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ANALYSIS OF FRACTURE SURFACE OF CFRP MATERIAL BY THREE-DIMENSIONAL RECONSTRUCTION METHODS

Raquel M. Lobo and Arnaldo H. P. Andrade

Instituto de Pesquisas Energéticas e Nucleares, IPEN - CNEN/SP
Av. Professor Lineu Prestes 2242
05508-000 São Paulo, SP
rmlobo@ipen.br

ABSTRACT

Fracture surfaces of CFRP (Carbon Fiber Reinforced Polymer) materials, used in the nuclear fuel cycle, presents an elevated roughness, mainly due to the fracture mode known as pulling out, that displays pieces of carbon fibers after debonding between fiber and matrix. The fractographic analysis, by bi-dimensional images is deficient for not considering the so important vertical resolution as much as the horizontal resolution. In this case, the knowledge of this heights distribution that occurs during the breaking, can lead to the calculation of the involved energies in the process that would allows a better agreement on the fracture mechanisms of the composite material. An important solution for the material characterization, whose surface presents a high roughness due to the variation in height, is to reconstruct three-dimensionally these fracture surfaces. In this work, the 3D reconstruction was done by two different methods: the variable focus reconstruction, through a stack of images obtained by optical microscopy (OM) and the parallax reconstruction, carried through with images acquired by scanning electron microscopy (SEM). The results of both methods present an elevation map of the reconstructed image that determine the height of the surface pixel by pixel,. The results obtained by the methods of reconstruction for the CFRP surfaces, have been compared with others materials such as aluminum and copper that present a ductile type fracture surface, with lower roughness.

1. INTRODUCTION

The flexibility of carbon fibers reinforced polymers (CFRP) is that made possible their use as structural material in advanced technology projects, also in the nuclear industry, by combining high modulus and resistance with a low density [1].

The fracture surfaces of CFRP materials shown a pronounced roughness due to the large variation in height produced by fibers pull-out, one of the more important modes of fracture [2]. Fracture occurs in the fibers and between fiber and matrix by debonding, which displays part of these fibers on the surface [3]. These pieces of exposed carbon fibers are the responsible for the high surface roughness.

Analysis of the fracture surfaces would be more effective with the knowledge of the distribution of exposed fiber heights for the energies calculation involved in the formation of such areas. The loss of vertical information for fractographic analysis by two-dimensional images produces inaccuracies in assessing the variation of the height of the exposed fiber.

The roughness can be better evaluated by three dimensionally reconstructed images [4], which can provide the vertical information required to analyze these areas.

The reconstruction was performed by two different methods [5,6]: the reconstruction of variable focus, through a stack of images obtained by optical microscopy (OM), and the reconstruction of parallax, using pairs of images obtained by scanning electron microscopy (SEM) . Both methods use equipment commonly used in microstructural analysis, revealing new opportunities to exploit these facilities, which are supported by the results.

2. RECONSTRUCTION BY VARIABLE FOCUS

The method of reconstruction by focus variable is applied to a stack of OM images obtained in the same region at regular intervals of height, around the focus position. Each one of the images of this stack contains parts of the original region that are in focus for the height considered. A map of elevations is built during processing in accordance with the focus position where each image pixel is in focus. The result is a completely focused reconstructed image, independent of the analyzed surface roughness.

The processing of the stack of images is based on the focus criterion, calculated by the application of a matrix on the image that defines a focus index for each pixel. This value can identify in which image of the stack one determined pixel is in focus allowing thus to compose the final image.

Reconstruction by varying focus was done on 1.2 mm nominal thickness specimens of multidirectional composite extracted from a broken cylinder after hydrostatic testing. The cylinder was manufactured by filament winding process. Samples were cut by laser to preserve the fracture surfaces. In Fig. 1 it is shown the sample side and the fracture surface with the exposed part of the fiber pullout.

The results show that the method of reconstruction by variable focus produces images surfaces with excellent quality. The superficial details are limited by the degree of image magnification available in an optical microscope. The high degree of image detailing reveals the precision with the elevation map was constructed, allowing a full visualization of the surface.

Although the process requires a large number of images, the results are compensating and of excellent quality. This quality varies with the range of focus and needs to maintain the same conditions of the microscope operation. The technique of reconstruction by variable focus also demonstrates that optical microscopy can play a relevant role to the surface analysis, providing excellent results within the limitations of the equipment.

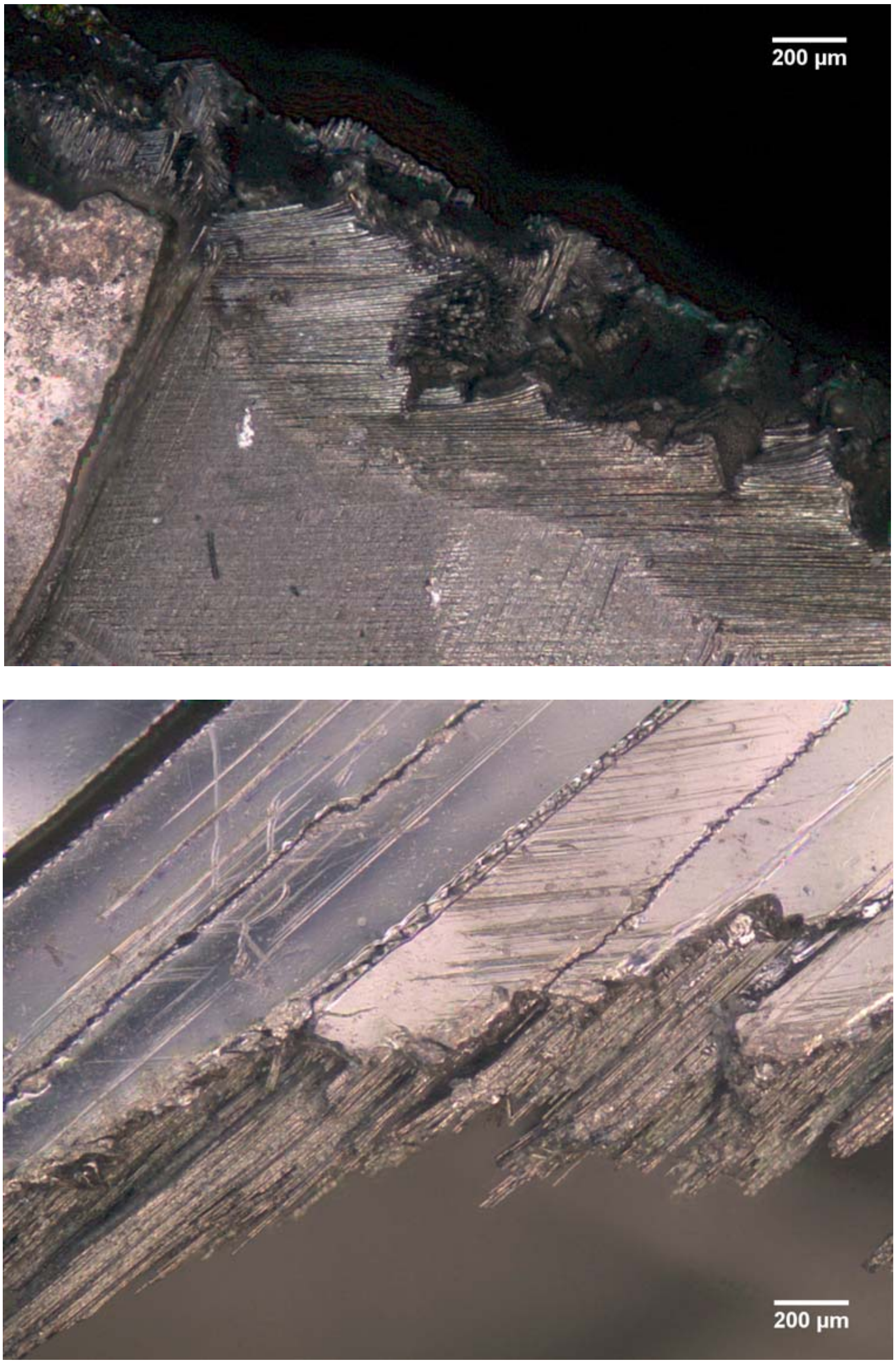

Figure 1. Images of the fracture surfaces of CFRP type composite materials, reconstructed by the method of focus variable. Above side of the sample and below surface with fiber pullout.

3. RECONSTRUCTION BY PARALLAX

Reconstruction by parallax is performed with pairs of SEM images from the same surface region, by tilting the sample in clockwise and counterclockwise direction with respect to a horizontal position. The difference between the projections in the two inclined images allows the determination of the elevation at each point. The equation for calculating the elevation is given by:

$$Z = \frac{1}{M}\left(\frac{X_L - X_R}{2sen\left(\Delta\Theta/2\right)}\right) \tag{1}$$

where M is the image magnification, X_L and X_R are the clockwise and counterclockwise projections on the images respectively, and Θ is the tilting angle.

The most important process step is the determination of similar positions in both images. The difference between the projections of the first and second image determines the elevation, point to point, on the map of elevations produced. The reconstruction quality depends on the matching accuracy between both images. The results presented in Fig. 2 show a pair of images inclined at ± 2 ° and the elevation maps in two and three dimensional modes.

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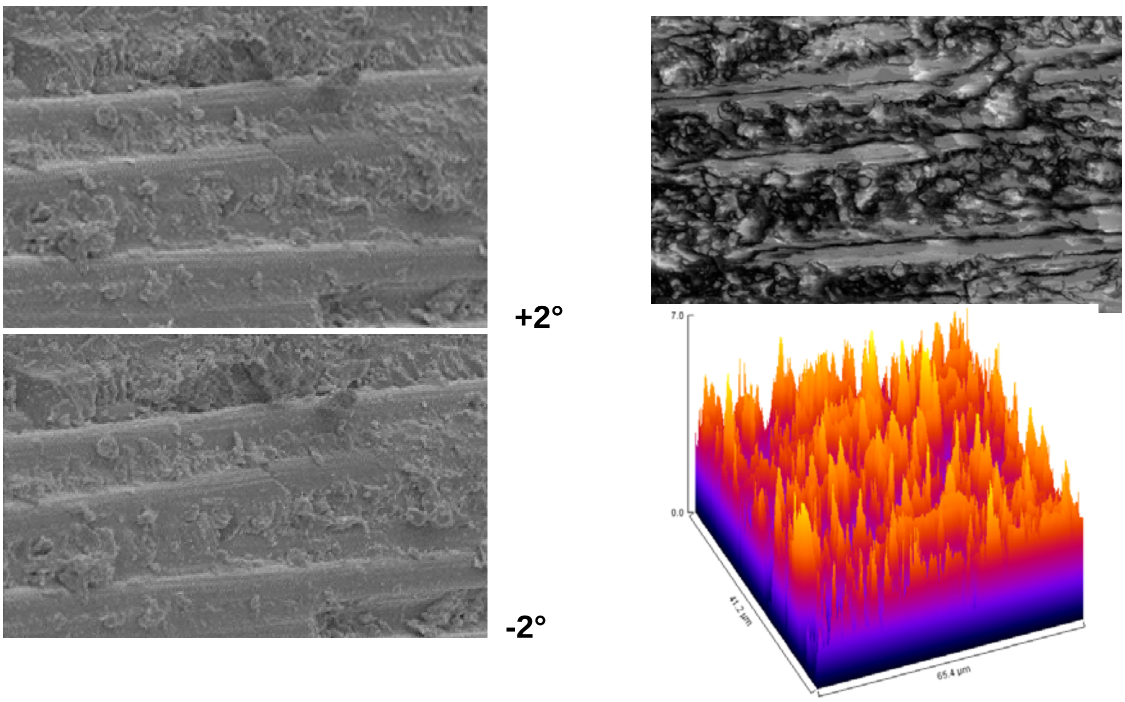

Figure 2. Images of the region of interest tilted at ± 2 ° and the map of elevations in the two-dimensional and three-dimensional modes.

Reconstruction by parallax performed for samples of CFRP type composite material shows a satisfactory result when examining the elevation map obtained. During specimen tilting it is possible to verify both the overlapping and the hiding of details that complicate the matching between images. Metallic specimens such as copper and aluminum do not have the same problem because their fracture surfaces have low roughness [7].

Images histograms from copper, aluminum and composite analyzed in several tilt angles shown variations only in the composite material indicating changes in the characteristics of the region of interest. To avoid such changes, the images should be acquired just in one direction: the counterclockwise one, and the program used for reconstruction should be modified to meet those conditions. The main cause of this problem is the secondary electrons detector position to the left of the camera SEM equipment. The specimen tilting in the clockwise direction enables that side features of the sample interfere with the image, changing its histogram. In a counterclockwise direction such interference does not occur, irrespective of the surface roughness.

4. CONCLUSIONS

The three-dimensional reconstruction of the CFRP materials fracture surfaces presented excellent results when using the method of focus variation with stack of optical microscopy images. The results with the parallax method are satisfactory, but the pronounced roughness of the fracture surfaces that occurs during the fiber pullout needs some modifications, like to acquire both images in the same direction, so that the overlapping and hiding of details do not interfere in the alignment between images in the reconstruction.

REFERENCES

1. G. Marinucci; A.H.P. Andrade, “Microstructural analysis in asymmetric and un-balanced composite cylinders damaged by internal pressure”. *Composite Structures*, **v.72**, pp. 86 - 90 (2006).
2. D. Purslow, “Some fundamental aspects of composites fractography”. *Composites*, pp. 241 -247 (1981).
3. M. Lienkamp; H. E. Exner, “Assessment of overload profiles and interfacial shear strength in unidirectional fibre composites via quantitative fractography”. *Materials Science and Technology*, **v. 10**, pp. 526-530 (1994).
4. P. W. R. Beaumont, “Targeting problems of composites failure”. *Journal of Materials Science,* **v. 33,** pp. 6575-6577, (2008).
5. L. R. O. Hein, “Quantitative fractography by digital image processing: NIH image macro tools for stereo pair analysis and 3-D reconstruction”. *Journal of Microscopy,* **vol. 204,** pp. 17-28 (2001).
6. E. F. Lucena, “Estudo de algoritmos para reconstrução de relevos de superfícies irregulares: aplicação na fractografia quantitativa e caracterização de materiais”. Doctoral Thesis, *Universidade Estadual Paulista (UNESP)* (2004).
7. R. M. Lobo, “Reconstrução tridimensional de superfícies de fratura de materiais compósitos do tipo CFRP”, Doctoral Thesis, *Universidade de São Paulo (USP)* (2009).