

## MONOFRACTAL BEHAVIOR OF FATIGUE CRACK GROWTH FOR 15-5PH STAINLESS STEEL

**Thaís Peres Zanetine Marques, thais\_pz@yahoo.com.br**

**Luis Rogerio de Oliveira Hein, rhein@feg.unesp.br**

Materials and Technology Department, UNESP – Faculdade de Engenharia de Guaratinguetá, Av. Dr. Ariberto Pereira da Cunha, 333, 12.516-410, Guaratinguetá, Brazil

**Abstract.** *Quantitative fractography is a tool which can be used in structural failures investigations or for processing and products development by relief quantitative studies. This study is based on the combination of surfaces topography measurement tools, as the reconstruction by extended depth-of-field method in the light microscope, with the analysis of fractal behavior of textures which are formed by relief details, related to the acting fracture mechanisms. The analyzed material was the 15-5PH stainless steel, whose specimens were tested until the fracture in crack growth fatigue tests according to ASTM E 647-08. The investigations were accomplished based on ordered image stacks obtained by light microscopy and processed to obtain the relief and the textures distribution formed in the fractured surfaces. From these data it was analyzed the relation between the fractal behavior and the tip crack position for different specimen thicknesses. It was observed that the scattering of fractal dimension values, represented by standard deviation, is more representative on analysis of relief changes than the simple comparison between the fractal dimensions values and the specimen thickness, once these values changed strongly. Moreover, the results analysis indicates that the textural dimension expresses the materials response for local conditions of fracture mechanical process while the structural dimension indicates homogeneity in the microstructural effects on fracture topography*

**Keywords:** *quantitative fractography, fractal, light microscopy, digital image processing.*

### 1. INTRODUCTION

Since the fractal geometry was proposed by Mandelbrot, many researchers have quantitatively described the roughness of fractured surfaces and tried to establish the relationship between the fractal dimension and mechanical parameters (Xie et al, 1998).

The word “fractal” refers to the multi-scale characteristics of surfaces or profiles in nature. For fractal surfaces, the fractal dimension is a statistical quantity that describes how these surfaces fill the space (Horovistiz et al., 2010). Borodich (1999) defines that fractals are sets with no integer fractal dimension. The dimension ( $D$ ) of a fractal curve is less than or equal to 2, i.e.,  $1 < D < 2$ . Similarly, the dimension of a fractal surface is less than or equal to 3, i.e.,  $2 < D < 3$ .

The fractal surfaces introduce the concepts of self-similarity for ideal fractals which presents the same behavior for any size scale or self-affinity, a general scaling transformation more appropriate to describe real fractal objects, due to the intrinsic anisotropy caused by complexity of the thermodynamics processes involved in the evolution of surface energies changes (Campos et al., 2009).

Real failure patterns, unfortunately, cannot be modeled by using statistical self-affinity or self-similarity concepts alone. Mixed fractals analysis provides a quantitative description of surface roughness that can be useful as a pointing for local complexity of fracture mechanisms and may also determine large and fine scale behavior of surface relief (Horovistiz and Hein, 2005; Russ, 1994).

In this work, it was investigated the relation between fractal dimension and the tip crack position for different specimen thicknesses and the effects on fracture micromechanisms for the 15-5PH stainless steel.

### 2. EXPERIMENTAL PROCEDURE

The crack growth fatigue tests were conducted according to ASTM E 647-08 (ASTM, 2008), using an Instron 8810 servo-hydraulic system. C-L oriented compact tension specimens were cut from a cylindrical bar of 15-5PH stainless steel and machined to three different thicknesses: 12.70mm 19.05 and 25.40mm.

Fractured surfaces were pictured using one Nikon Epiphot 200 reflected light microscope equipped with one Zeiss AxioCam ICc3 digital camera, using 200x magnification in all cases. The images were performed from pre-crack until the end of the fracture following the centerline relative to specimen thickness (Fig 1). They were captured with 2.0 mm pitch at the stable crack propagation region and with 1.0 mm pitch at the unstable crack propagation region. At each position, image stacks were pictured for ordered and successive vertical positions, using 1.0  $\mu\text{m}$  intervals for 3D mapping by an extended depth-of-field reconstruction algorithm (Fig. 2a).

Fractal dimension data were computed from elevation maps, using the plugin for NIH Image J, the “Map Fractal Count”, based on the Minkowski–Bouligand method, also known as box-counting dimension (Chen et al., 2003). It systematically lays a series of grids of decreasing box size over the grayscale elevation map and records the number of boxes for each successive grid size, finding the fractal dimension  $D$  as the slope of the logarithmic regression line for

the box numbers and grid sizes. NIH Image J (Rasband, 2009) is a freeware image processing software was used for overall image processing.

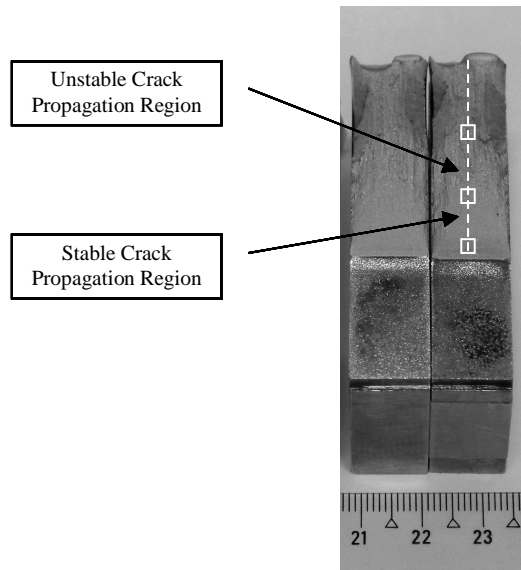


Figure 1. Scheme of the sampling for extended depth-of-field reconstructions. Images were pictured from precrack to end of fracture.

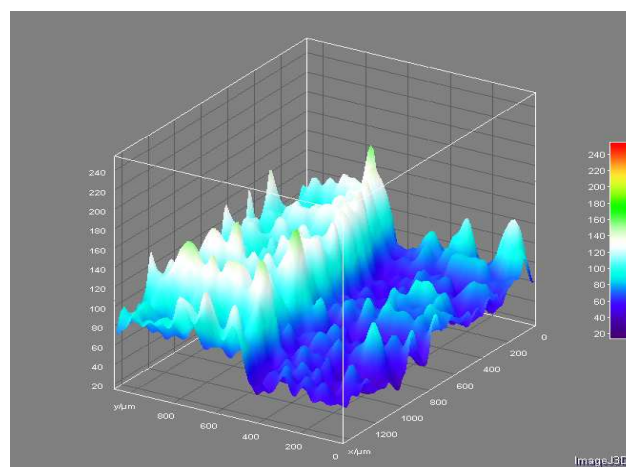
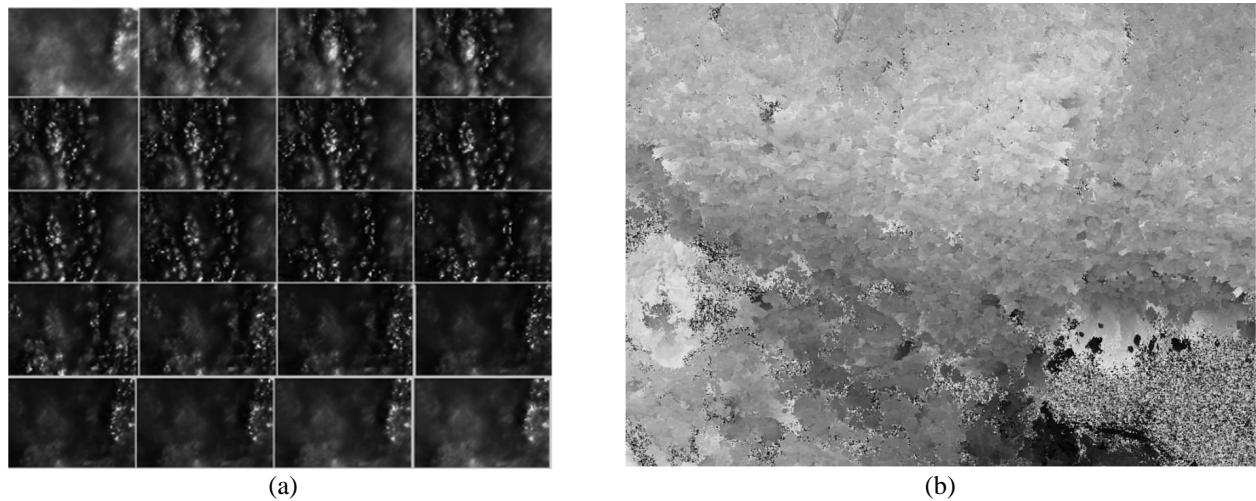


Figure 2. Example of extended depth-from-focus reconstruction process: (a) images stack with progressive movement of objective lens; (b) corresponding elevation map of precrack (scale bar = 10  $\mu\text{m}$ ); (c) corresponding 3D elevation map, axes scales in  $\mu\text{m}$ .

### 3. RESULTS AND DISCUSSION

After the reconstruction from images stacks, the box-counting method was applied to evaluate the fractal dimensions, resulting in characteristic plots as shown in Fig. 3. These plots can be approximated in two regions: one with the lowest angular coefficient which represents the microscale range (textural dimension – Dt) and the other with the highest angular coefficient that is associated with macroscale (structural dimension – Ds).

The threshold between textural and structural fractal ranges was determined as the most evident discontinuity in the graph of the first derivative of the log (box count) against -log (box size), after median filtering (Fig. 4). This procedure is robust since the less important discontinuities are naturally discarded, revealing the more regular topographic behavior at both micro- and macro-ranges, validated by the very small dispersion in threshold values for the whole set of fractal curves (Horovistiz et al., 2010)

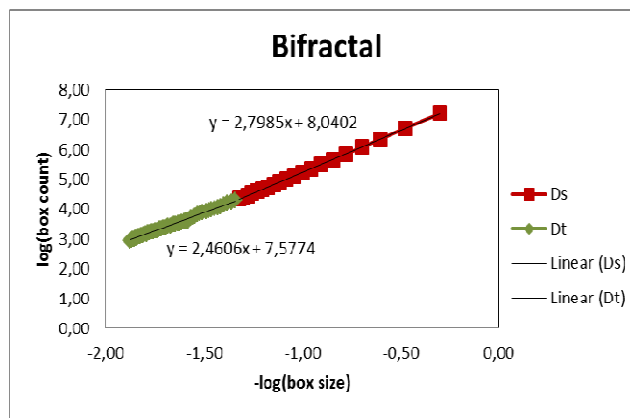


Figure 3. Multifractal characterization of elevation maps: the bifractal approach with the determination of textural and structural fractal dimension values.

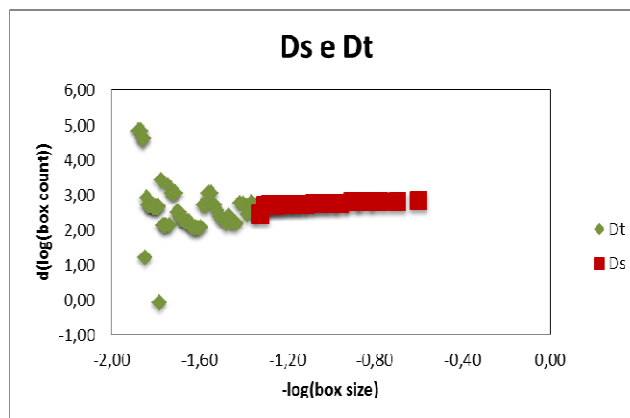


Figure 4. Threshold between textural dimension and structural dimension.

The fractal dimensions values and their respectively standard deviations, for all specimen thicknesses, are summarized in Tab. 1.

Table 1. Fractal dimension values dispersion to specimen thickness

	Thickness[mm]								
	12.70			19.05			25.40		
	Monofractal	Ds	Dt	Monofractal	Ds	Dt	Monofractal	Ds	Dt
Average dimension	2.71	2.81	2.56	2.65	2.79	2.46	2.69	2.79	2.55
Standard deviation	0,02	0,04	0,04	0,03	0,04	0,05	0,02	0,03	0,05

According to Tab. 1, the scattering, represented by the standard deviation, is reduced at macroscale relative to textural values. This implies that structural dimension describes homogeneity in the microstructural effects on fracture topography while the textural dimension indicate that this measure express the materials response for local conditions of fracture mechanical process.

The results for the fractal dimensions on the positions forward the crack, for the three kinds of specimens, are showed in Fig. 5a, 5b and 5c to check and compare some tendencies.

In all scale ranges, fractal data have presented no evident correlation to investigate positions in each corresponding specimen. It suggests that the monofractal approach is not appropriate to describe the fracture events.

For microscale or textural fractals (Dt), some characteristics could be observed as the large heterogeneity on crack path and no evident correlation with crack positions, the scattering may be explained due to local changes in activation of fracture micromechanisms associated to microstructural heterogeneities, at microscale, or the local changes in micromechanics during the fracture process. For macroscale or structural fractals (Ds), it was found that heterogeneity on crack characteristics and scattering is reduced at macroscale relative to textural values, but it is still significant and there is no significant correlation with crack positions, too (Horovitz et al., 2010).

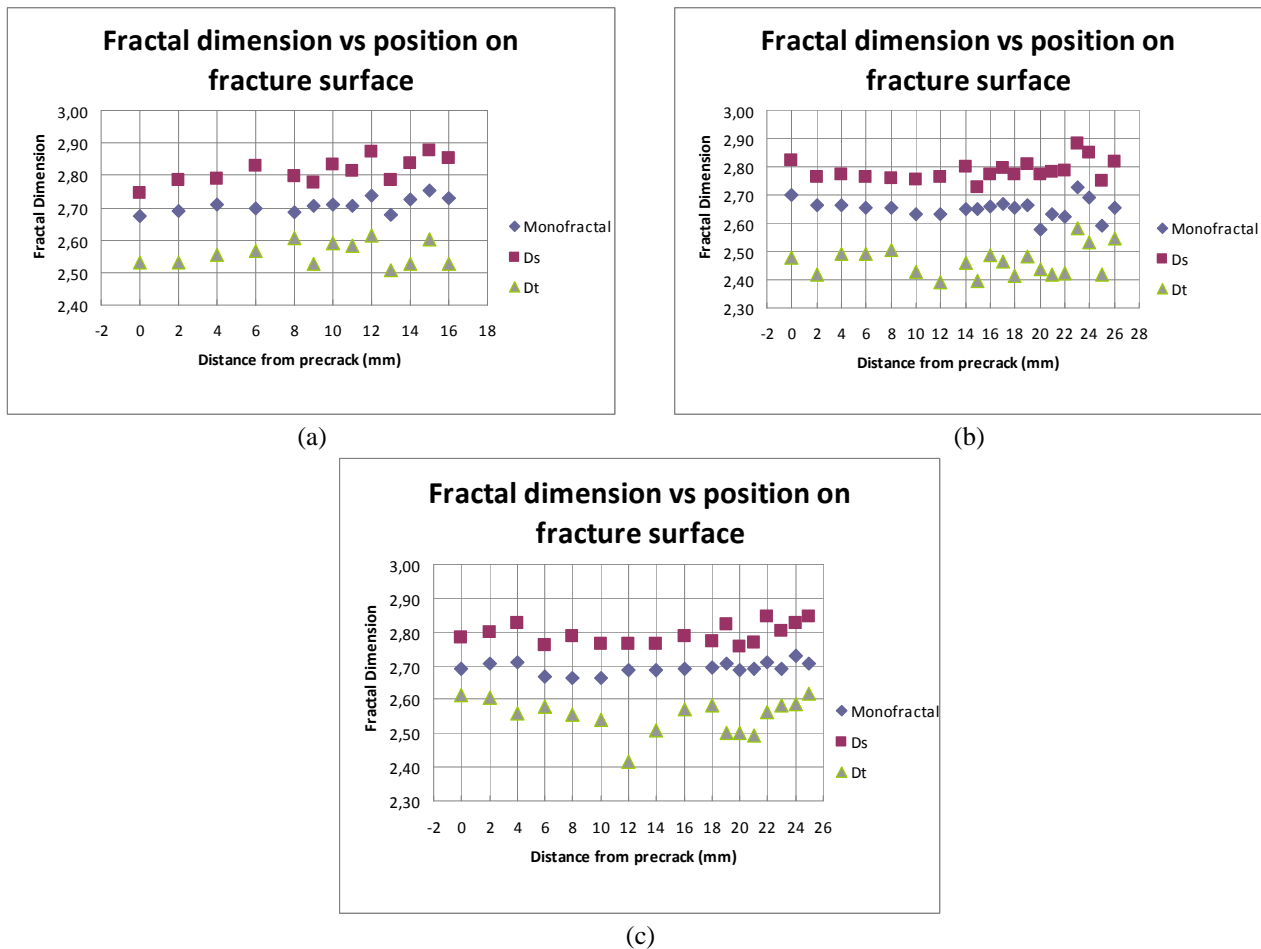


Figure 5. Behavior of fractal dimension data versus position on fractal surface for specimens with different thickness: (a) 12.70mm; (b) 19.05mm; (c) 25.40mm.

It is possible to observe that the textural dimension values, for all specimen thicknesses, have presented a light decrease in the transition of the stable region to the unstable region of crack propagation. It may be explained by the plasticity in front of the crack that leads to decrease its velocity. Therefore, the fractal dimension values could be considered sensitive for the fracture micromechanisms, crack propagation velocity, plasticity in front of the crack, due to present a scattering behavior at the unstable region of crack propagation.

#### 4. CONCLUSIONS

In summary, the following comments can be done:

- Fractal dimension is a sensitive parameter for the analysis of features that contribute on fracture surface formation since it is able to describe its behavior, but it is, in fact, a measure of local entropy.
- It was found that the scattering of fractal dimension values is more representative on analysis of relief changes than the simple comparison between the fractal dimension values and the specimen thicknesses because these values can change strongly.

- The bifractal approach is a good approximation due to the shape of box-counting curves and the inherent multifractality in elevation maps.
- The microscale, or textural, corresponding to the microstructure and micromechanics 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.

## 5. ACKNOWLEDGEMENTS

This work was supported by FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo), under grant numbers 2009/08760-9 and 2010/02721-9.

## 6. REFERENCES

- ASTM E 647, 2008. "Measurement of Fatigue Crack Growth Rates".
- Borodich, F.M., 1999, "Fractals and fractal scaling in fracture mechanics", *International Journal of Fracture*, Vol. 95, pp. 239-259.
- Campos, K.A., Yoshino, C. and Hein, L.R.O., 2009, "Fractal behavior throughout stretch zone of 15-5PH steel under elastic-plastic loading conditions", *Materials Science and Engineering. A, Structural materials: properties, microstructure and processing*. Vol. 525, pp. 37-41.
- Chen, W.A., Yuan, S., Hsieh, C.M., 2003, "Two algorithms to estimate fractal dimension of gray-level images", *Optical Engineering*, Vol. 42, pp. 2452-2664.
- Horovistiz, A.L., Campos, K.A., Shibata, S., Prado, C.C.S. and Hein, L.R.O., 2010, "Fractal characterization of brittle fracture in ceramics under mode I stress loading", *Materials Science and Engineering*, Vol. 527, pp. 4847-4850.
- Horovistiz, A.L. and Hein, L.R.O., 2005, "Fractal analysis along for an aluminum alloy", *Materials Letters*, Vol. 59, pp. 790-794.
- Rasband, W.S., 1997-2009, "Image J", .S. National Institutes of Health, Bethesda, Maryland, USA. 25 Jan. 2011 <<http://rsb.info.nih.gov/ij/>>.
- Russ, J.C., 1994, "Fractal surfaces", Ed. Plenum Press, New York, United States.
- Xie, H., Wang, J. and Stein, E., 1998, "Direct fractal measurement and multifractal properties of fracture surfaces", *Physics Letters*, Vol. 242, pp. 41-50.

## 7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.