

CHARACTERIZATION OF PARTICLE SHAPE

T. F. DUMM¹ AND R. HOGG²

¹GE Superabrasives, Worthington, OH 43085

²Mineral Processing Section, University Park, PA 16802

Abstract. A simple shape description scheme has been developed which has the specific aim of distinguishing between angular and more rounded particles. The procedure involves fitting a general polygon (usually about 20 sided) to the particle profile. Geometric shape descriptors have been defined based on variations in the angles between adjacent sides and their radial displacement from the particle centroid.

A two-parameter shape description, incorporating an angular variability and an elongation index, has been shown to be clearly consistent with visual observations. A single-parameter angularity index has been shown to be very sensitive to small differences in particle roundness and seems to provide a better description of angularity than other approaches such as signature and fractal analyses. The scheme has been applied to three sets of fine quartz particles produced by different grinding procedures. The results indicate that the technique is capable of distinguishing between angular and relatively rounded particles and can quantify their specific shape features.

INTRODUCTION

Scientific investigations into the causes of Coal Worker's Pneumoconiosis and other similar respiratory diseases have generally focused on the size and compositional characteristics of respirable dust. However, an important, but not well understood, characteristic of all particles, in addition to size and composition, is their shape or morphology. It has often been suggested for example, that the presence of sharp angles on particles may be a contributing factor in the toxicity of respirable dust. The validity of such hypotheses, however, has been difficult to assess because of a lack of reliable, quantitative criteria for describing these shape features.

Brittle fracture of solids often leads to the production of particles which have sharp angular corners and straight edges. Elongated splinters or shards are also common from this kind of breakage. Abrasion processes, on the other hand, lead to the removal of sharp corners etc., and tend to produce more rounded particles. Both of these kinds of processes can occur in mining and processing operations.

The primary objectives of the work described in this paper were to evaluate existing shape characterization schemes and to develop suitable criteria for use in the quantitative evaluation of the kinds of shapes produced during particle formation and in studies of the role of shape in dust behavior and dust toxicity.

DESCRIPTION OF PARTICLE SHAPE

It must be emphasized at the outset that, due to the lack of practical, three-dimensional imaging capability especially for fine particles, shape analysis is generally restricted to two-dimensional particle profiles as obtained by optical or electron microscopy. Any such profile can be represented by a vector of Cartesian (x,y) or polar (R,θ) coordinates of the perimeter of the particle. These can be expressed mathematically by Fourier analysis, leading to relationships of the form:

$$R(\theta) = a_0 + \sum_{n=1}^{\infty} [a_n \cos n\theta + b_n \sin n\theta] \quad (1)$$

where the a_n ($n=0,1,2,\dots$) are a set of Fourier coefficients which contain all information on (two-dimensional) particle shape.

Particle Signature

Meloy⁽¹⁾ has shown that, for many shapes, the set of Fourier coefficients can be described by a simple power-law relationship:

$$A_n = A_1 n^{-s} \quad (2)$$

in which

$$A_n = \sqrt{a_n^2 + b_n^2} \quad (3)$$

A_1 and s are the "particle signature" parameters and are characteristic of particle shape.

Fractal Analysis

For highly complex profiles, the mathematical transform approach becomes impractical. Fractal

analysis(2) provides an attractive alternative and has been widely applied to particle systems in recent years(3-5). The essence of fractal analysis is to estimate the perimeter by walking around the profile using a fixed step-length. If the procedure is repeated using different step lengths, a power-law relationship between measured perimeter P and step length λ is frequently observed. Thus,

$$P = K\lambda^{(1-D)} \quad (4)$$

where K is a constant and D is known as the fractal dimension of the profile.

Geometric Parameters

Various geometric factors have been used to provide quantitative descriptions of particle shape. One example has been designated nodularity k_n and is obtained from

$$k_n = 4\pi A/P^2 \quad (5)$$

where A is the cross-sectional area of the profile. k_n is equal to one for a circle.

Shape Classification

In order to determine meaningful shape information, it is important first to define what features are of interest. Consider two extremes in particle shape. The first is simply a sphere (or circle) which contains no angular features and has a single radial dimension from its center of gravity. The second is a long, sharp shard which has a very acute angle at the tip of the longest protrusion from the center of gravity of the profile. There are two shape features which differentiate the shard from the sphere: the presence of angles (angularity) and the elongated nature (elongation) of the profile. These features are to some extent independent of each other so that a shape description scheme can be developed as shown in Figure 1. This scheme shows that it is possible to have particles which are

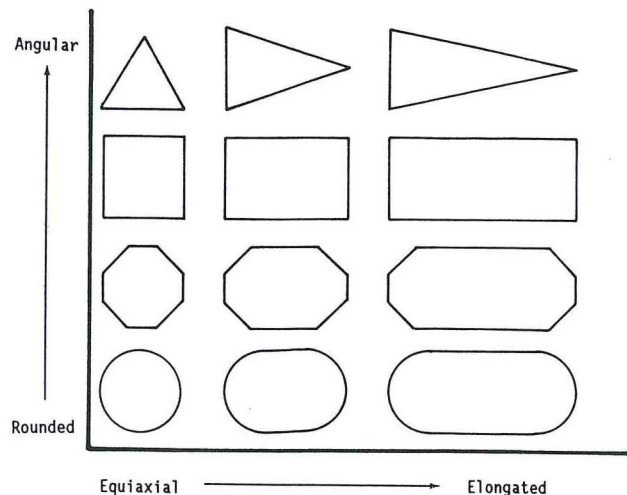


Figure 1. A simple shape classification scheme showing extremes in particle shapes.

fairly equiaxial yet quite variable in the degree and number of angles. Alternatively, particles with similar angular characteristics can have very large differences in axial dimensions. Both features can be expected to influence particle behavior and should be included in a shape description scheme.

Geometric Shape Descriptors

The angularity/elongation criteria indicated in Figure 1 have been used to develop a simple shape characterization scheme based on a set of geometric shape descriptors(6). The procedure is as follows:

1. A finite number (n) of perimeter points is used to represent the particle profile as a n -sided polygon (see Figure 2).
2. The coordinates of the centroid of the particle are determined.
3. The area A of the profile is measured and the corresponding equivalent-circle radius, R_0 is calculated.
4. The radial vectors (R_i) from the centroid to each of the perimeter points are evaluated.
5. The angles (ϕ_i) between each pair of adjacent faces are determined.
6. The set of Ferret's diameters d_{F_i} are estimated.

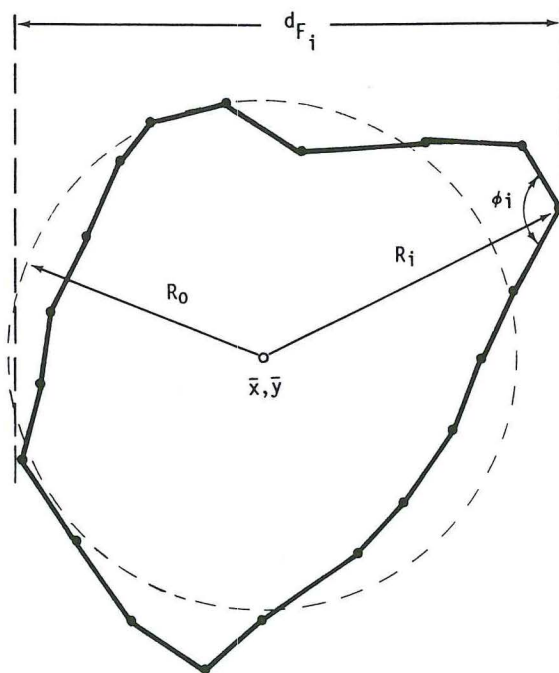


Figure 2. Representation of a general particle profile of 20 points showing the centroid (\bar{x}, \bar{y}) , R_0 , d_{F_i} , ϕ_i , and R_i values measured for each profile.

Based on these measurements, the following geometric shape descriptors have been defined:

a) Angular Variability V_ϕ

$$V_\phi = 1 + \sum_{i=1}^n (\phi_c/\phi_i - 1)^2 \quad (6)$$

where ϕ is the angle between adjacent faces of an n-sided polygon fitted to a circle, i.e.

$$\phi_c = \pi(n-2)/n \quad (7)$$

b) Radial Variability V_R

$$V_R = 1 + \sum_{i=1}^n (R_i/R_0 - 1)^2 \quad (8)$$

c) Angularity $V_{R\phi}$

$$V_{R\phi} = \sum_{i=1}^n (\phi_c/\phi_i - 1)^2 (R_i/R_0 - 1)^2 \quad (9)$$

d) Elongation $E^{(7)}$

$$E = (d_f)_{\pi/2} / (d_f)_{\min} \quad (10)$$

where $(d_f)_{\min}$ is the minimum of the set of measured Feret's diameters and $(d_f)_{\pi/2}$ is the Feret's diameter measured perpendicular to $(d_f)_{\min}$.

EVALUATION OF SHAPE DESCRIPTORS

In order to evaluate the utility of the various shape descriptors discussed above, especially with respect to their ability to discriminate between angular and more rounded particles, the various descriptors have been determined for the two profiles shown in Figure 3. These were drawn somewhat arbitrarily but in such a way as to represent "typical" shapes of irregular particles. Visually, it is clear that profile 2 includes some relatively sharp angles while profile 1 is generally more rounded. The values of the shape descriptors are compared in Table 1.

It is readily apparent from the table that the particle signature s , the fractal dimension D and the nodularity parameter n_k do not provide a clear distinction between these two profiles. The elongation factor E is somewhat larger for profile 2 as would be expected visually. The geometric descriptors V_ϕ , V_R and $V_{R\phi}$ do indicate significant differences between the two profiles, reflecting the more angular nature of profile 2.

APPLICATION TO REAL PARTICLES

The use of the geometric shape descriptors for characterizing shape in systems of real particles has been investigated using crushed quartz particles, prepared by sieving into a

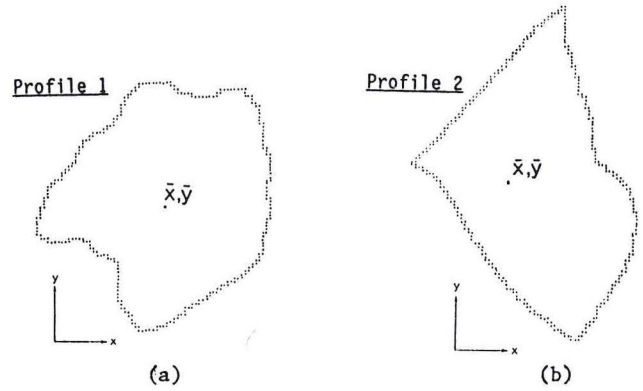


Figure 3. Hand-drawn profile of (a) a roughly equiaxial and rounded particle, and (b) a more elongated and angular particle.

Table 1. Comparison of particle shape descriptors for the irregular particle profiles shown in Figure 3.

Descriptor	Value	
	Profile 1	Profile 2
Signature s	1.63	1.58
Fractal Dimension D	1.06	1.04
Nodularity n_k	0.73	0.72
Elongation E	1.18	1.71
Angular Variability V_ϕ	2.13	7.62
Radial Variability V_R	1.30	2.57
Angularity $V_{R\phi}$	0.04	2.85

narrow size fraction (26x38 μm). The particle profiles were obtained using a computer-controlled, JEOL Model 50A, scanning electron microscope. The data so-obtained consist of a very large number of coordinate points. These were reduced to a more manageable level by selecting every n^{th} point based on the ratio of the actual number of points counted to the number desired to represent the profile. By trial and error, it was found that a total of 20 points was generally adequate to provide a polygon fit to the profile, which retained the essential features of the particle shape. It is recognized, however, that more sophisticated fitting techniques might offer improved shape description. The procedure described previously was then used to evaluate the geometric shape

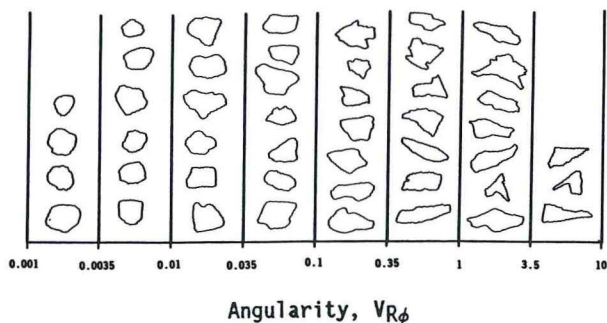


Figure 4. Profiles of real quartz particles classified according to angularity $V_{R\phi}$.

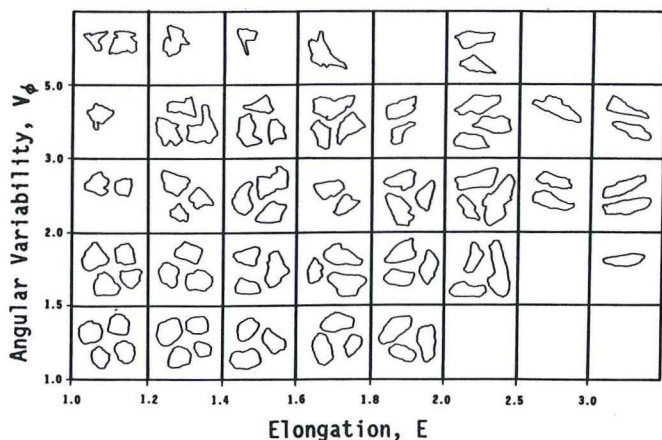


Figure 5. Profiles of real quartz particles classified according to angular variability V_ϕ and elongation E .

descriptors V_ϕ , V_R , $V_{R\phi}$ and E . Some examples of the results are shown in Figures 4 and 5.

The classification of particle shape according to the angularity parameter $V_{R\phi}$ is illustrated in Figure 4, which shows a consistent, progressive decrease in the relative roundedness of the profiles as $V_{R\phi}$ increases. This is consistent with the result shown in Table 1 in which $V_{R\phi}$ was found to provide the most sensitive measure of angularity of the various geometric descriptors considered. There is some question, however, of the ability of this measure to discriminate between elongated but relatively rounded particles and more angular but less elongated particles (see for example the columns corresponding to angularities between 0.1 and 1.0 in Figure 4).

A more complete shape description scheme can be obtained using combinations of the descriptors - a two-parameter description. An example of this approach is shown in Figure 5 where particles are classified according to both angular variability V_ϕ and elongation E . This scheme clearly sorts particles into groupings which are visually similar in shape.

Particle Shape Distributions

It is obvious, of course, that no two particles will be identical in shape and that any system of real particles will possess a distribution of shapes. These shape distributions have been investigated for quartz particles of similar size ($26 \times 38 \mu\text{m}$ fractions prepared by sieving) produced using different grinding techniques (single particle crushing and ball mill grinding for different times). Some typical scanning electron micrographs are shown in Figure 6. The shapes were analyzed using the procedures described above; the mean values of the various geometric descriptors are presented in Table 2. The results indicate that the shapes become progressively more rounded with increased grinding time in the ball mill - presumably due to abrasive wear and the removal of extremities by chipping. Again, the single-value angularity parameter $V_{R\phi}$ seems to provide the most sensitive measure of this effect.

Table 2. Mean values of geometric shape descriptors for $26 \times 38 \mu\text{m}$ quartz particles produced by different grinding procedures.

Production Method	Elongation E	Angular Var. V_ϕ	Radial Var. V_R	Angularity $V_{R\phi}$
Roll Crusher	1.54	2.90	2.24	0.77
Ball Mill (8 min)	1.61	2.29	2.37	0.32
Ball Mill (256 min)	1.28	1.70	1.44	0.04

The distributions of angularity are shown in Figure 7. It is obvious from the figure that the particles subjected to long-time (256 min) ball mill grinding possess a significantly different shape distribution from those produced by single-particle crushing or subjected only to a short time in the ball mill. It is interesting to note that the distributions conform quite closely to the log-normal form and that the ball mill grinding leads to a shift in the median angularity to lower values and a slight narrowing of the distribution.

CONCLUSIONS

The following general conclusions can be drawn from the results of this investigation:

1. Fourier analysis can provide a complete description of particle profiles but is unwieldy for practical application. Simplifications such as signature analysis seem to be insensitive to features such as angularity.
2. Fractal analysis is excellent for describing fine-scale features but is relatively ineffective for distinguishing between angular and rounded particles.

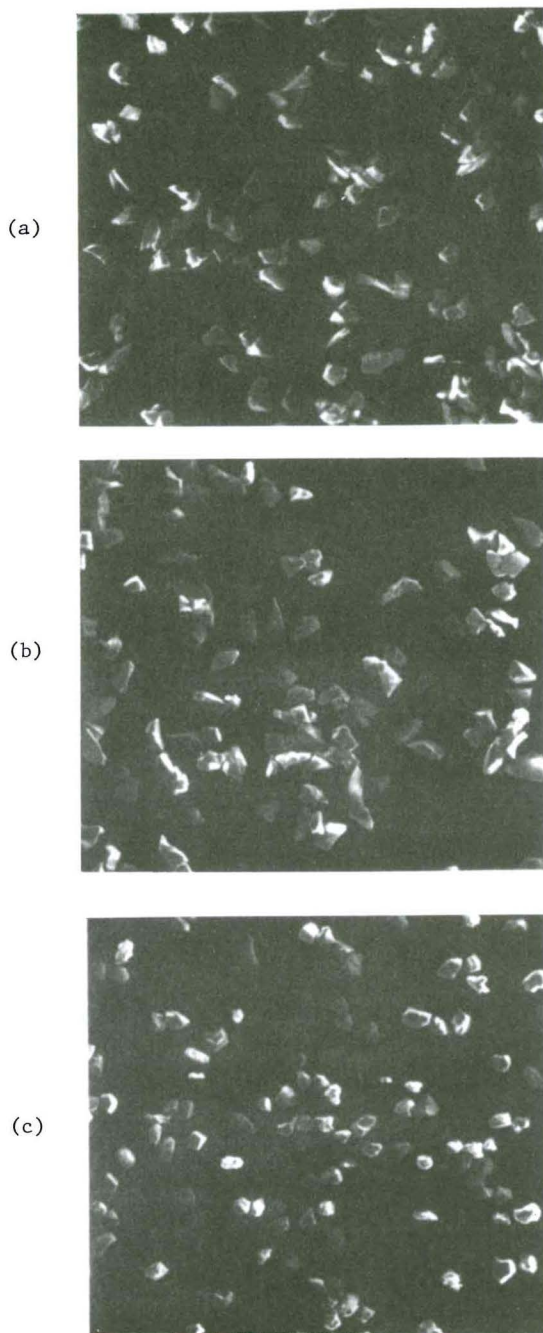


Figure 6. Scanning electron micrographs of quartz particles (26 to 38 μm) produced by different grinding techniques.

- (a) Angular particles produced by single particle crushing.
- (b) Particles produced by short-time (8 minutes) grinding in a ball mill.
- (c) Relatively rounded particles produced by long-time (4 1/2 hours) grinding in a ball mill.

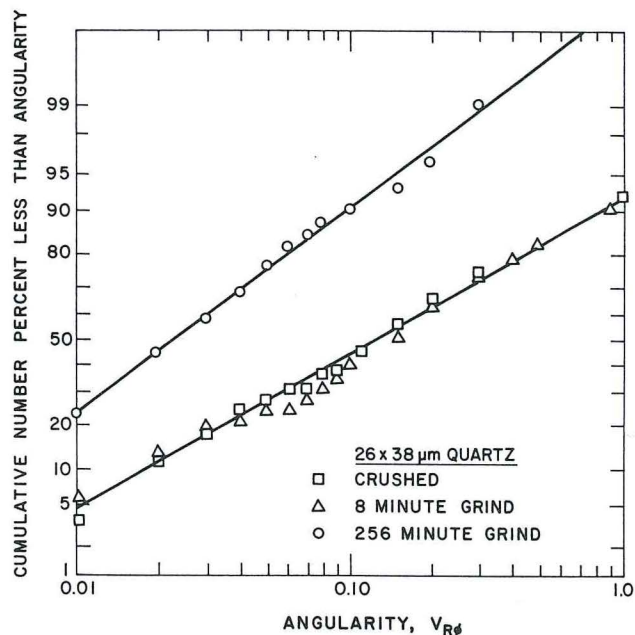


Figure 7. Cumulative number distribution of angularity values determined for over 100 particles each of the crushed quartz and quartz ground for 8 and 256 minutes in a ball mill.

- 3. A 20-sided polygon fitted to the particle profile seems to provide an adequate representation of the essential features of the particle shape.
- 4. A two-parameter shape classification scheme based on angular variability and elongation factors gives a very good description of particle shape characteristics.
- 5. A single-parameter angularity factor is especially sensitive to small differences in relative angularity or roundness.
- 6. Distributions of angularity can readily be obtained using image analysis techniques and offer considerable potential for quantitative shape characterization on collections of particles.

REFERENCES

- 1. T.P. Meloy, "Fast Fourier Transforms Applied to Shape Analysis of Particle Silhouettes to Obtain Morphological Data," Powder Technol. **17**, 27-35, (1977).
- 2. B.P. Mandelbrot, Fractals, Form, Chance and Dimension, W.H. Freeman, London, 1977.

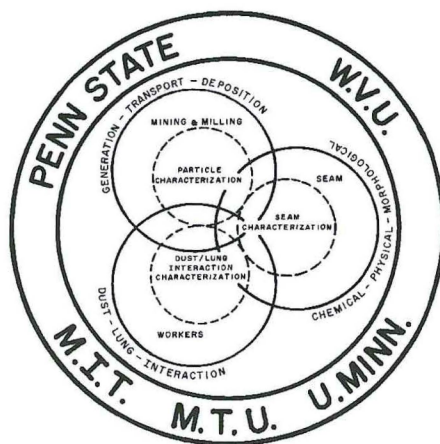
3. B.H. Kaye, "Characterization of the Surface Area of a Fine-Particle Profile by its Fractal Dimension," Proceedings, Particle Size Analysis Conference, Salford, Chem. Soc. Anal. Div., London, 1977.
4. B.H. Kaye, "Specification of the Ruggedness and/or Texture of a Fine-Particle Profile by its Fractal Dimension," Powder Technol. 21, 1-16, (1978).
5. D.A. Weitz and J.S. Hwang, "Self-Similar Structures and the Kinetics of Aggregation of Gold Colloids," in Kinetics of Aggregation and Gelation. F. Family and D.P. Landau, Eds., Elsevier, Amsterdam, 1984.
6. T.F. Dumm, "Characterization of Size/Composition and Shape of Fine Coal and Mineral Particles," PhD Thesis, The Pennsylvania State University, 1989.
7. J. Tsubaki and G. Jimbo, "A Proposed New Characterization of Particle Shape and its Application," Powder Technol., 22, 161-169, (1979).

ACKNOWLEDGEMENTS

This research has been supported by the Department of the Interior's Mineral Institutes program administered by the Bureau of Mines through the Generic Mineral Technology Center for Respirable Dust under allotment grant number G1135142.

3rd SYMPOSIUM ON RESPIRABLE DUST IN THE MINERAL INDUSTRIES

Edited by
ROBERT L. FRANTZ
and
RAJA V. RAMANI



Published by
Society for Mining, Metallurgy, and Exploration, Inc.
Littleton, Colorado • 1991

TN 312
.I 61
1990

Copyright © 1991 by the
Society for Mining, Metallurgy, and Exploration, Inc.

*Printed in the United States of America by
Cushing-Malloy, Inc., Ann Arbor, MI*

All rights reserved. This book, or parts thereof, may not be
reproduced in any form without permission of the publisher.

**Library of Congress Catalog Card Number 91-66952
ISBN 0-87335-098-7**

RESPIRABLE DUST IN THE MINERAL INDUSTRIES

Proceedings of the 3rd Symposium on Respirable Dust
in the Mineral Industries
October 17-19, 1990
Pittsburgh, PA

Sponsored by

The Generic Mineral Technology Center for Respirable Dust
The Pennsylvania State University
West Virginia University
University of Minnesota
Massachusetts Institute of Technology
United States Bureau of Mines (USBM)
Mine Safety and Health Administration (MSHA)
National Institute for Occupational Safety and Health (NIOSH)
American Conference of Governmental Industrial Hygienists (ACGIH)