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Angularity determination of abrasive powders

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Abstract

The influence of particle shape on abrasive processes is not well understood, but the angularity of the abrasive powders is assumed to be an important parameter. For that purpose an automatic angularity determination program was developed, based on the curvature of a two-dimensional projection of a particle. This paper describes the algorithm used and the preliminary measurements and results. Aspects still open for improvement are: filtering of the pixel noise, reproducibility and the discriminative power of the algorithm. The most important question to answer was: "What is a corner?". In fairness it should be concluded that this question can only be answered successfully in combination with a particular application.

Keywords: Particle shape; Abrasive particles; Curvature plot; Angularity; Pixel noise

1. Introduction

Two-body abrasion, three-body abrasion and powder-blasting (or erosion) are important finishing and material removing processes in a wide range of industrial operations. The description of these processes is rather complex since so many factors are involved [1]. The shape of the abrasive particles can have a significant influence on the mechanism of material removal. Daubrée [2] found that the rate of grinding wear of the workpiece is noticeably more rapid for angular than for well-rounded particles. Fang et al. [3] concluded that the morphology of the particle determines whether a particle will roll or slide in three-body abrasion processes. Sharp particles are assumed to leave a trace of indentations and in that case the quasi-static indentation theory will generally be used in the modelling of abrasive processes [4–6]. Worn particles will give a lower removal rate than as-received particles. This is believed to be caused by changes in particle shape and size due to chipping and fracturing of the grain during abrasion. To what extent these changes in shape and size will have an influence on the process is not well understood and therefore a closer look at the particle shape of abrasive powders and its influence on the process is necessary.

Shape is taken to include every aspect of external morphology, like form, roundness and surface texture. Characteristic values for these properties should be size-independent

[7]. Known methods for shape characterization are the determination of shape factors from packing density [8] or the Fourier shape analysis [9]. Other investigators used the term "angularity" as a basis for their shape analyses. Yuhdbir and Abedinzadeh [10] quantified angularity in terms of the average number of tangents. Lees [11] calculated a value for the degree of angularity of a single corner, measured in one plane with the formula $(180 - \alpha)x/r^2$, where α is the measured angle of the corner, x is the distance of the tip of the corner from the centre of the maximum inscribed circle and r is the radius of the maximum inscribed circle. The magnitude of a corner under consideration was determined as the angle between the faces of the nearest possible reasonably simple angular outline. He defines the total angularity as the sum of all corners measured in three mutually perpendicular planes. Lees showed that angularity is not just the absence of roundness, but a distinct concept. Barrett [7] argued that Lees' method did not lead to an independent angularity value, and that his results also included information about form and roundness, certainly giving rise to difficulties in the analysis and interpretation of the results. Comparable to Lees, Wadell [12] defined a corner as "every such part of the perimeter of an area (projection area) which has a radius of curvature equal to or less than the radius of curvature of the maximum inscribed circle of the same area". Theories as described above are either laborious or not useable in image analysing systems. Moreover, they all lead to the same key question in angularity measurements: "What is a corner?"

2. Automatic angularity determination

2.1. Definitions of corners and curvature

In the introduction given above, two key issues are mentioned;

- which aspects of shape are process related?
- what is a corner?

With respect to the first question, it is supposed that the angularity of a particle is one of the important factors in abrasive processes, since in many abrasive models the indenting angle has to be determined or estimated, see, for example, [4]. Therefore, an automatic determination program has been developed for the determination of the mean particle angle, as a measure of angularity. This program differs from the methods described above, since it determines the mean angle of an abrasive particle from curvature plots.

The second question is more difficult to answer. In this paper, we define a corner as a part of an outline with a certain (high) curvature. The first step in the development of an independent angularity measurement is thus the determination of the curvature of a particle contour. Here we use the contour of a two-dimensional projection of an abrasive particle. The curvature $\kappa(s)$ of the contour is defined as the second derivative of the position vector $r(s)$, with the arc length s as parameter:

$$\kappa(s) = \left| \frac{d^2r(s)}{ds^2} \right| \tag{1}$$

2.2. Filtering pixel noise

Automatic digitalization of the particle contour introduces pixel noise. Taking the second derivative of the position $r(s)$, will intensify the pixel noise considerably. An effective filter is required, which is not easy to find as will be shown later. Filtering has been performed by linear mean filtering (LMF) and by least-squares fitting (LSF). LMF is probably the most simple method of filtering and is given by:

$$x_i' = \frac{1}{2n+1} \sum_{j=-n}^{+n} x_{i+j} \tag{2}$$

where x is the old vector, x' is the new vector and n defines the number of points taken left and right of the observed point. By taking too many points into account (n large), the shape will be changed with respect to the angularity. For a few particles a 9-point and a 21-point filter has been tried, but neither was effective enough. After filtering a considerable amount of noise remained in the curvature plot. LSF, with a second order polynomial in s calculated from a defined number of x and y coordinates of the particle outline (from $i-n$ to $i+n$), has been used as a filtering method:

$$r(s) = (A_x s^2 + B_x s + C_x) \mathbf{i} + (A_y s^2 + B_y s + C_y) \mathbf{j} \tag{3}$$

where A , B and C are the polynomial constants and \mathbf{i} and \mathbf{j}

are the unit base vectors of the coordinate system. The curvature of this locally fitted shape is easy to calculate. The absolute value of the second derivative of the polynomial (see Eq. (3)) yields the curvature in every point of the outline:

$$\kappa = \sqrt{\left(\frac{d^2x}{ds^2}\right)^2 + \left(\frac{d^2y}{ds^2}\right)^2} = \sqrt{(2A_x)^2 + (2A_y)^2} \tag{4}$$

LSF gives a better result than LMF. Fig. 1(a) gives the (digitized) outline of an abrasive particle. Fig. 1(b) gives the curvature plot of this particle obtained with LSF.

Starting at the origin and walking along the outline counter-clockwise, it is easy to correlate the corners in Fig. 1(a) with the peaks in Fig. 1(b). Although LSF is a more successful filter than LMF, the pixel noise problem is still not solved satisfactorily. Further improvement will be necessary.

2.3. Angularity determination from the curvature plot

From the curvature plots (see Fig. 1(b)), the corners must be determined. Some criteria can be drawn up to make this possible.

1. A corner is a part of the contour with a high curvature. This means that the curvature has to exceed a certain level: $\kappa > \text{level 1}$.
2. The corners must be distinct. Between successive corners, the curvature must lie within a certain noise band around

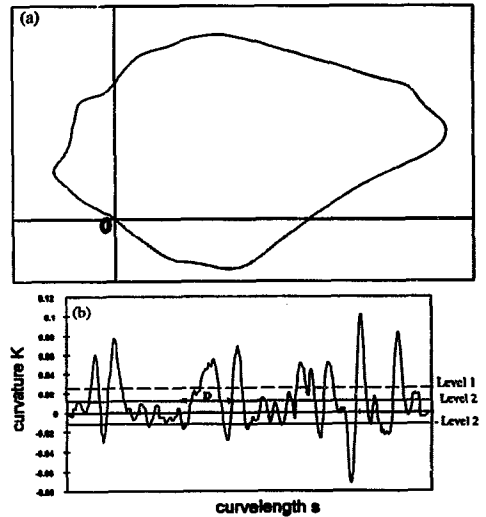


Fig. 1. Algorithm used for the angle determination. (a) Digitized outline of an abrasive particle. An arbitrary origin O is indicated. (b) Curvature plot of the particle shown in (a), obtained by least-squares fitting. Indicated is the level to be exceeded for a corner (level 1). Also indicated are the noise band (\pm level 2) and the associated distance D .

zero (\pm level 2 in Fig. 1(b)) and must remain so over a certain distance D . This distance is inversely related to the area under the peak.

The various levels are schematically shown in Fig. 1(b). Note that re-entrant angles give negative values for the curvature. These angles will not be taken into account, because they will not have any contribution in the abrasive process.

Finally, the angles (or the angularity) can be calculated from the begin and end points of the corner peaks. There are various possibilities for the determination of these begin and end points. In this work the points where the curvature is zero or passes a positive minimum are taken as begin and end points. Next, the tangents through a begin and end point are calculated. The angle of the corner is calculated as the angle between the two tangents.

3. Experiments, results and discussion

3.1. Experimental work

Two types of abrasive alumina powder were used: Al_2O_3 F320 and Al_2O_3 F240. The particle size was determined by sedimentation using a Sedigraph 5100 (Micromeritics), yielding a mass modal diameter of the powder, here denoted by d . The automatic angularity program was tested using these powders. Images were obtained using loose particles distributed on a transparent holder. For each powder 70–80 particles, equal to 425–500 corners, were measured. These images show the maximum projected areas of the abrasive particles. For non-isometric particles a preferred orientation is thus present which is an obvious disadvantage of this sampling method.

3.2. Reproducibility

For Al_2O_3 F240 a reproducibility test was executed by measuring the angularity of the original powder three times. The results of these tests are given in Table 1. The average standard deviation in the mean angle is about 1.5° . The differences in the repeated measurements of the same powder are in the order of two standard deviations and hence within expectation. For detection of small changes in angle it is, however, necessary to improve the reproducibility. Apart from the obvious increase in number of measurements, hopefully, the reproducibility can be improved in future by improving the pixel noise filtering and the sampling method.

Table 1
Results of the reproducibility test for the original Al_2O_3 F240 powder

Measurement	Mean angle	Sample standard deviation σ	Number of angles measured n
1	119.3	32.1	496
2	122.2	33.3	578
3	117.4	32.5	482

3.3. Angularity changes in abrasive processing

Investigation of the angularity changes during abrasive processes has been performed by angularity measurements on:

1. the original powder
2. the powder used for erosion of glass at low speed
3. the powder used for erosion of glass at high speed
4. the powder used for three-body abrasion of glass

Theoretically two extreme fracture processes can be distinguished for the abrasive particles. The particles can either break into a few large pieces or become blunt by chipping off small pieces. These mechanisms will result respectively in a decrease and an increase of the mean angle. It is assumed that angularity measurements can give information about the mechanism of particle failure during abrasion.

Table 2 gives the results of the angularity measurements and the corresponding size measurements. Conforming to expectations, it can be seen that generally the particle size decreases during abrasive processing. It is not clear why the mean particle diameter of Al_2O_3 F240 powder eroded at high speed is larger than the powder eroded at low speed. The average of the mean angles for the three abrasive processes also decreases. The differences for the individual processes are, however, so small that it is impossible to discriminate between the various processes. For Al_2O_3 F240 the decrease in the average seems more clear than for Al_2O_3 F320. This could mean that the F240 particles are breaking mainly into a few large fragments while during use of the F320 powder chipping is growing in importance. The small differences in angularity can be either real or due to a changed preferred orientation in the sample of the powder used in the abrasive process. The validity of these considerations should be investigated and supported with more measurements.

4. Conclusions and recommendations

Since the indenting angle is an important parameter in abrasive processes, an automatic angularity determination program has been developed. In this paper a new method for the determination of the mean angle of a powder has been introduced. In the algorithm a corner is defined as a part of the contour with a high curvature. Curvature plots have been determined after automatic digitalization of abrasive particles, which introduced a considerable amount of pixel noise.

Table 2
Angularity results for Al₂O₃ F320 and F240

Alumina	Specification	Mean angle	Sample standard deviation, σ	Number of angles measured, n	Mass modal diameter, d (μm)
F320	original	113.5	36.4	491	28.4
	erosion (low speed)	108.0	38.3	423	25.5
	erosion (high speed)	112.4	36.8	499	24.7
	three-body abrasion	113.0	36.2	464	25.7
F240	original	119.3	32.1	496	44.2
	erosion (low speed)	113.6	36.1	471	38.4
	erosion (high speed)	111.8	37.1	514	39.9
	three-body abrasion	109.1	36.7	450	35.0

Although least-squares fitting gave better results than linear mean filtering, further improvements are desired.

In order to determine the angularity from the curvature plots, (subjective) corner criteria had to be defined. What should be regarded as a corner on the scale of the particle depends on the process. It is clear that abrasive processing decreases the particle size and angularity, although the individual differences are small.

Consequently, for the investigation of angularity changes during abrasive processes, the angularity determination program should be improved further. This can probably be realised by improvements of the filtering method. Furthermore, achievement of better corner criteria could be attempted, or other algorithms could be tried, e.g. Fourier analyses or methods without derivatives, apart from or in combination with the algorithm discussed in this paper. In the near future the possibilities of other filters, criteria and algorithms will be investigated for their applicability in shape studies of abrasive materials.

Although in Euclidean geometry an angle is a well-defined concept, an automatic determination of the mean angle of a contour of a real particle turned out to be rather difficult. In image analyses investigators have to define their own criteria for the automatic determination of the mean angle of a contour. These subjective criteria result in an algorithm in which the question "what is a corner?" can only be answered in combination with a particular application.

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Biographies

Ir. M.A. Verspui: graduated as chemical engineer from the Eindhoven University of Technology. Since May 1994 she has been working as a Ph.D. student on the abrasive processing of brittle materials in cooperation with Eindhoven University of Technology and Philips Research Laboratories.

Ir. P. van der Velden: after his studies at the Institute for Higher Professional Education in Dordrecht, he graduated as a chemical engineer from the Eindhoven University of Technology in 1995, having worked on the angularity determination of abrasive powders. Since April 1996 he has been working at the Philips Research Laboratories in Eindhoven on chemical mechanical polishing.

Prof. Dr. G. de With: is full professor in materials science. He graduated from Utrecht State University and received his Ph.D in 1977 from the University of Twente on the 'Structure and charge distribution of molecular crystals'. In the same

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Ir. P.J. Slikkerveer: graduated as a mechanical engineer from Delft University of Technology in 1987. He joined the Philips Research Laboratories in Eindhoven in that year. Here he worked on a number of research subjects concerning rheology, glasses and thermosetting materials. Since 1994 he has been concerned with abrasive machining.