and the appearance of the porosity are very crucial to the mechanical properties of castings especially the fatigue property because the pores in the micro scale are primary source of initial cracks for the final failure (4). In the developed countries, maintenance engineers perform critical analysis of the microstructure of the materials to use in order to detect any defect which can cause catastrophic failure in the materials (5). In order to forestall the incidences of fatal accidents in aircrafts and automobiles due to materials failure, there is need to dwell more on this aspect of materials research. This research work is an improvement on the work done by (6).The aim is to predict the point of crack initiation in the microstructure of a unidirectional solidified Al 4.5wt%Cu alloy, transverse section at a distance of 14mm from metal/chill mold interface.

MATERIALS AND METHOD

As a new approach, fractal geometry provides a mathematical basis for measurement of irregular (chaotic) objects (7) with power law modified as follows

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

$$A = A_E \delta^{D-1} \quad (2 < D < 3 \quad and \quad \delta_m < \delta < \delta_M) \tag{2}$$

Where the subscript E denotes Euclidean measurement, D is the "fractal dimension" for length (perimeter) P and area A, respectively, and δ is the yardstick dimension. It should be noticed that values of D are not integers for irregular objects. The fractal dimension, D, therefore describes the complexity of the contour of an object. It can be more practically called the roughness (3).

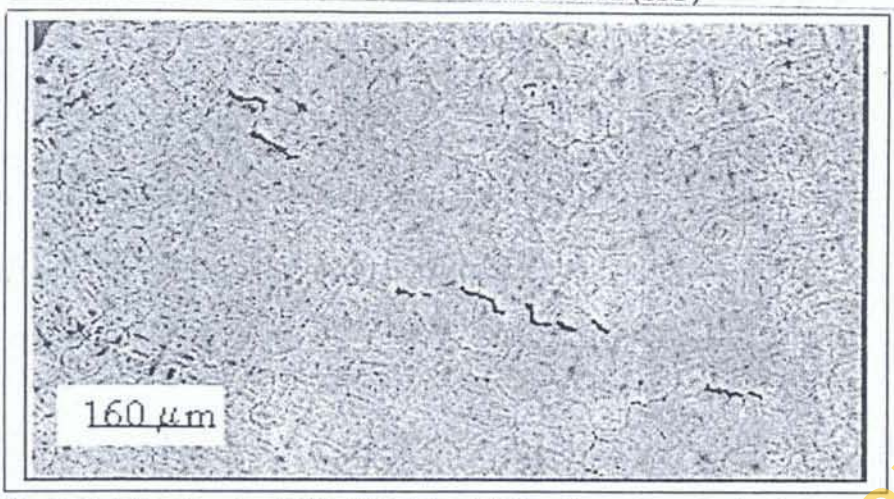


Fig.1: Unidirectional solidified Al 4.5 wt % Cu alloy micrographs, transverse section at a distance of 14mm from the metal/chill mold interface showing the micro porosities. Magnification 60x

When $\delta < \delta_m$ the measurement is not sensitive to the yardstick chosen, therefore giving a smaller value of the slope, while when
$\delta > \delta_M$ (maximum), the size of the yardstick exceed that of the individual feature being measured so that the measurement loses meaning because the object falls below resolution limit of the yardstick used for the measurement (7-11).

Sphericity, β, another dimensionless number, is used together with roughness, D, to describe the shape of the pores formed. It can be expressed as

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

where $P = P_E \delta^{D-1}$ and

$$(\beta = 4\pi A / P_E^2)\, \delta^{2(1-D)} \qquad (0 < \beta < 1 \text{ and } 1 < D < 2) \qquad (4)$$

Where β = 1 and D = 1, a perfect circular shape is formed by the pore in the microstructure. For shrinkage pore $\beta < 0.3$ and for gaseous pores $\beta > 0.3$. As β decreases along the axis, the shapes become more elongated showing a departure from perfect sphere (3).
The locations of $1 < D < 2$ represents less regular shapes.
It was also discovered that the larger the roughness, the more irregular a pore and thus more stress concentration.

Using multi-stage random sampling (MRS) and spatial point pattern (SPP) methods.
The first stage involves the division of the microstructures into four quadrants (lower left, upper left, lower right, and upper right) as shown in Fig. 2. The second stage is the random selection of six pores from each quadrant while the third stage is the purposive selection (purposive sampling) of the "worst" and the "best" pores from the twenty-four pores selected from the microstructure. The fourth stage is the categorization of the porosity distribution map into random, regular, clustered, and clustered with random background. Fifth stage is the discrimination between the shrinkage and the gaseous pores. In this stage, the patterns described in stage four are associated with different types of porosity: Regularity is associated with gas porosity because the gas pores are always formed at a distance from their immediate neighbor due to depletion of the hydrogen gas in the area surrounding each pore while clustering is associated with shrinkage porosity because of the sectioning effect of the arms with shrinkage pores. Meanwhile, in clustering on random background, the clusters are associated with shrinkage pores while the random background are associated with gaseous pores. With these, the point of crack initiation was determined. The values of the fractal dimension and sphericity were obtained using the expressions in equations 1, 2 and 3 above.

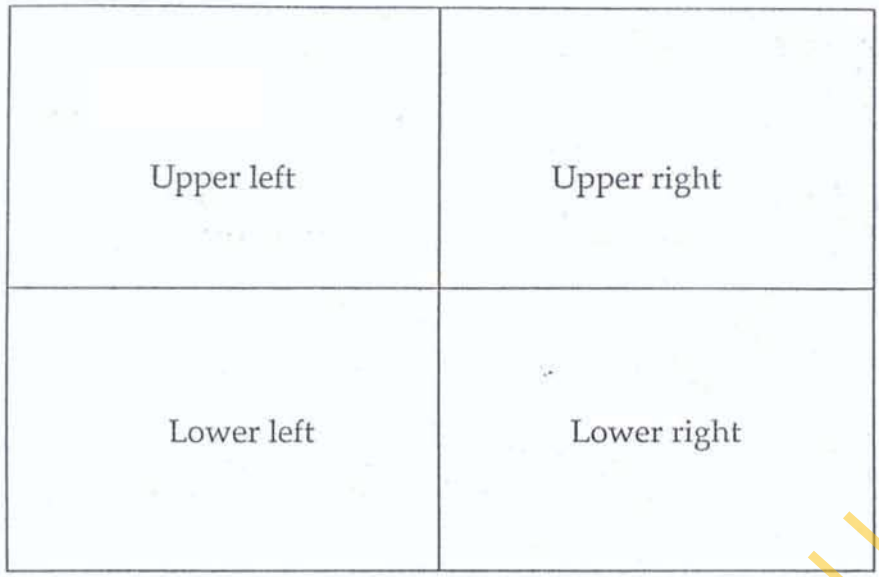
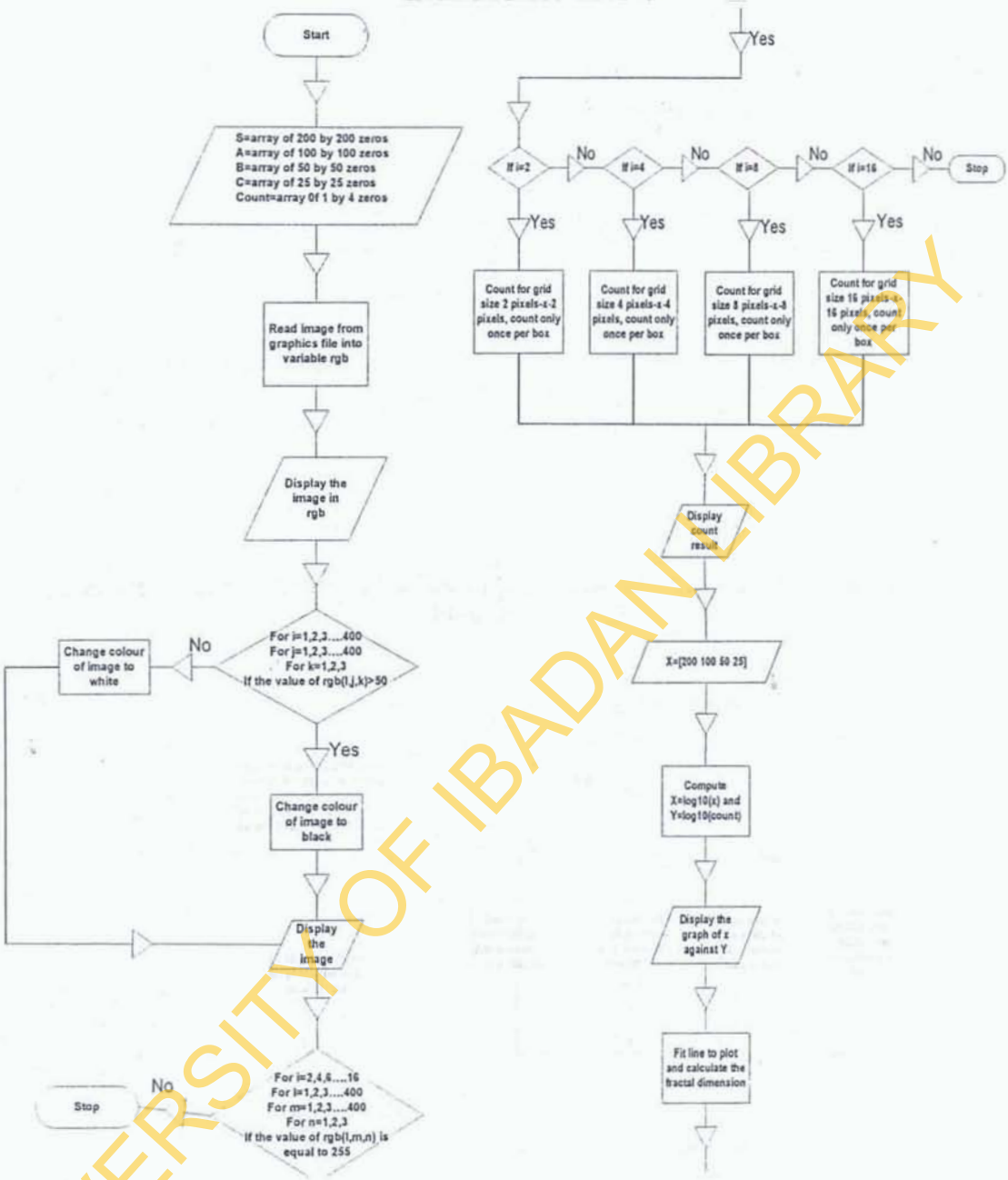


Fig. 2: The Multi-Stage Random Sampling Method of Dividing a Microstructure into four Quadrants.

Using the equations (1), (2) and (3) above, interactive programme (flow chart is shown Fig. 3) in Matlab programming language is developed to obtain the numerical values of the roughness D and the sphericity β for some selected pores in the various quadrants of the microstructure (Fig.1).



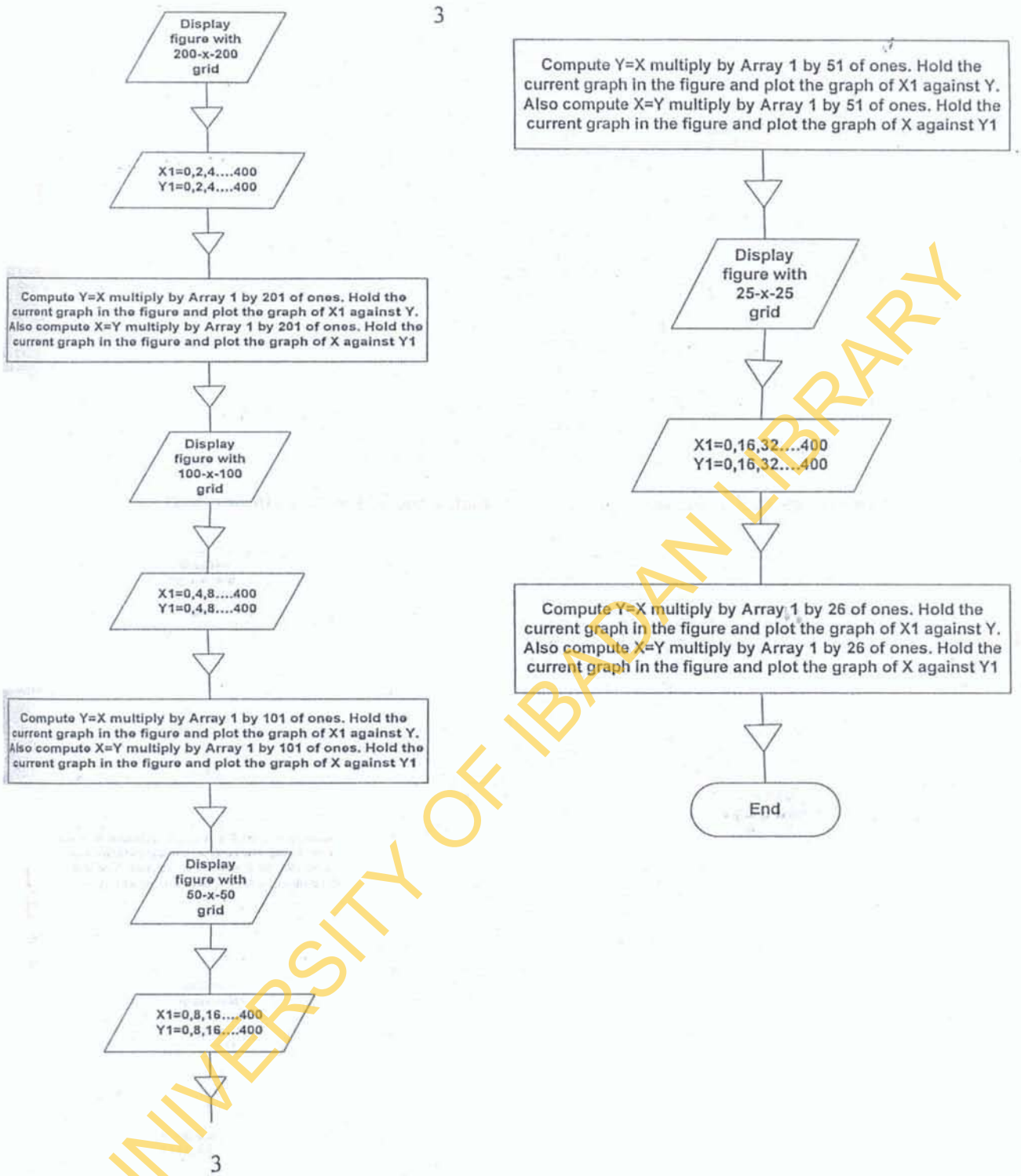


Fig. 3: Flow Chart for Fractal Analysis of the pores

RESULTS AND DISCUSSIONS

Table 1 shows the values of roughness D and sphericity β obtained after the fractal analysis of the pores in the different quadrants. If all the quadrants are subjected to the same loading, failure of the material will start from the region with the lowest value of β and highest value of D.

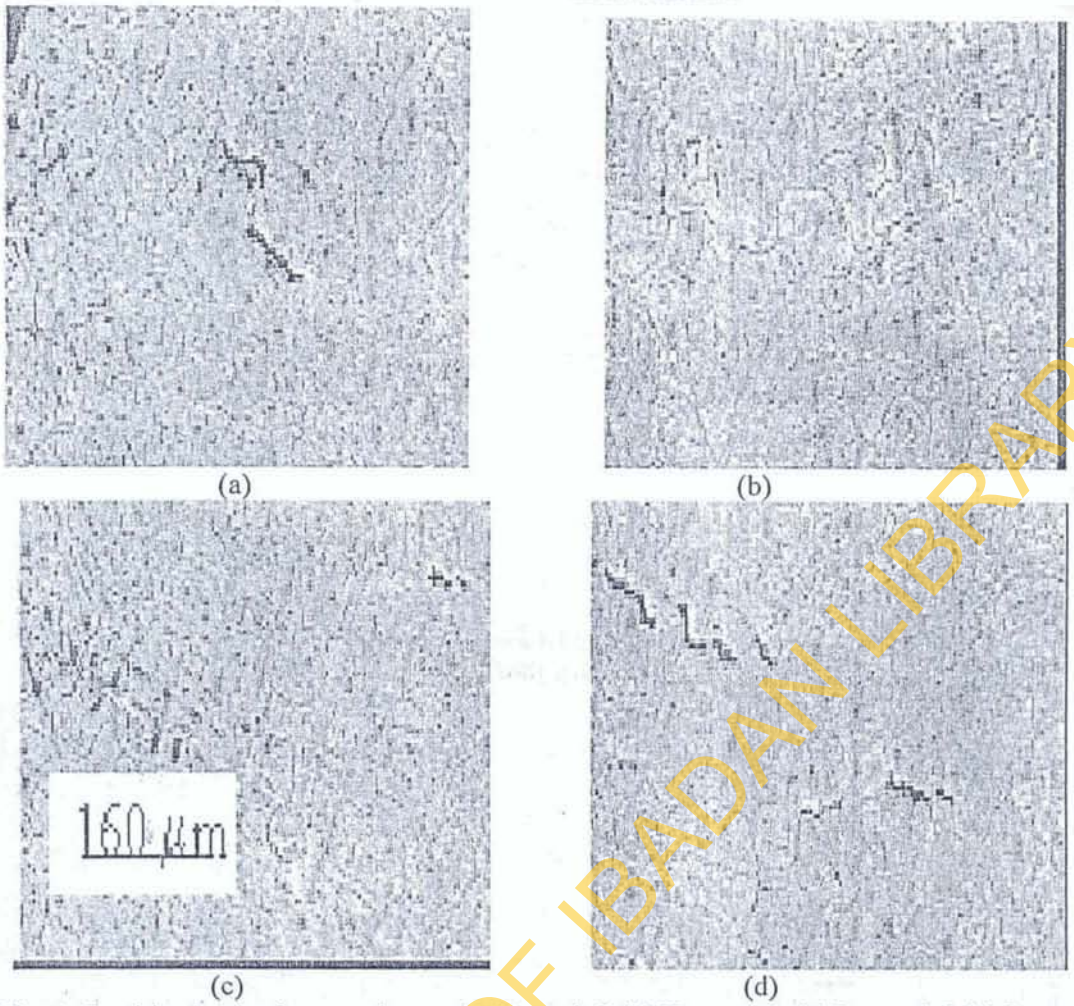


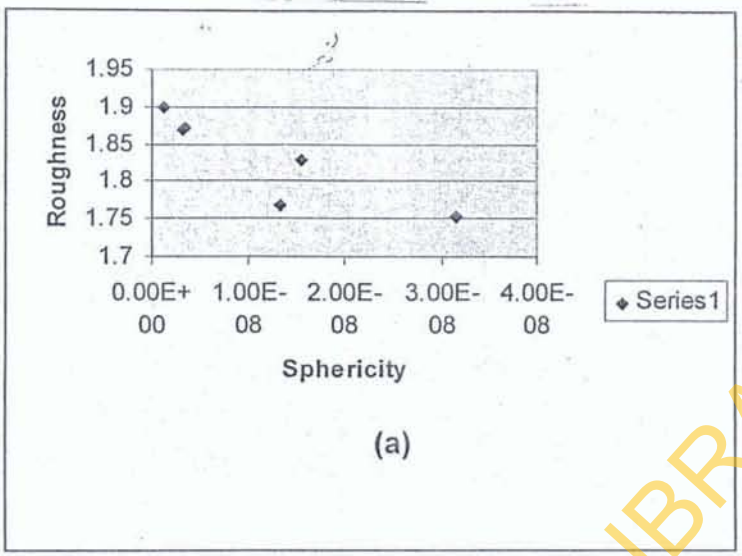
Fig. 4: Prosities in the four quadrants (a) Upper left (b) Upper right(c) Lower left (d) Lower right of the microstructure Fig.1.

From Fig. 4, dark spots represent the pores while the grey areas denotes inter-metallic compound with white spot showing the aluminum matrix. It is also observed that from the values obtained (i.e $\beta < 0.3$ and D approaching 2) all the pores are shrinkage pores. In the Upper right quadrant, the "worst" shape is the pore with β = 1.3092e-009 and D = 1.8985 while the "best" shape is β = 3.1537e-008 and D = 1.7525. In the Lower right quadrant, the "worst" shape is the pore with β= 3.6565e-009 and D = 1.9418 while the "best" shape is β = 3.0581e-007and D = 1.7292. In the Upper left quadrant, the "worst" shape is the pore with β= 5.3078e-010and D = 1.8949 while the "best" shape is β = 6.1820e-009 and D = 1.8161. In the Lower left quadrantthe "worst" shape is the pore with β= 1.8054e-009 and D = 1.8369 while the "best" shape is β = 1.0261e-007 and D = 1.7520.

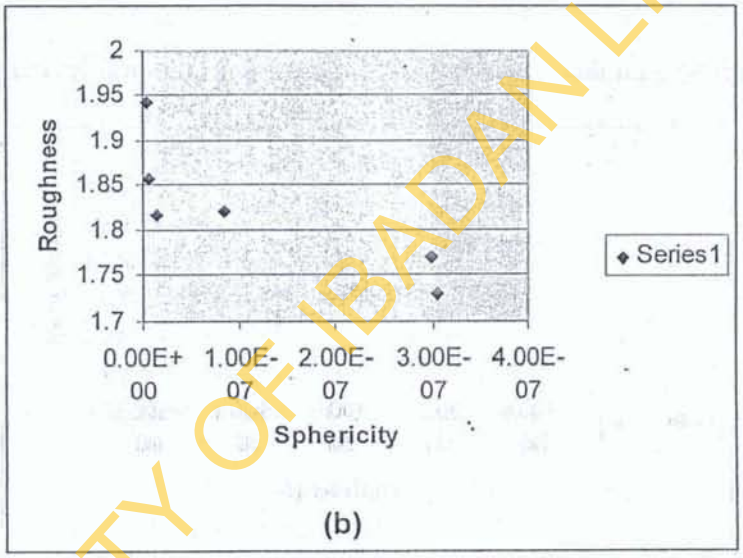
Table 1: Values of roughness D and sphericity β obtained after the fractal analysis of the pores in the different regions / windows

S/N	POSITION	D	B	TYPE OF PORE
1	Upper right	1.8680	3.2554e-009	shrinkage
2	Upper right	1.7679	1.3243e-008	shrinkage
3	Upper right	1.8281	1.5565e-008	shrinkage
4	Upper right	1.8985	1.3092e-009	shrinkage
5	Upper right	1.8725	3.3554e-009	shrinkage
6	Upper right	1.7525	3.1537e-008	shrinkage
1	Lower right	1.8169	1.5120e-008	shrinkage
2	Lower right	1.7709	2.9924e-007	shrinkage
3	Lower right	1.7292	3.0581e-007	shrinkage
4	Lower right	1.8222	8.5273e-008	shrinkage
5	Lower right	1.8568	5.9138e-009	shrinkage
6	Lower right	1.9418	3.6565e-009	shrinkage
1	Upper left	1.8161	6.1820e-009	shrinkage
2	Upper left	1.8949	5.3078e-010	shrinkage
3	Upper left	1.9044	2.2142e-009	shrinkage
4	Upper left	1.8343	2.4167e-009	shrinkage
5	Upper left	1.8816	1.3785e-009	shrinkage
6	Upper left	1.8131	2.0679e-009	shrinkage
1	Lower left	1.7710	1.7392e-008	shrinkage
2	Lower left	1.7363	1.2721e-008	shrinkage
3	Lower left	1.8369	1.8054e-009	shrinkage
4	Lower left	1.8077	1.0251e-008	shrinkage
5	Lower left	1.8526	3.0973e-009	shrinkage
6	Lower left	1.7520	1.0261e-007	shrinkage

From the graph below, fig.3 it is observed that the pores in the Upper left region (a) are clustered on regular background . Thus, these are primary sources of crack initiation and which will eventually grow to a level causing fracture



(a)



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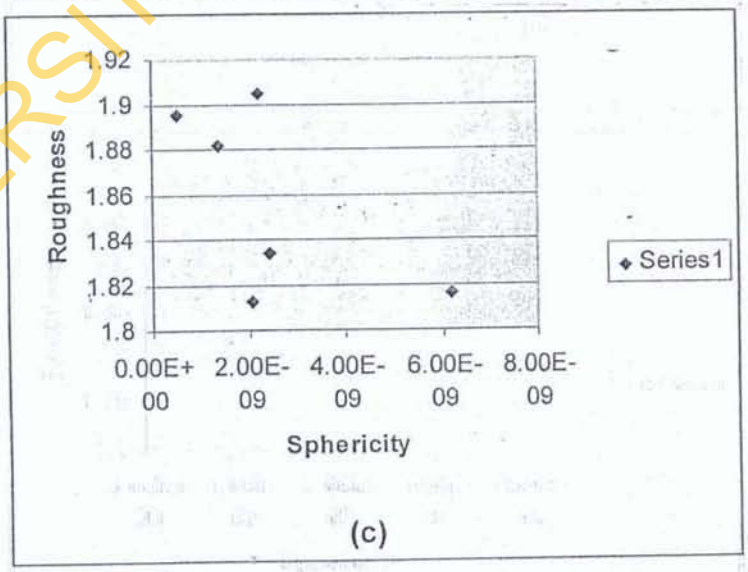

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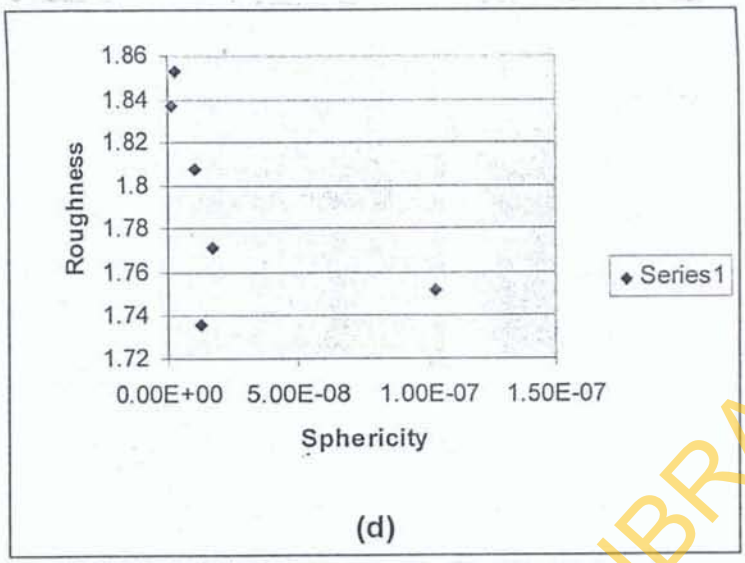

Fig. 5: Porosity Distribution Maps of (a) Upper right region (b) Lower right region (c) Upper left region (d) Lower right region

From Fig. 5, and using SPP for categorization of pore distribution, Table 2 can be set up.

Quadrant	Pore category	Pore shapes
Upper right	Cluster on random background	Shrinkage pore
Lower right	Random	Gaseous pore
Upper left	Random	Gaseous pore
Lower left	Random	Gaseous pore

CONCLUSIONS

1. All the pores in the microstructure Fig.1 are of shrinkage types.
2. The "worst" of all the pores considered is the one located in the upper left quadrant with β= 5.3078e-010 and D = 1.8949.
3. From the analysis, failure of the material will start in the upper left region.

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