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Morphometry of diamond superabrasives using image analysis

1. Introduction

The physical properties of diamonds used in sawing applications are controlled by changes in pressure, temperature and growth rate during their synthesis. In order to meet the needs of cutting tool applications, it is important to develop non destructive quantitative characterization methods known to correlate with the mechanical performance of the superabrasives. Shape is considered to be a critical parameter and the most regular crystals (cuboctaeders) are typically selected for high performance cutting of hard granite rocks whereas the more irregular crystals are send to less demanding applications in concrete and marble sawing.

Shape-sensitive mechanical separation devices like delta vibrating tables are of daily use in the diamond industry. While useful as a sorting technique, this method provides little quantifiable information on the crystal shape and there is a real need for more accurate shape analysis systems in the quality control of superabrasive batches.

2. Diamond samples

The starting point for this study was a set of four synthetic diamond productions with qualities designated respectively by MBS 960; MBS 945; MBS 920 and MBS Y9. A fraction of each product with a narrow size range was fed into the delta vibrating tables. The physical principle behind the delta vibrating table is to submit a particle to an acceleration perpendicular to the slope of the table. Basically, this means that the most rounded particles should follow the main slope and be recovered in the lowest boxes, while rougher particles having a high contact surface with the table should be

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recovered in higher boxes. Vibrating tables are very useful in that they physically separate particles into different batches (Table 1) which during mechanical testing display different behaviours.

Quality	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Mbs960	1.07	4.58	**9.57**	**13.74**	**13.85**	**9.82**	4.80	1.47	0.26	0.05	0.01	-	-	-
Mbs945	0.67	3.16	**7.37**	**11.93**	**13.30**	**10.32**	5.15	1.56	0.29	0.02	0.01	-	-	-
Mbs920	0.19	1.09	2.98	6.28	**9.94**	**12.07**	**11.25**	**6.92**	3.68	1.34	0.27	0.06	0.02	0.06
MbsY9	0.01	0.05	0.15	0.53	1.68	4.15	**7.90**	**12.09**	**10.16**	**8.40**	4.36	1.74	0.66	0.94

Table 1. Individual weights (in grams) of the diamond batches recovered from the vibrating table. The cells with a grey background indicate the four most abundant classes for each quality.

Shape is probably the dominant factor causing segregation of particles on the vibrating table. But, in order to understand properly the mode of action of the table, it is mandatory to quantify the geometric features of individual particles using image analysis. Due to the very limited number of diamonds available in most batches, it was decided to take 30 diamonds per batch and to sample one batch out of three.

3. Digital imaging

Individual diamonds were imaged with a transmitted light optical microscope using a 2.5x objective. Because the diamonds were resting on a glass slide, the observation yielded their outline in the plane perpendicular to their smallest dimension. Images of individual particles were taken with a standard video camera (Ikegami ICD-290) and digitised through a framegrabber (Euresys Brio) giving 512 x 512 square pixels. The practical resolution (distance between two pixels) of the digital image is 4.55 µm, yielding a digital representation between 7 000 and 10 000 pixels of area per grain. Figure 1 displays some typical images.

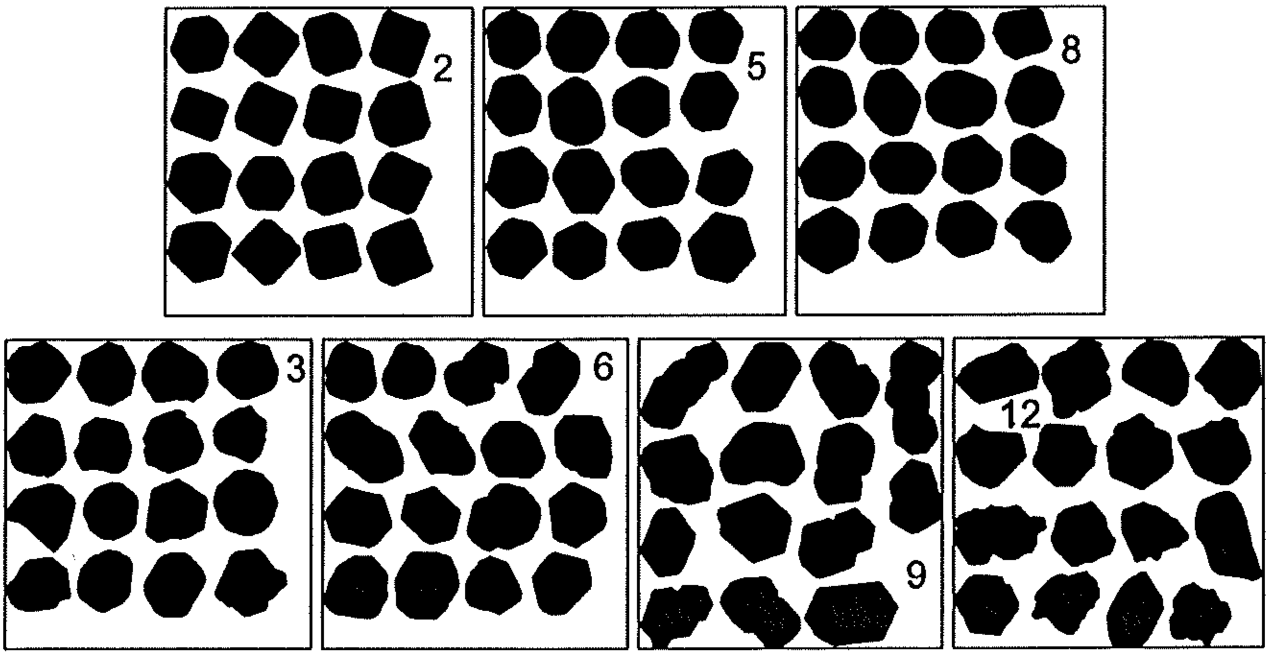


Figure 1. Digital images of individual diamonds for Mbs 960 (2-5-8) and Mbs 920 (3-6-9-12) qualities. The numbers refer to the classes of the vibrating table.

4. Morphometric Analysis

Shape analysis has been adressed by a large number of authors using very different techniques. Assuming that it is impossible to catch the whole spectrum of shape information within a single parameter, it appears to be most adequate to subdivide the analysis procedure into several steps ranging from global analysis down to local analysis (figure 2).

4.1. Elongation

The measurement of elongation or aspect ratio on two dimensional grain outlines can be performed using either Feret diameters in a set of directions or using inertia moments [1] .Both methods give similar results but one must be careful to compute a reasonable number of Feret diameters (at least 16) to correctly estimate the minimum diameter. The diameter of the equivalent inertia ellipse gives a very robust estimate but tends to overestimate the real dimension of the particle. A practical compromise is to compute the orientation of minimum and maximum inertia moments and to use this information to measure the Feret diameters in the same orientation. In the present study, the aspect ratio (El) was directly computed from the inertia moments without any correction.

4.2. Local analysis

The measurement of shape features like asperities at a given scale could be asked for by a particular application, but in most cases the scale of investigation is not clearly fixed. Therefore, techniques analysing the whole spectrum of shape features (at all scales) are most often preferred. Among the most popular spectral shape description methods are Fourier transforms [2], fractals [3] and mathematical morphology [4].

All three methods share a lot of similarities because they convert the outline of a shape into a graph of amplitudes at various scales of scrutiny. The Fourier analysis uses the frequency of the harmonic as a scaling parameter, whereas fractal analysis and mathematical morphology specify the length of a compass or the size of a structuring element. Apart from different mathematical heritages, it also appears that the way in which the amplitude graph obtained for each particle is summarized into pertinent parameters is different from one technique to the other. For Fourier analysis it is most often suggested to use partial amplitude sums [2]. In fractal analysis the slope of the log-log plot is used to summarize the shape features. Finally, negative first order moments of the amplitude graphs are recommended in mathematical morphology [4,5]

Spitefully, up to now no in depth comparison has been performed to guide practicionners towards the most efficient approach in multiscale shape analysis and the choice between Fourier, fractals and mathematical morphology still appears as an affiliation to a given school of thinking. It must be recognized that all three methods are sensitive to changes in digitization conditions and to the use of non-euclidean metrics.

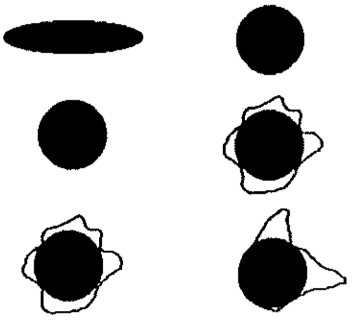


Figure 2. Shape analysis can be split into several levels of information ranging from elongation (global) to roughness, roundness and angularity measurements (local) [6].

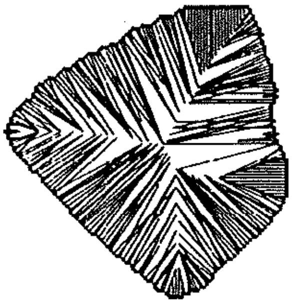


Figure 3. Representation of the geometric information contained in the calypter of a grain.

4.3. Calypter based shape measurements

In a recent paper we further developed the ideas used in mathematical morphology by implementing openings based on perfectly circular structuring elements and we summarized the results of the amplitude graph by referring to the physical principles of abrasion [6]. The method will be briefly recalled hereunder and used for characterisation of the diamond samples.

The binary image of a diamond grain is first transformed by attributing to each pixel in the image the value corresponding to its shortest distance to the contour. This is the so-called euclidean distance transform [7] that we further simplify into a holodisc distance transform by rounding down to the closest integer. Next, a climbing algorithm is used starting from each contour point to identify the steepest path along the relief generated by the distance function. It can be shown that this path will necessarily reach the centre of the maximum inscribed disc (MID) tangent to the contour at the given starting point. By associating the centre and radius of its MID to each point along the contour we get a descriptor of the euclidean skeleton of the particle called *calypter* (figure 3). Clearly the information collected in the calypter can be summarized in several ways depending on the desired analysis.

By denoting λ_i the radius of the MID tangent to the i^{th} point of the contour we have suggested [6] the *equivalent roundness (W_V)* given by :

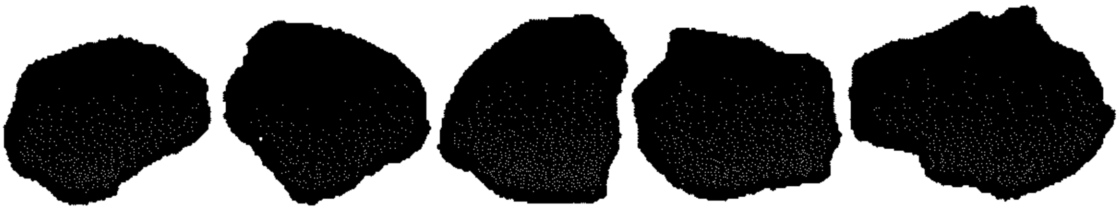
$$W_V = \frac{1}{\sqrt{\overline{V}} - 1} \quad with \quad \overline{V} = \frac{1}{N}\sum_{i=1}^{i=N}\left(1 + \frac{max(\lambda_i)}{\lambda_i}\right)^2 \qquad [1]$$

N is the total number of contour points.

One important advantage of formula [1] with respect to other shape parameters is that it is not dependent on the operator's choice for fitting limits to a partial sum of amplitudes or for adjusting a regression line.

4.4. Visual comparison

The concept of equivalent roundness has been designed to measure the maturity of a weared particle with respect to an abrasion process. Basically, the notion is very close to the one used in the design of visual control charts widely used in geology and material sciences [8]. Table 1 presents some results obtained with three different methods on a set of five grains.



P_{10}	4,10	3,88	3,86	3,97	4,74
P_{20}	1,44	1,35	1,39	1,59	1,51
Δ_M	1,008	1,013	1,010	1,010	1,019
W_V	63,14	58,27	46,63	39,00	36,15

Table 1. Quantitative results of spectral shape analysis techniques on a set of five grains. P_{10} and P_{20} are partial sums of the normalized Fourier amplitudes for the first and second decade of harmonics respectively. Δ_M is the covering dimension obtained from hexagonal dilations up to half the maximum inscribed radius. W_V is the equivalent roundness.

Visually, the grains range from more rounded to more angular from left to right. Fourier parameters give no consistent response and are difficult to relate to any particular shape. Δ_M and W_V give very similar classifications but taking into account the error associated with individual measures it is clear that W_V is more sensitive. Considering all possible rotations of the grid, the third decimal of Δ_M cannot be considered as significant whereas W_V can be estimated with a precision of $\sigma = 1.6$ %.

5. Results

Table 2 displays the statistical results obtained for elongation and equivalent roundness on the individual batches for the four different qualities of synthetic diamonds.

	MBS960-2		MBS960-5		MBS960-8		MBS945-4		MBS945-7		MBS945-10	
	m	IC(μ)	m	IC(μ)	m	IC(μ)	m	IC(μ)	m	IC(μ)	m	IC(μ)
Db	445.1	8.17	441.0	8.66	423.8	8.43	438.1	9.56	429.2	13.86	415.8	9.92
El	1.062	0.018	1.101	0.022	1.146	0.025	1.120	0.026	1.150	0.029	1.199	0.053
Wv	57.75	2.58	65.63	2.28	70.52	2.27	69.12	2.29	65.51	2.25	52.06	5.06

	MBS920-3		MBS920-6		MBS920-9		MBS920-12	
	m	IC(μ)	m	IC(μ)	m	IC(μ)	m	IC(μ)
Db	442.6	8.68	426.5	11.69	435.6	14.59	445.7	12.03
El	1.098	0.025	1.236	0.063	1.536	0.129	1.252	0.086
Wv	59.85	3.92	61.67	2.59	58.19	3.05	47.48	3.10

	MBSY9-2		MBSY9-5		MBSY9-8		MBSY9-11		MBSY9-14	
	m	IC(μ)	m	IC(μ)	m	IC(μ)	m	IC(μ)	m	IC(μ)
Db	453.0	14.70	452.5	11.36	458.5	12.47	449.8	20.01	474.0	15.82
El	1.207	0.051	1.209	0.060	1.248	0.055	1.482	0.114	1.216	0.055
Wv	58.32	3.86	58.48	2.60	54.28	2.07	47.15	2.29	43.09	2.43

Table 2. Sample means (m) and 95% confidence intervals for the population mean ±IC(μ) computed for the smallest inertia ellipse diameter (Db in μm), the inertia ellipse elongation (El) and the equivalent roundness (W_V in %).

The results are presented in graphical form either as histograms per batch or as quality control charts. The latter ones are an interesting way of controlling the action of the vibrating tables. The central line gives the mean value for all diamonds and can be assimilated in the present case to the mean value of the feed. The upper and lower values indicate the confidence limits for this mean. If the mean of a particular batch (cf. table 2) falls outside the confidence limits, than it is clear that the process has induced a significant differentiation among the diamond batches.

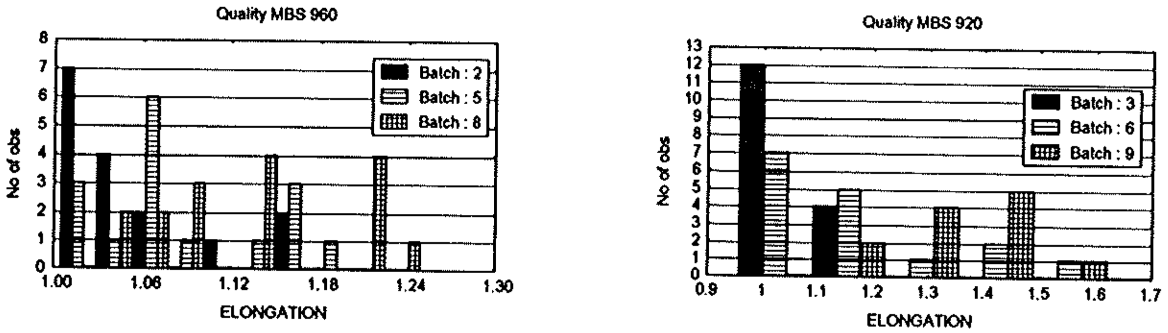


Figure 2. Histograms of elongation measurements performed on the batches selected from qualities MBS 960 and MBS 920.

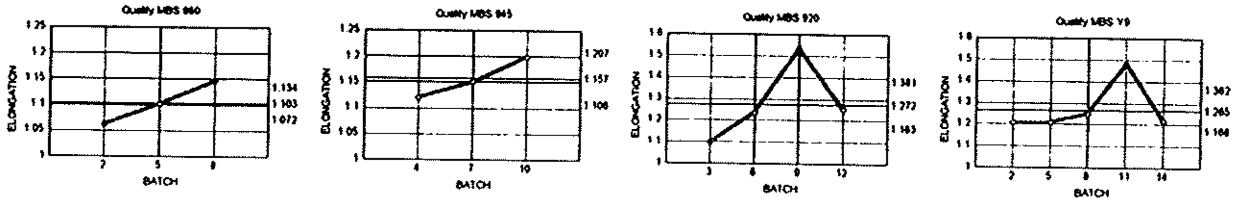


Figure 3. Process control charts for elongations on each of the four qualities. The individual batch means are plotted with respect to the mean and 95% confidence limits for the feed.

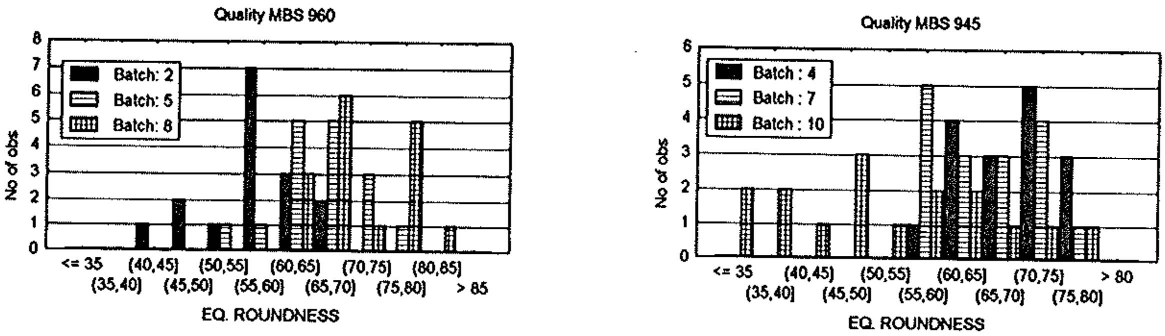


Figure 4. Histograms of equivalent roundness measurements performed on the batches selected from qualities MBS 960 and MBS 945.

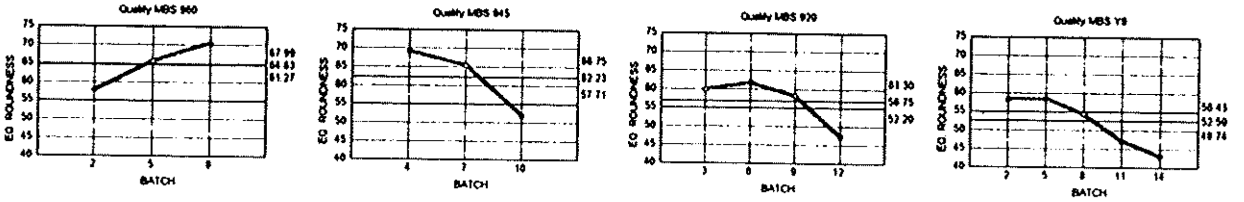


Figure 5. Process control charts for equivalent roundness on each of the four qualities.

6. Discussion

Despite the very limited number of diamonds per batch, the process control charts clearly demonstrate that the vibrating tables operate by rejecting more elongated and more irregular crystals towards higher order classes. The highest quality of MBS 960 diamonds display what might appear at first sight to be a reverse behaviour with respect to roundness. However, a closer look to individual diamonds reveals that low order classes (MBS960: 1 to 4) contain a lot of cuboctaedral crystals whereas high order classes (MBS960: 5 to10) display more rounded grains. Because W_V is best suited to describe the departure from perfect roundness (100 % for a disc) of « random » shapes, it is useful to develop an additional deterministic parameter for describing the geometric outlines of cuboctaedric projections. Facet length and angular measurements are among the parameters readily accessible from the calypter data. Proposals for description of perfectly cuboctaedral crystals have been presented in [9] and appear interesting in that they relate to mechanical behaviour of the diamonds. Nevertheless the approach taken by these authors is non robust for shapes departing from cuboctaedral geometry.

Further work is also necessary to correctly identify broken crystals that are hybrids between perfectly geometric and more random outlines.

7. Conclusion

Elongation and roundness measurements have been selected for the present study because of their high sensitivity and good robustness with respect to digital imaging conditions. These parameters together with facet length descriptors appear to be an adequate non destructive quality control method for checking the output of vibrating tables and correlating with the mechanical behaviour of individual crystals.