ABRASIVE PARTICLE CHARACTERIZATION FOLLOWING DIFFERENT MEASUREMENTS OF SHAPE FACTOR

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Abstract. The abrasion of equipments and components is a significant problem for earth moving operations. The wear rate is affected by the characteristics of abrasive particles. The effects of particle size and hardness of abrasives have been extensively studied. However, the shape of particles is the most difficult parameter to incorporate in the wear models. Besides the qualitative descriptors, obtained from a visual inspection of bi-dimensional images, these particles can be characterized by quantitative parameters that are able to give information about the geometry. In this paper many shape parameters are investigated, such as the roundness factor, the aspect ratio, as well as the spike parameters early developed. Initial results of a computational routine developed in Surface and Contact Lab are presented in order to characterize the shape of abrasive particles, and a new spike parameter is proposed, SPL. Additionally, a theory of particle size effect on abrasion can be discussed based on experimental results for glass particles.

Keywords: *abrasion, shape characterization, image analysis*

1. INTRODUCTION

The abrasion of metals is an important failure mode for many components, as the grinding bodies and powder and slurry pipes. This kind of wear can be considered as the most important wear mode, because it corresponds about 50% of total losses by wear (Stachowiak and Batchelor, 2001).

The shape of particles in these tribological systems has been studied, in order to predict the wear rates. The usual approach to describe and differentiate the particle shape is the visual inspection by means of microscopy. Besides this type of analysis, there are quantitative parameters that relate the shape with the capacity to remove material from surface.

In this paper the classic shape parameters will be described, as the aspect ratio, roundness factor, as well as the spike parameters developed by Hamblin and Stachowiak (1995). Moreover, a new proposition to describe the particle shape is presented, denominated as modified spike parameter, SPL.

2. SHAPE CHARACTERIZATION OF ABRASIVE PARTICLES

A usual description of shape factors is based on how the bi-dimensional projection of particle differs from that describes a circle. The particles can be grouped in three families of shape, having a circle as their origin (Wojnar, 1999). The former corresponds to ellipses with different elongations (Fig 1a), the second case represents the situations where the shape keeps rounded, but there is an increase in the irregularity of border (Fig 1b), and the last case is a combination of the previous cases, i.e., there is an elongation of shape and an increase in the complexity of the border (Fig 1c). For each one, a most adequate factor to describe the particle shape could be assumed.

The roundness factor is one of the most used parameters to characterize the shape of abrasive particles. It can be defined as the relation between the area of the bi-dimensional projection of particle, *A*, and the corresponding area of the circle that has the same perimeter L (Eq 1).

$$f_1 = \frac{4\pi A}{L^2} \tag{1}$$

This factor is a good solution to define the case shown in Fig 1b. In these cases, where the particle is rounded, the factor is sensible to border irregularities. For a circle, $f_1 = 1$, and as the border becomes irregular, its value decreases.

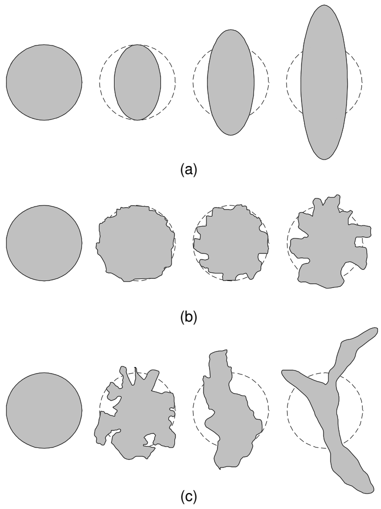


Figure 1. Three families of shape originated from a circle: (a) Ellipses with varied elongations; (b) rounded shapes with different irregularities; (c) combination of the previous cases (Adapted from Wojnar, 1999).

The elongation, presented in Fig 1a, is very common in nodular particles plastically deformed, due to the action of axial stresses, for example. An efficient manner to measure the elongation is use the factor presented by Heywood in 1937 (ASM Handbook, 1998), known as aspect ratio, defined as the ratio between the major and the minor dimensions of the rectangle (a and b, respectively) with a minimum area that contains the bi-dimensional projection of particle. This factor is also known as elongation ratio. The aspect ratio can be determined as the ratio between the major and the minor axis (*a* and *b*, respectively) of the ellipse that better adapt to the particle format (Fig 2).

$$f_2 = \frac{a}{b} \tag{2}$$

For the case shown in Fig 1c, which the particle is elongated and irregular, the parameter shape factor, defined as the ratio between the minimum diameters, inscribe and circumscribe, is more appropriated than the previous ones (Wojnar, 1999).

$$f_3 = \frac{r_i}{r_e} \tag{3}$$

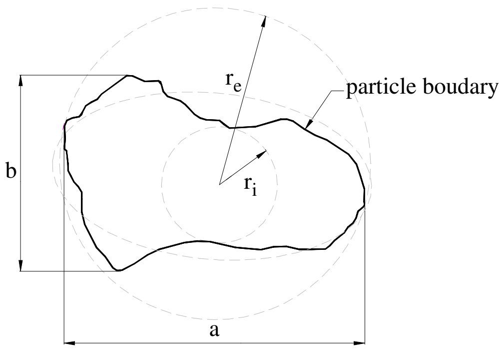


Figure 2. Geometry quantities required for the calculus of different shape factors.

Fractals (from the Latin *fractus*) are geometric forms that can be divided indefinitely in similar parts to the original object. The geometry of fractals is an extension of classic geometry and can be used to build models capable to represent the most complex aspects of nature forms. In Tribology this concept was introduced to describe the characteristics of borders of abrasive particles, resulting in parameters that indicate the irregularities. Pioneers works were performed by Mandelbrot (ASM Handbook, 1998). A usually employed technique is the structured walk, also known as the Richardson method (Podsiadlo and Stachowiak, 1998), which the particle border is scanned for a given step length, resulting in a polygon (Fig 3a). The process is repeated for many step lengths, leading the Richardson curve in logarithm scale (Fig 3b). From the slope, m, generated by the best fitting to the curve, the fractal dimension is calculated by

$$f_4 = 1 - m \tag{4}$$

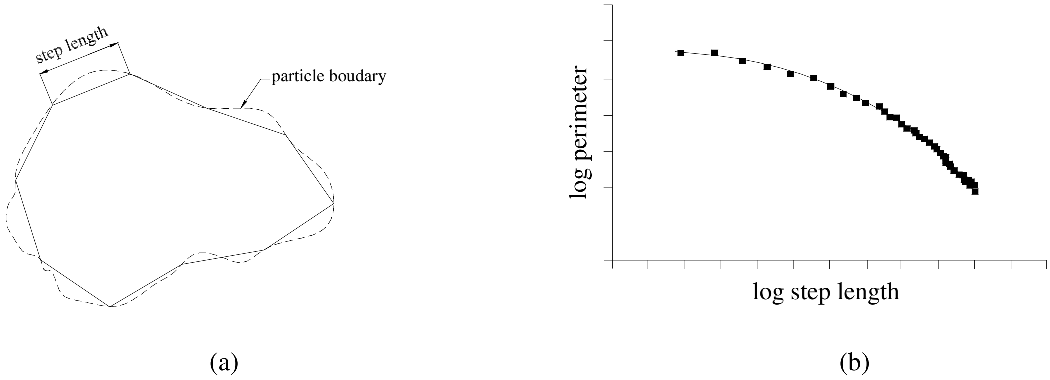


Figure 3. Richardson's curve for fractal dimension calculus.

Two new parameters were introduced by Hamblin and Stachowiak (1995) to describe the angularity. One of them, called spike parameter – linear fitting (SP) is based on the border representation by a series of triangles, in similar process to the method to calculate the fractal dimension. It is assumed that the sharper the angle, and the higher the triangle size, the higher is the abrasivity. In order to characterize both the angularity and the size, the spike value, sv, defined in Eq 5, is used, where θ is the angle of vertices and h is the height of triangle (Fig 4).

$$sv = \cos(\theta / 2)h \tag{5}$$

For each resulted triangles, the maximum spike value is determined. The process to the calculus of spike value is repeated for all steps along the perimeter. After a cycle is completed, the maximum value is determined. The procedure should be repeated for all possible starting points at the border, resulting in an average spike value. The spike parameter – linear fitting, SP, is thus calculated following this equation (Hamblin, Stachowiak, 1995):

$$SP = \frac{1}{n}\Sigma\left[\frac{1}{m}\Sigma\left(\frac{sv_{\max}}{h_{\max}}\right)\right] \tag{6}$$

where:

$sv_{\max} = \max(\cos[\theta/2)h])$ for a given triangle base;

$h_{\max}$ is the corresponding height for $sv_{\max}$;

m is the number of spike values valid for a given step size;

n is the number of different step sizes used;

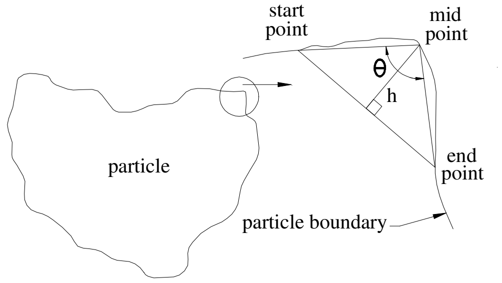


Figure 4. Method to calculate the spike parameter SP.

The other parameter (Hamblin and Stachowiak, 1996), called spike parameter – quadratic fitting (SPQ) is based on the localization of the centroid of the bi-dimensional section of particle and the circle that radius is equal to the average radius of particle (Fig 5). The areas outside from circle are considered as interest regions, while the bulk is suppressed. The maximum local diameter is determined for each region outside the circle and this point is treated as spike vertices, M. The spike laterals, which are between the segments sp-mp and mp-ep are represented by polynomial quadratic functions. Differentiating the functions at point mp, led in the apex angle θ.

$$sv = \cos(\theta / 2) \tag{5}$$

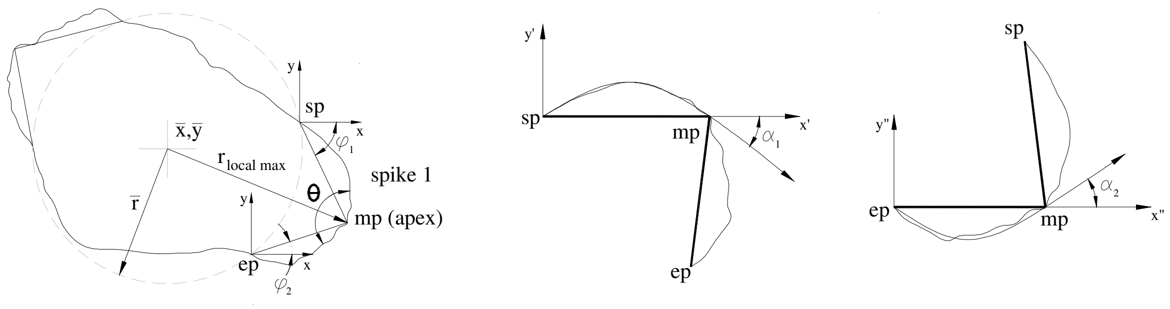


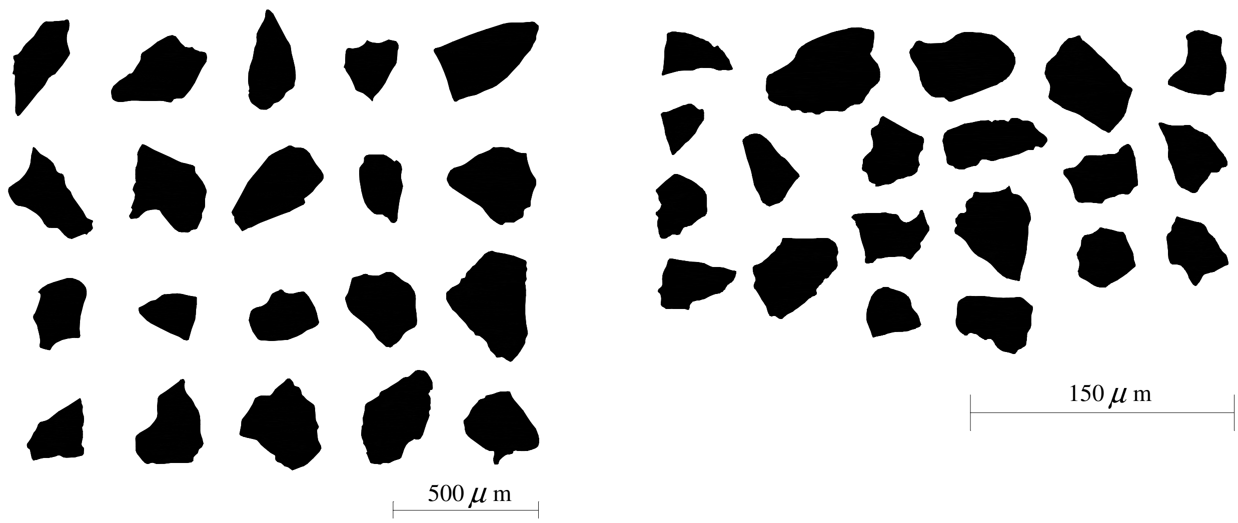
Figure 5. Method to the calculus of spike parameter SPQ.

The spike parameter – quadratic fitting (SPQ) is thus obtained from the average value of valid spikes, where n is the number of found spikes:

$$SPQ = \frac{1}{n} \sum sv \tag{7}$$

4. MATERIALS AND METHODS

Twenty particles were randomly selected from two samples of glass, whose average size are 72 and 455 μm. These particles were removed from papers of #80 and #240 mesh, respectively. The images obtained from optical microscope were submitted to threshold process in Image-Pro Plus software to convert the grayscale image to binary (Fig. 6). The output binary images has values of 1 (white) for all pixels in the input image with luminance greater than defined level and 0 (black) for all other pixels. The transition level was based on the histogram of images.



(a) (b)

Figure 6. Binary images of glass particles: (a) 72 μm and (b) 455 μm average size.

Using the Image-Pro Plus software, the average values of roundness factor, fractal dimension and aspect ratio were determined for each group of glass particles. The spike parameter SPL, proposed from a modification on SPQ, was determined by means of a computational routine developed with the application of digital image processing techniques (Gonzalez et. al, 2004), using the Image Processing Toolbox of Matlab software. From the individual binary images of particles, with a resolution of 600 x 600 pixels, the spike parameter SPL is obtained in accord with the following protocol:

(a) Determination of the particle centroid, $\bar{x}$, $\bar{y}$;

(b) Calculus of the average radius $\bar{r}$, defined as the average of radius with origin at the centroid that turn round the particle border;

(c) Detection of the outer regions to the circle defined by the average radius, for those $r > \bar{r}$. These regions are identified as spikes;

(d) Each detected spike is defined by two segments of straight line EM and SM, formed by the intersection points of circle with the border (E and S) and the point determined by the maximum local radius of spike (M);

(e) The spike value is determined by Equation 8 for each interesting region, defined as the cosine of half angle among the segments, θ;

(f) The modified spike parameter is thus calculated from the average of spike values:

$$SPL = \frac{1}{n}\sum sv \tag{9}$$

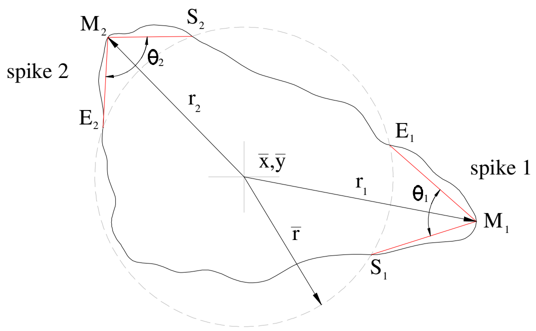


Figure 7. Methodology to calculate the modified spike parameter, SPL.

In order to compare SPL with those parameters developed by Hamblin and Stachowiak (SP and SPQ), five minerals – silica sand, garnet, silicon carbide, quartz and crushed sintered alumina (Fig. 8) - were selected, whose values of SP and SPQ are known (Hamblin and Stachowiak, 1996). For each mineral with average size between 250 and 300 μm, the SPL was determined using the developed computational tool. Moreover, the aspect ratio, fractal dimension and roundness factor were calculated using the Image-Pro Plus software.

(a) (b) (c) (d) (e)

Figure 8. Abrasive grits: (a) silica sand, (b) garnet, (c) silicon carbide, (d) quartz, and (e) crushed sintered alumina. (Adapted from Hamblin and Stachowiak, 1996).

5. RESULTS AND DISCUSSION

In Table 1 are presented the shape factors for glass particles (Fig.6) and the wear rates provided by Pintaude et al. (2009) for quenched and tempered 52100 steel with 4.07 GPa Vickers hardness, after sliding abrasion tests.

Table 1. Shape factors results for glass particles.

Average size (μm)	Wear rate (m^3/m)	Aspect ratio	1/Roundness	Fractal dimension	Spike Parameter SPL
72	7.25E-12	1.5 ± 0.3	1.4 ± 0.1	1.06 ± 0.01	0.7 ± 0.1
455	6.84E-11	1.5 ± 0.3	1.5 ± 0.1	1.07 ± 0.01	0.7 ± 0.1

The wear rates were very much affected by the glass particle size. The increase from 72 to 455 μm particle size caused an increase of one order of magnitude in wear rates. This behavior has a lot of explanations, including the effect of particle geometry. Following Sin et al. (1979), smaller particles loss their cutting capacity, because they would be naturally blunt. The values of shape factors presented in Tab.1 do not corroborate this theory, since there is no difference among them, considering the analyzed average sizes. The SPL values of glass particles are in good agreement with the other presented in Tab. 1, i.e., the particle size did not influenced the shape factor.

The range of application of this new spike parameter is checked with the comparison with those proposed by Hamblin and Stachowiak (1996) (SP and SPQ), and they are presented in Tab. 2 for five minerals described in Fig. 8.

Table 2. Numerical results of five minerals for the investigated shape factors (SP and SPQ values extracted from Hamblin and Stachowiak, 1996).

Abrasive material	Aspect ratio	1/Roundness	Fractal dimension	Spike parameter SP	Spike parameter SPQ	Spike parameter SPL
Silica sand	1.22	1.19	1.01	0.21 ± 0.02	0.19 ± 0.09	0.63
Garnet	1.06	1.22	1.01	0.22 ± 0.03	0.25 ± 0.1	0.86
Silicon carbide (SiC)	1.66	1.53	1.01	0.29 ± 0.04	0.4 ± 0.1	0.71
Quartz	1.62	1.68	1.02	0.32 ± 0.02	0.5 ± 0.1	0.86
Crushed sintered alumina	1.65	1.94	1.04	0.36 ± 0.03	0.6 ± 0.1	0.71

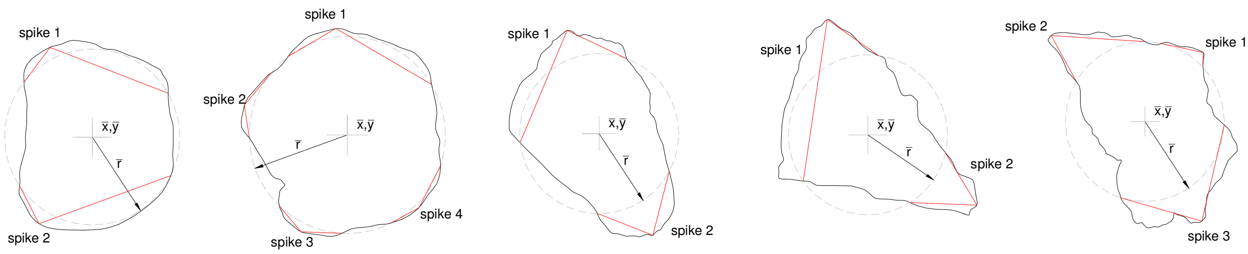
A visual inspection allows distinguishing these five minerals in two groups: the sharp particles, composed by crushed sintered alumina, quartz and silicon carbide, and the blunt ones, silica sand and garnet. In the former group the spikes are very remarkable, in opposition to the observed geometry of silica and garnet.

The comparison between results shown in Tab.1 with those of Tab.2 allows concluding that the glass particles have a sharp characteristic. The values of SPL, aspect ratio and roundness factor obtained for glass were similar to those for SiC, and the analysis of Figs. 6 and 8(c) shows that actually there is a shape similarity between SiC and glass.

A positive fact in the evaluation of SPL parameter was its coefficient of variation. Considering the values of Tab.1, a coefficient of variation of 14% is observed, a similar value of SP parameter presented for SiC particle. Moreover, considering also SiC as a reference, 25% of coefficient of variation was observed for SPQ parameter.

Now we will compare directly the modified spike parameter SPL with SP and SPQ, based on results of Tab. 2 only. SPL values were always higher than those expressed by Hamblin and Stachowiak (1996). A possible explanation for this fact is the linear approximation of border sections between the segments SM and ME when SPL definition is applied. Thus, the vertices angles of spikes are small, and consequently, a high value is obtained for this parameter. The detected spikes for each particle are presented in detail in Fig. 9.

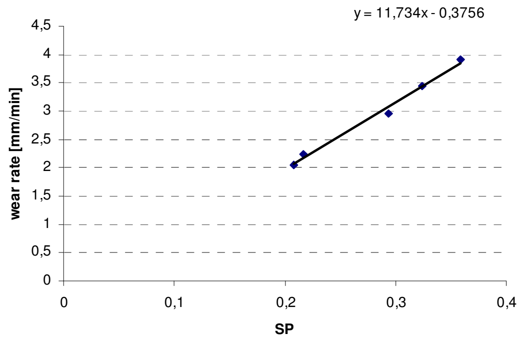
Another important analysis to qualify the use of modified spike parameter is the establishment of a ranking among the studied images. The SP and SPQ parameters gave the same crescent order: silica sand, garnet, silicon carbide, quartz and crushed sintered alumina. Likewise, the roundness factor led to a same sequence. On the other hand, the SPL parameter resulted in the following order: garnet, silica sand, crushed sintered alumina, silicon carbide and quartz. One can observe that there were two changes in the ranking predicted by SP and SPQ parameters. Moreover, the great change occurred for garnet. Further, this fact should be investigated in the light of the number of measurements. While Hamblin and Stachowiak (1996) reported an average value based on 20 measurements (as made for glass particles), here an only one determination was performed.

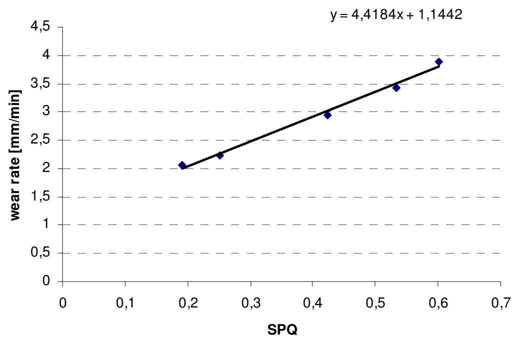


(a) (b) (c) (d) (e)

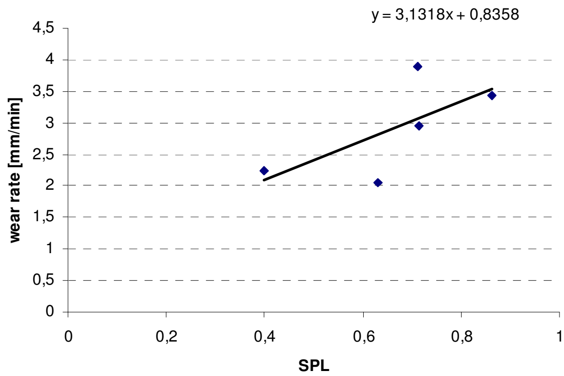
Figure 9. Details of detected spikes for each mineral: (a) silica sand, (b) garnet, (c) silicon carbide, (d) quartz, and (e) crushed sintered alumina.

Finally, a correlation between shape factor and abrasion resistance can be described. Figs 10a and 10b present the already published results of Hamblin and Stachowiak (1996), where the wear rate of a chalk specimen caused by sliding abrasion is well correlated with SP and SPQ parameters. Fig 10c shows that the SPL value for garnet seems too high (four spikes detected in Fig.9), while for the alumina it sounds too low (only three spikes in Fig.9). This result implies that SPL should be received further investigation in relation to the abrasion wear rates.





(a) (b)



(c)

Figure 10. Plot of average wear rates *vs*. different spike parameters: (a) SP for different abrasive types, 20 particles measured for each abrasive type, (b) SPQ for different abrasive types, 20 particles measured for each abrasive type, (c) SPL for different abrasive types, only one particle measured for each abrasive type.

6. CONCLUDING REMARKS

A brief review of shape factors used to describe the abrasivity of particles was presented. A new spike parameter was proposed, called modified spike parameter, SPL. However, further investigation is necessary to explain a high value of SPL for garnet and a low value for crushed sintered alumina.

Additionally, the particle size effect on abrasive wear rates could not be explained by means of shape factors, because they were insensitive to the average sizes of glass, while the wear rates change in one order of magnitude.

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