Digital Image Analysis of Materials

In materials science, the microstructure is often the link between process and properties, and the extent to which the analyst can quantify the microstructure determines the strength of the link. Whether one is making standard measurements in a metallography laboratory or trying to discover new relationships, the microstructure provides valuable information. For example, in steel and many other metals, the relationships between microstructure and properties are well known. But even in systems where these relationships have yet to be established, analysis of the microstructure can provide data that points in the direction of fruitful research.

Most digital imaging operations are categorized as either image processing or image analysis. Image processing operations (for example, edge finding or crispening) change one image into another. Image analysis operations (for example, area fraction or average particle diameter) quantify some aspect of the image. If the ultimate goal is image analysis, most analysts would prefer to do little or no image processing in order to save time and avoid altering the original data. However, it is often necessary to do some processing to prepare an image for analysis. For example, it may be necessary to reconstruct grain boundaries to compensate for imperfect etching before performing an image analysis operation such as grain sizing.

Both image processing and image analysis assist the investigator in gathering and displaying information. In many cases, the digital imaging system can both gather a great deal of information and display that information in a way that is most clear to others.

Contrast Mechanism

Before attempting to quantify some aspect of an image, the analyst must make sure that the selected signal carries a contrast mechanism that is meaningful for quantification. Often materials science laboratories have access to both LOMs and SEMs. Some of the more commonly available contrast mechanisms are listed in Table 1.

Digital Image Sources and Resolution

A digital image contains a discrete number of pixels, each of which has an intensity value between 0-255. Digital images can come from a still or video digital camera, a scanner, or a digitizing tablet. They can also be digitized from an analog camera. On the SEM, digital beam control positions the electron beam, and either captures a digital signal or digitizes the analog signal. Image resolutions of 512 or 1024 pixels in one direction are common.

LOM Signal	Contrast Mechanism
Transmitted light	True color Interference colors (polarized light)
Reflected light	Topography Grain structure True color
SEM Signal	**Contrast Mechanism**
Secondary electrons	Topographic Various voltage & magnetic
Backscattered electrons	Atomic number Trajectory Crystallographic (EBSD & ECP)
Specimen current (absorbed electrons)	Atomic number Charge (EBIC) Crystallographic (ECP) Magnetic type 2
X rays	Composition

Table 1. Signals and contrast mechanisms in the LOM and SEM..

Limitations to Resolution

Although the resolution of a camera is limited only by the CCD resolution, when installed on a LOM, the actual resolution is limited by the numerical aperture (NA) of the microscope. Thus pixel resolutions >640 do not provide more information, but they may look better.

In the SEM, resolution is defined as how finely the beam can be positioned. The DACs that do the positioning in the PGT system have a precision of 1:64,000, and the user can select resolutions in powers of two from 64 - 4096. Of course, it is not possible to display a complete 4096 image on a CRT, but it allows pan and zoom, and image analysis of large and small features is possible simultaneously.

Depth of Digitization (Gray Levels)

LOM and SEM Electron Signals

The signal at each pixel is digitized to some discrete number of intensity levels, commonly 256 (8-bit). When more levels are needed (for example, after image processing) 16-bit images are used.

X-ray Signal

A case requiring special consideration is x-ray mapping. The intensity value stored in each pixel of a PGT map corresponds to the actual number of x-ray counts collected during the total dwell time. The software allocates only the minimum number of bits required for the number of counts at each pixel. As more counts are received, the bit planes are promoted as necessary, keeping file sizes to a minimum.

Pseudocolor

Although the human eye can only discriminate about 20 levels of intensity at the same time, it can distinguish about 350,000 shades of color. The significance of this fact is that pseudocolor can be used in an image to convey details that would be lost in the gray scale image. A scale that corresponds to the colors of an incandescent body, called the "thermal scale," is sometimes used to convey intensity gradients intuitively to an observer unfamiliar with the underlying contrast mechanism.

Image Analysis

After selecting an imaging signal having a contrast mechanism that can distinguish the phases of interest from one another, the image is digitized. Most systems require the user to binarize the image before making measurements, meaning that in a multiphase microstructure, only one phase can be measured at a time. The PGT "Universal Feature Analysis" program, however, is a multiphase image analysis program. It measures features of different phases simultaneously, reporting the results by phase, if so desired.

Measurements

Image measurements fall into two categories: field measurements and feature measurements. Field measurements consist of one number per field of view, and feature measurements are specific to individual features. Examples of field and feature measurements are given in Table 2.

Results of Image Analysis

The results of these measurements on multiple fields of view can be reported as summary statistics and statistical distributions, including all the descriptors for every feature, as shown in Table 3. Graphical output in the form of histograms and scatter plots is also provided, as illustrated in Figures 2 and 3.

It should be noted that with modern Automatic Image Analysis (AIA) systems, making hundreds of measurements on thousands of particles is virtually instantaneous. The challenge is in making the right measurements and correctly interpreting them. In the case of this iron-ore pellet, the amount, size, and distribution of porosity would be expected to correlate with blast furnace performance.

Direct Field Measurements	Direct Feature Measurements
Area fraction (A_A)	Area
Number of features (N)	Perimeter
Number of features/area (N_A)	Length Breadth Diameter
Number of intercepts/length (N_L)	X-ray intensity in the SEM
Computed Field Measurements	**Computed Feature Measurements**
ASTM grain size (G)	Aspect ratio
Surface/volume	Circularity Form factor Roughness

Table 2. Field and feature measurements.

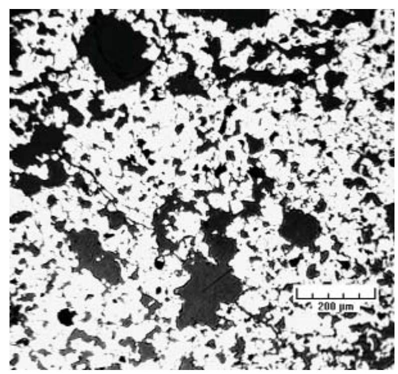

Figure 1. LOM image of an iron-ore pellet.

Universal Feature Analysis

A significant step beyond measuring the size and shape of features one phase at a time is to measure multiple phases and keep track of their adjacencies. PGT's Universal Feature Analysis does this. It is universal because the system has a full description of each feature plus their spatial relationships (adjacency), and composition information, so the microstructure can be completely characterized. In materials science, this knowledge can be used in the analysis of complex inclusions, in metal- and ceramic-matrix composites, and other multiphase materials.

Image Processing

Even when the goal is image analysis, some preprocessing is often necessary to enhance the microstructural features to be analyzed (for example, to separate agglomerated particles or reconstruct incomplete grain boundaries). Although the goal of

Measurement	Average	Median	Minimum	Maximum	1σ
Feature Number	462.66	435.00	2.00	1050.00	295.94
Area	702.44	101.75	23.66	94377.93	5372.94
Average Diameter	24.69	14.10	5.86	755.46	48.30
Length	30.36	17.16	6.40	970.21	61.61
Perimeter	138.98	47.64	16.13	12271.82	715.63
Breadth	18.71	11.28	3.71	486.34	33.38
Form Factor	0.5443	0.5491	0.0079	1.1430	.2388
Circularity	2.6122	2.3844	1.3530	8.0879	.9901
Aspect Ratio	1.6385	1.5193	1.000	3.9995	.4644
Fiber Length	61.84	18.00	0.00	6120.49	357.17
Fiber Width	5.27	4.70	0.00	21.07	3.94

Table 3. Summary statistics from analysis of the porosity shown in Figure 1.

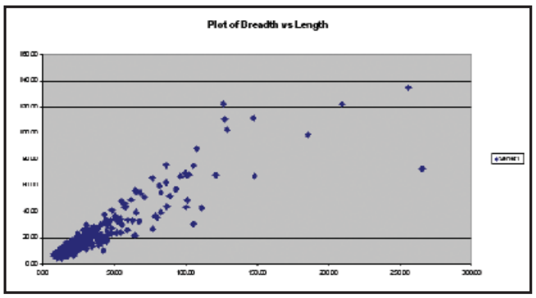

Figure 2. Scatter plot of Breadth vs. Length of pores.

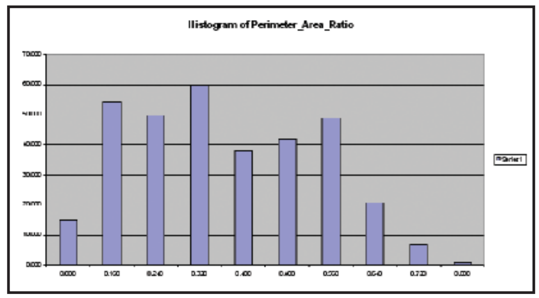

Figure 3. Histogram of perimeter/area ratio.

image processing is to improve the image, the only thing certain is that the image is changed. No information can be extracted that was not present in the original image, and artifacts can be introduced.

Other forms of image processing operate on the entire gray scale image and transform the contrast. Some uses for these operations include:

- Background equalization
- Crispening
- Edge detection
- Noise removal
- Hole filling

The list of image processing operations is extensive, but most digital imaging systems provide standard image processing tools.

Applications of Digital Imaging in Materials Science

Light Optical Microscope Applications

Common applications of image analysis that use the LOM include the many metallographic and ceramographic measurements that are performed routinely as a part of materials testing and acceptance.

Microstructural measurements that may relate to process or properties include:

- Grain size
- Particle size
- Nonmetallic inclusion rating
- Coating thickness
- Banding
- Point counting
- Stereological measurements

The advantages of the LOM, besides cost, include ease of use, many contrast mechanisms available from etching, and ease of calibration.

Scanning Electron Microscope Applications

The LOM is the first instrument of choice for materials analysis. However, there are certain jobs that the SEM can do better. The user would choose the SEM over the LOM, when there is a need for:

- Higher resolution
- Greater depth of focus
- 3-D stereoscopy
- Imaging of as-received materials, such as fracture specimens
- Compositional or crystallographic information

Combined Imaging/X-ray Applications

Two generic capabilities are available on EDS/Imaging systems that make use of both the electron and the x-ray signals: spectrum imaging (position-tagged spectrometry) and chemical classification.

Position-tagged spectrometry stores an entire EDS spectrum at every pixel in the image; thus a spectrum image is a file, whose dimensions are x, y, and energy. From that file, one can extract x-ray maps for any element or spectra from any region, including discontiguous ones. The computer can even automatically sort data into phases. By combining image processing with microanalysis, the analyst can define regions such as grain boundaries or interfaces and measure their composition or compositional gradients.

In chemical classification, a feature analysis is performed to find and measure all features of interest in the SEM. The beam then is driven only to those features that possess specified criteria based on size or shape. For example, the analyst could select the high-aspect ratio features (perhaps inclusion stringers), then collect a spectrum of each one and sort them into user-defined classes (for example, sulfides, silicates, oxides and complex inclusions).

Standard Procedures

Before automatic image analyzers (AIA) were available, methods were developed to quantify various aspects of a microstructure. Many of these were then adapted to AIA, and a list of some ASTM standards applicable to the LOM is given in Table 4. Some of these procedures have been adopted by the standards organizations of other countries and by ISO.

ASTM Designation (Manual/AIA)	Description
E562	Point counting
E112/E1382	Grain size
E45/E1122	Inclusion rating
E1245	Stereology
B487	Coating thickness
E1268	Degree of banding
E883	Reflected light microscopy
Various	Microscopy of specific materials

Table 4. List of ASTM standards applicable to light microscopy.

Besides those standard procedures that were written principally for the LOM, there are others that were written specifically for the SEM. A list of some of these is given in Table 5.

ASTM Designation	Description
E766	SEM magnification calibration
E986	SEM beam size measurement
E1508	Quantitative analysis by EDS
E1588	Gunshot residue
E2142	Inclusions by SEM/EDS
B748	Coating thickness

Table 5. List of ASTM standards applicable to the SEM.

Trends

As the price/performance ratio of PCs goes down, we find powerful computers in search of applications that need computing power. Image processing and analysis are such applications. Mass storage media is also available to archive images and analytical results. While general purpose imaging software is commonly available, these packages consist mostly of digital darkroom capabilities; that is, they provide functions to change the appearance of an image. However, in the microscopy laboratory, the trend is toward more application-specific software.

Summary

The need for quantification of the microstructure, and sometimes macrostructure, has been understood by materials scientists for a long time. Computers are now sufficiently powerful that these operations can be performed in software, obviating the need for expensive imaging hardware. Whether one is using the microscope for research, production, or quality assurance, digital imaging is a powerful technique for:

- Gathering information not available without a computerized system.
- Obtaining enough reproducible information to be statistically valid.
- Displaying such information.

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