The Quantitative Measurement of Pigment Dispersion by Fractal and Other Methods

Gordon Hardy, Hunt Imaging, Berea, Ohio, USA

Abstract

Lacunarity analysis is a method for describing fractal patterns with spatial or textural variations. This method has also been applied to nonfractal and multifractal patterns such as texture, roughness, and porosity. In this paper, an approach is presented for quantitatively describing the nature of particle dispersion in toner by analysis of digitized photomicrographs with fractal dimension and lacunarity analysis. Image analysis of computer synthesized dispersion profiles varying in such properties as mean agglomerate size, agglomerate size distribution, loading, and spatial homogeneity is presented. We find that agglomerate size can be measured by changes in the fractal dimension as determined by modified Richardson plots obtained by a box counting method. Additionally, we find that the spread in the agglomerate size distribution and the spatial homogeneity of the dispersion are correlated with lacunarity as measured by the sliding box algorithm.

Introduction

Toner particles are a mixture of several relatively incompatible materials. At the very least, a modern toner contains resin, wax, pigment, and charge control agent. It is well established that several performance characteristics of the toner depend on how well the pigment,[1] wax,[2] and charge control agent[3] are dispersed in the resin matrix. As a result, the level of dispersion of these components is crucial in the development of new toners and new toner processes. Controlling these dispersions is not simple. Process conditions that are beneficial to the pigment dispersion can be different from the conditions required for the optimum dispersion of wax or charge control agent.

Most commonly, the dispersions of these materials are not directly measured but are evaluated indirectly based on their effects on toner performance or other physical properties. Performance characteristics such as image background or photoconductor filming are indicators of dispersion quality as are physical properties such as the dielectric constant or the triboelectric charge.

Direct measurement of dispersion is usually taken from photomicrographs. These can be either from a toner smear under an optical microscope, or a section from transmission electron microscopy (TEM). Evaluation of the dispersion from photomicrographs can be made by visual comparison with a set of standard photos. Alternatively, dispersion parameters such as agglomerate size can be measured either manually, or by software operating on digitized photomicrographs.

Mathematical methods have been developed over the past 20 years specifically to describe complex systems. Mandelbrot's introduction of fractal geometry[4] in 1982 has since been applied to various natural systems whose geometry lies somewhere between the topological dimensions of Euclidean geometry. More recently, lacunarity analysis[5] has been applied to further describe systems with the same fractal dimension but very different visual appearance or texture. The work described in this paper is an effort to apply fractal geometry and lacunarity analysis to quantitatively describe pigment dispersion in toner.

Methods

Images used in this analysis are 800 × 600 pixels. The images are digitized over an adjustable threshold so that every pixel is either black (image) or white (background).

Fractal Analysis

The fractal dimension is a measure of the ratio of increasing detail with increasing scale. Analysis of the fractal nature of the images is performed by the standard box counting method. In this method, grids of sizes ranging from 2 to 64 pixels in length are placed over the image and the numbers of boxes that contain image pixels are counted. The fractal dimension (D_B) is negative the slope of the least squares regression line of the log-log plot of box count as a function of box size (modified Richardson plot). These analyses are completed with the aid of ImageJ software, a public domain image analysis package.[6]

Lacunarity Analysis

Lacunarity is a scale dependent measure of heterogeneity. It is a measure of the "gappiness" or visual texture of an image. Analysis of the lacunarity is performed by the gliding box algorithm. In this method, boxes of size ranging from 1 to 270 pixels are scanned over the image at overlapping intervals. The number of image pixels contained in the box is counted at each step. Once the entire image is scanned, the average number and standard deviation of pixels for that box size are recorded. Lacunarity is calculated as

$$\Lambda_\varepsilon = 1 + (\sigma_\varepsilon/\mu_\varepsilon)^2 \qquad (1)$$

where ε is the scale defined as the box size divided by the image size, Λ_ε is the lacunarity at scale ε, σ_ε is the standard deviation of the pixel count at scale ε, and μ is the mean pixel count at scale ε. These analyses are completed with a plug-in for ImageJ called FracLac.[7]

Simulated Photomicrographs

Fractal and lacunarity analyses are performed on simulated photomicrographs. In this way, the parameters that affect dispersion can be accurately and independently controlled. The image analysis results are then compared to the known differences in the images. Four dispersion related variables are identified. These are the mean particle size (M), the particle size distribution (D), the spatial distribution (XY), and the total particle concentration or load (L).

Images are computer generated based on these four input variables. The mean particle size is defined as the diameter of the particle in pixels. The particle size distribution is defined as the spread in particle diameter in pixels such that a value of 1 indicates uniform particle diameters and a value of 10 produces a total spread of 10 pixels normally distributed about the mean. Similarly, the spatial distribution is generated as a normal distribution with a value of 1 indicating total uniformity and higher values generating greater spatial variation. While the program is designed to control spatial distributions in the x and y directions independently, these parameters are varied together in the images generated here. Finally, the particle load is taken as the total percent of pixels containing particles such that a load of 5 would generate an image containing 5% particles by area. No effort is made to prevent particle-particle contact or overlap in the simulated images.

Results and Discussion

Fractal Analysis

The fractal analyses of three images generated with identical dispersion input parameters are nearly super imposable. As a result, any differences found in the fractal analyses varying parameters can be interpreted as significant. Also, no differences are observed in the fractal plots of images varying the particle size distribution from 1 to 20, indicating that the fractal dimension is independent of the particle size distribution. While slight differences are observed in the fractal plots of images varying only spatial distribution (especially at larger box sizes) this parameter is nearly independent of fractal dimension as well.

Significant differences are observed in the Richardson plots of images varying mean particle size and particle load. These plots are not perfectly linear indicating that the images are not pure fractals. Rather, the plots indicate two linear regions. The fractal dimensions in the lower box size region correlate well with the mean particle size. These results are summarized for images varying M with D = 1, XY = 1, and L = 5 in Table 1.

In the cases of varying particle load, differences in the fractal dimension are minor while differences in the Y axis intercept correlate well with the load. These results are summarized for images varying L with M = 5, D = 1, and XY = 1 in Table 2.

In summary, the fractal analysis results are for the most part independent of particle size distribution and spatial distribution variables. The fractal dimension at low box size is mostly dependent on the mean particle size. Certainly, in cases where the toner formulator is controlling the particle load, any differences in fractal dimension at low box size would be indicators of differences in mean particle size.

Lacunarity Analysis

Differences in the distribution variables dominate the lacunarity analysis. Plots of Lacunarity (Λ) versus scale (ε) usually demonstrate a peak at low scale (near ε = 0.01), a minimum at higher scale (ε between 0.01 and 0.1) and increasing values above ε = 0.1. The low scale peak is independent of load and spatial distribution. The low scale peak varies linearly with the particle size distribution. The variation of the low scale peak with particle size distribution for images with M = 5, XY = 1 and L = 5 are shown in Table 3.

The lacunarity at high scale is independent of all of the dispersion parameters except spatial distribution. The differences are particularly evident when choosing an arbitrary high scale value (ε = 0.333). These values are summarized in Table 4 varying XY with M = 5, D = 1, and L = 5.

Table 1: Mean Particle Size and Fractal Dimension

Mean Particle Size	D_B at Low Box Size
1	0.48
3	0.84
5	1.03
7	1.09
9	1.15

Table 2: Particle Load and Fractal Measures

Load(%)	D_B	Y Intercept
1	1.01	3.64
3	1.05	4.12
5	1.11	4.36
7	1.12	4.50
9	1.17	4.62

Table 3: Size Distribution and Low Scale Lacunarity Peak

Size Distribution	Low Scale Peak
1	1.55
3	1.60
5	1.66
7	1.73
9	1.77

Table 4: Spatial Distribution and Lacunarity

Spatial Distribution	Lacunarity at ε = 0.333
1	1.28
3	1.48
5	2.02
7	2.74
9	2.93

In summary, the lacunarity analysis results are separated into low scale peak and high scale values. The low scale peak is independent of load and spatial distribution while reflecting mean particle size and particle size distribution information. The high scale values reflect differences in spatial distribution independent of all other variables.

Conclusions

Pigment dispersion is defined according to four parameters. These parameters are independently controlled in computer simulated photomicrographs and analyzed by fractal and lacunarity methods. The mean particle size can be determined by the fractal dimension at low box size independent of size distribution and spatial distribution parameters. The size distribution can be determined by the lacunarity peak at low scale and the spatial distribution can be determined by the lacunarity value at high scale. These methods can be used to assist toner formulators in achieving optimum pigment dispersions.

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Author Biography

Dr. Gordon Hardy received his Ph.D. in chemistry from UCLA in 1979. He worked at Procter and Gamble Company Corporate Research until 1986 when he joined Nashua Corporation as a Senior Chemist. He became Project Coordinator at the Goodyear Chemical Resin Group in 1995 and later a Research Manager in the Goodyear spin-off, Eliokem. In 2004, he joined Hunt Imaging as a Research Specialist. He has authored 13 technical publications and has 2 US patents.