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Fractal Description of Fracture Surfaces of TiO_2 Ceramic Materials by Digital Image Processing

A.L. Horovistiz(1), S. Shibata(1), C.C.S.Prado(1) and L. R. O. Hein(1)*

(1) DMT, Campus de Guaratinguetá, Universidade Estadual Paulista, e-mail: rhein@feg.unesp.br
* Corresponding author.

Abstract – The self-affine behavior of Brazilian disk test specimens for K_{Ic} measurement was investigated from 3-D elevation maps obtained by extended depth-of field reconstruction (Fig. 1), pictured at regular intervals following crack extension. The box-counting method was applied to determine fractal dimension values associated to micro (D_1) and macro (D_2) resolution scales. No correlation could be determined between D_1 values, related to microstructure heterogeneities, and crack front topography (Fig. 2), but a significant correspondence between D_2 and fracture positions (Fig. 3) was found, suggesting a relationship between fractal measurements and stress intensity factor. Finally, K_{Ic} could not be estimated from fractal data.

Central cracked Brazilian disc test specimens for determining mode I fracture toughness were prepared by using titanium oxide. These were uniaxially pressed and calcined at 1000 °C for 1 h before machining central notches. The resulting pallets were sintered at 1450 °C for 5 h. Diametral compression tests were performed on an Shimadzu AG-X machine at 1 mm/min displacement rate. Fractured surfaces were investigated by light microscope, at regular displacement intervals, from crack initiation to end of fracture. At each position, image stacks were pictured for ordered and successive vertical positions, using 1.0 µm intervals for 3-D mapping by an extended depth-of-field reconstruction algorithm. Fractal dimension data were computed from elevation maps by using Minkowski-Bouligand method, also known as box-counting dimension. Fracture surfaces were also evaluated by measuring the multifractal spectra, confirming the multifractal character of every surface, associated to their self-affine scaling laws. NIH Image J was used for overall image processing.

Mecholsky [1] assumes the monofractal behavior for fracture of brittle materials, finding relationships between the fractal dimension and the square root of fracture toughness or theoretical strength. Russ [2] describes fracture surfaces as mixed fractals, or multifractals, due the natural heterogeneity of fracture processes, combining the influences of microstructure and applied loading, proposing two scales for fractal analysis: the microscale, or textural, corresponding to the microstructure effects on fine roughness; and the macroscale, or structural, describing the large anisotropic relief behavior due to the evolution of stress fields at crack front. In this work, fracture surfaces were characterized as bifractals, being evident this behavior in every elevation map measured for each specimen. The microscale values for fractal dimension (D_1) have not presented correlation to investigated positions, as checked by paired t-tests for each specimen. It suggests that the random heterogeneities of microstructure, characteristics of the adopted ceramic processing, induce the scattering of textural fractal values. On the other hand, the structural or macroscale approach results in significant correspondences in paired t-tests for D_2 values and fracture positions. It indicates that structural fractal dimension, or the larger roughness details in fracture surface, is dependent on the evolution of stress intensity factor, which grows with crack tip advance during fracture processes. It is also coherent with the self-affine character, described by the confirmed multifractal condition, of fractured relief, since crack propagation in brittle materials tends to assume a bidimensional behavior with the growth in the speed of crack tip, being more heterogeneous to better dissipate large amounts of energy. In this way, D_2 fractal dimension values increase with the distance to crack initiation position, representing the elevation on surface roughness with the larger speed of crack tip advance. Finally, no square root relationship has been found between mean fractal values and mode I fracture toughness, but there are correlations between mean values of D_1 and D_2 with K_{Ic} data, suggesting that the overall fracture process is dependent on microstructure heterogeneities and stress intensity factor evolution with crack propagation.

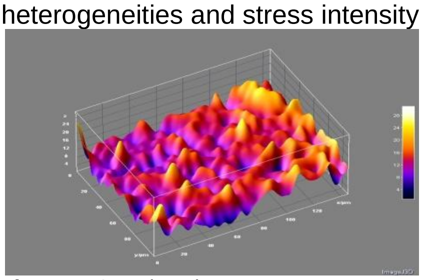

Figure 1: 3-D elevation map

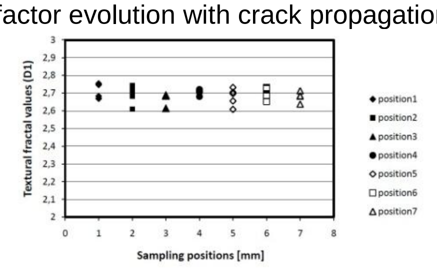

Figure 2: Textural values scattering

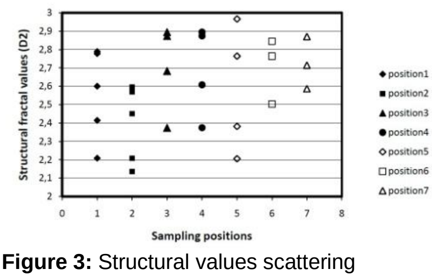

Figure 3: Structural values scattering

[1] Mecholsky Jr. J.J., Mat. Letters, 60 (2006), 2485-2488
[2] Russ J.C., Fractal Surfaces, New York: Plenum Press, 1994