Reconstruction of fiber reinforcement in epoxy-based composite

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Abstract—**Polymer matrix composites (PMCs) are very attractive materials due to a possibility to achieve versatile properties by combining with ceramic or metal reinforcement in different shapes and sizes. As a result, PMCs have found application in nearly every field, from household appliances to aerospace industry. Modern microelectronic devices contain conductive polymers with fillers that enhance their electrical properties. In addition, PMCs are being used as insulators and adhesives, contributing to the long life of electronic devices. Epoxy resins are the most commonly used insulators and adhesives. In order to improve their fracture toughness, glass fibers can be used as an efficient reinforcement. However, with the purpose of designing a composite with good mechanical properties and durability, deep knowledge of microstructure is required. In addition, microstructural analysis can be used to connect shape and size of pores or reinforcement with various physical properties. Fractal nature analysis is a valuable mathematical tool that can be employed for different shapes and forms rendering. In this manner, successful design and prediction of composite's properties could be obtained. In this research, field emission scanning electron microscopy (FESEM) images were used for fractal analysis of glass fibers, with the aim of reconstructing the shape.**

***Index terms*— Fractal analysis; Composites; Epoxy; Microelectronics.**

I. Introduction

Composites represent multiphase materials containing two or more phases distinct by an interface [1-3]. Physical properties of composites are significantly different from the initial constituents' properties [4,5]. Civilization modernization was followed by increased production and development of composites both at the research and industrial scale. With composite design and processing, structural, thermal, electrical and other properties of the constituents are improved. Synergetic effect of matrix and reinforcement properties results in lightweight materials with high toughness and strength that can be resistant to corrosion, chemicals and temperature [6]. Nowadays, there are many efficient ways to process composite with targeted functional properties, with structure control at micro- and nanoscopic level [7-12]. Polymers are very attractive as matrix materials in composites, due to their low price and density, as well as wide range of good physical and chemical properties. Conductive polymers like poly(vinylidene fluoride) polypyrrole are investigated and implemented in various electronic parts. Composites with epoxy matrix are used as insulators, offering device stability and durability [13]. Since epoxy generally has low fracture toughness, fibers are usually incorporated for the reinforcement. They increase toughness, specific strength and modulus of elasticity [14,15] In order to avoid delamination and fiber separation from the matrix, thorough insight into the structure in desirable [16-18]. Fractal nature analysis is a powerful mathematical tool for the investigation of materials morphology that is used for characterization of grains and pores [19]. However, it can also serve to describe and predict the shape and size of reinforcement, enabling more efficient future composite design. In this manner, processing-structure-property circle can be closed. FESEM images can be used for the shape and size reconstruction of the fibers.

A. Fractal nature analysis

The fractal nature exists within physical systems structures and contact surfaces, from microstructures, down to the nano-scale level, up to the global bulk and massive shapes. Fractal nature analysis presents a possible approach for the investigation of contact phenomena establishing the grain contacts models, offering ceramics and other materials structure analysis, description and prediction of grains' and pores shape, along with relations between structure and electric-dielectric properties. Contribution of fractals correction could be observed and explained on intergranular Heywang capacity model, Schottky barrier, Curie-Weiss law, Clausius-Mossotti relation and other parameters in the field of dielectric and ferroelectric materials, by introducing complex fractal correction factor α (grain and pores surface influence and Brownian particle motion). The development of fractal

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analysis idea is inspired by self-similarity in nature biosystems, where the chaotic structures could be controlled by recognized geometry structure or just to have disorder controlled towards the order. One of the goals is to recognize and develop the bridge between biosystem of living organisms and physical systems condense matter particles. In this manner, we use the inspiration from nature for better understanding the particles physics motions, which could be observed as biomimetic system.

Every fractal object (FO) has its fractal dimension – Hausdorff dimension (D_H), a real number, smaller compared to the geometric dimension of the FO minimal space. Influence of pores' and grains' fractal dimension on materials properties has already been established [20-25]. Unlike ideal, natural fractals have scale-dependent fractal dimension [26]. Nature objects, such as water surface, air particles, trees and many others do not show intrinsic structural, but statistical self-similarity; therefore, they are considered as almost fractals. Reconstruction of such shapes requires modified mathematical approach, offered by fractal geometrical analysis. This mathematical technique can be performed on field emission scanning electron microscopy (FESEM) images, by identifying fiber phase and pores shapes and boundaries, as well as fiber-matrix bonding at the interface. In this study, fiberglass mat was used for the reinforcement of epoxy. FESEM image of enlarged fiber after the composite fracture was used for the reconstruction of data.

II. THE METHOD

A. Fractal reconstruction of data

Fractal nature analysis of experimentally determined physical properties is performed using a novel affine fractal regression model described by the equations published in our previous research. The aim is to find coefficients that fit experimental data for the following equation system:

$$\varphi\left(\frac{x+j}{p}\right) = a_j\varphi(x) + b_j x + c_j \qquad (1)$$

where $x\in[0,1)$, $0\le j\le p-1$, a_j represent fractal and b_j directional coefficients, with $0<|a_j|<1$, with domain [0,1), p stands for fractal period. Real solution equation system is called fractal function $\varphi:[0,1)\rightarrow R$, having mathematical fractal structure – function graph plot represents fractal curve. Higher a_j appear in the case of strong fractal oscillations. The curve fractal level defined by the equation system is L; the first fractal level is replicated in the entire domain over every of the p sub-intervals, building the second fractal level.

In order to obtain coefficients that fit the data, explicit solution of the problem that depends on the p-expansion of numbers in [0,1) is used. For L=2, this solution is

$$\varphi(0) = \frac{c_0}{1-a_0} \qquad (2)$$

$$\varphi\left(\frac{\xi_1}{p}\right) = a\xi_1\frac{c_0}{1-a_0} + c\xi_1, \xi_1 \ne 0 \qquad (3)$$

$$\varphi\left(\frac{\xi_1}{p}+\frac{\xi_2}{p^2}\right) = a\xi_1\left(a\xi_2\frac{c_0}{1-a_0}+c\xi_2\right) + b\xi_1\frac{\xi_2}{p} + c\xi_1, \xi_2 \ne 0 \qquad (4)$$

For obtaining the best coefficients, the theoretical approach computes the SSR - sum of square residuals in between the formal definition and the real values. Afterwards, the partial derivatives of SSR are equalled to zero, for minimizing the error. The best solution of the problem is given when:

$$\frac{\partial SSR}{\partial a_j} = 0, \frac{\partial SSR}{\partial b_j} = 0, \frac{\partial SSR}{\partial c_j} = 0 \qquad (5)$$

for all j=0,1,2,…,p-1. This is a problem with 3p parameters, to estimate where the equations to solve are nonlinear.

The mathematical analytical solution of this partial derivative system is not possible to compute, and a numerical approach is needed. With the software for numerical computation of the solution, called Fractal Real Finder, we worked on samples and obtained estimated curves and estimates of Hausdorff dimension. With the input of the real data, the program executes simulations and gives an output with a fractal curve as modelled above.

With the estimated fractal curves, we may estimate the Hausdorff dimension. The Hausdorff dimension is an indicator of the chaotic/irregular data behavior. The classical dimension is represented by integer: 1 for lines and curves, 2 for 2D objects, 3 for solid 3D objects. There are structures that have characteristics in between two integer dimensions. In that case, we may estimate a non-integer dimension. The fundamental theoretical mathematical non-integer dimension is Hausdorff dimension, sometimes referred as fractal dimension. The box dimension is a simplified indicator that provides estimates for the real Hausdorff dimension of real data.

Proposition. The Hausdorff dimension D of the function graph, φ solution of the above system is upper bounded by the solution of:

$$\sum_{j=0}^{p-1}\beta_j^{\,D} = 1 \qquad (6)$$

$$where\ \beta_j = max\left\{\frac{1}{p}, |a_j|\right\}, 0 \le p \le p-1$$

The coefficients with fractal relevance are those a_j such that $|a_j|>1/p$.

From the following image (Figure 1), we selected a centre small part (lighter bar) and zoomed in it to a new image (Figure 2).

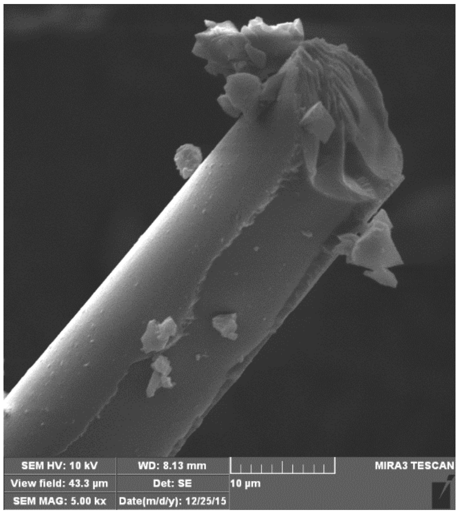

Fig. 1. FESEM of a broken glass fiber.

III. Results and Discussion

We inserted red points circling a contour of the tip of the glass fibre in a polar grid, as the following figure.

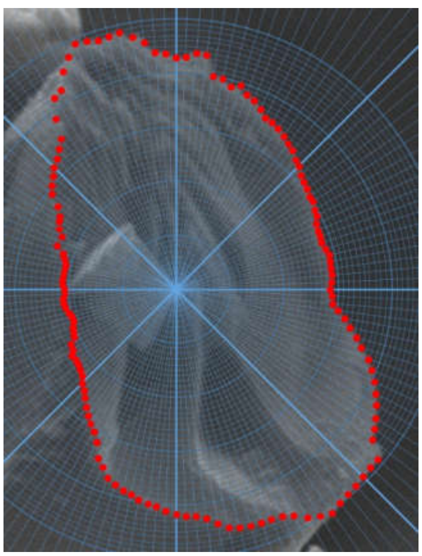

Fig. 2. Enlarged tip of the broken fiber.

We introduced red points in a border line. The fractal reconstruction is plotted in the figure next to the selected part of the image. In this case, we put the default domain in the vertical axis and upside down to match with the position of the image.

From a change of variables, from polar to cartesian variables, we run the Fractal Real Finder software for the sequence of radiuses and obtain the estimated fractal model with coefficients, as in Table below. The sequence of points is the set of radiuses corresponding to $p^L = 12^2 = 144$ angles around the image.

TABLE I
Estimated Coefficients for the Fractal Curve of the Radius

	0	**1**	**2**	**3**	**4**	**5**
a_j	0.081	-0.044	0.012	-0.002	-0.017	0.014
b_j	0.731	-2.212	-0.805	-0.098	0.603	1.362
c_j	3.951	4.989	2.695	2.118	2.156	2.852
	6	**7**	**8**	**9**	**10**	**11**
a_j	0.027	-0.057	-0.013	0.021	-0.013	0.024
b_j	0.695	-0.005	-1.654	-0.037	0.517	0.712
c_j	3.957	5.072	4.608	2.821	2.868	3.304

This fractal reconstruction reveals no fractal coefficients (those bigger than $1/p = 0.8(3)$) and, in consequence, the corresponding Hausdorff estimate is 1. Returning to polar coordinates (radius and angle), we plot the estimated curve as follows.

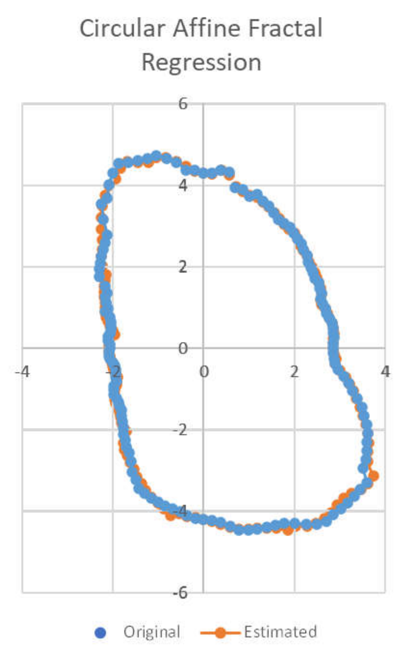

Fig. 3. Fractal curve of the fiber shape

IV. Conclusion

In this paper, fractal nature analysis was applied on fiber-reinforced composite for the reconstruction of fiber shape. The analysis with software Fractal Real Finder, fractal curve depicting the shape was obtained, as well as Hausdorff dimension of 1.21968. This indicates that the fibers have been successfully reconstructed. The finding achieved in this study enables the use of the fractal software analysis for the design and prediction of efficient reinforcement for epoxy-based composites in the future.

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