# Characterisation of abrasive particles and surfaces in grinding

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*Machining with abrasive particles presents problems in statistics, geometry, mechanics, materials and thermodynamics. Combined, these elements give rise to interesting challenges when modelling machining processes. This paper discusses the measurement and description of abrasive shape, the problems with existing methods, and the potential of new techniques based on stereoscopy. One important aspect of this work is to improve measurement of grinding wheel surfaces so that better predictions of grinding performance can be obtained. An advantage of stereoscopy is that it is a non-contact technique capable of measuring large surface gradients. This feature is beneficial for measuring the shape of abrasive surfaces and particles alike. Despite the advantages of stereoscopy, its success is sensitive to surface and image quality. It is primarily used with scanning electron microscope images which benefit from excellent depth of field and contrast. This work demonstrates that, using suitable enhancement techniques, optical microscope images may also be adopted, thus broadening the scope for using stereoscopy for performance prediction and condition monitoring of grinding surfaces.*

## 1. Introduction

The characterisation and measurement of grinding wheel surfaces is important owing to the dramatic influence that shape can have on grinding performance. The stress fields induced in the workpiece by action of the cutting edges determine material removal efficiency and finish quality. Optimisation in terms of these competing outcomes stands to benefit from an improved ability to measure and describe abrasive shape.

Measurement of abrasive surface shape is not easy because of the large range of scales that need to be measured. Moreover, the non-stationary statistical traits that random surfaces exhibit makes calculated parameters sensitive to measuring instrument bandwidth. Stylus profilometry has established itself as the most robust technique for characterising grinding wheel surfaces, yet finite radius and geometry of the stylus limit reconstruction fidelity. This applies especially to grinding surfaces, which by their very nature, are extremely rough. Consequently, it is undesirable that the large surface slopes that promote cutting efficiency should be inadvertently filtered by the limitations of the profiling technique.

It is with this in mind that quantitative stereoscopy is being investigated as an alternative to stylus profilometry. Stereoscopy benefits from being a non-contact technique. Moreover, a very broad range of scales can be sampled by using optical and scanning electron microscopy. Consequently, grinding wheels composed of virtually the entire gamut of abrasive particle diameters can be analysed.

Stereoscopy obtains three–dimensional height data by comparing the differences in two images taken at different tilt angles. The technique is not new, but only recently has it become available as a commercial software package. Despite the attractiveness of the technique, it suffers some limitations with regards to the types of surfaces that can be successfully analysed. Overcoming these limitations by image enhancement and surface coatings is currently being investigated. Successful application of the technique promises to be useful for applications ranging from wheel condition monitoring to dressing optimisation.

This paper also presents an overview of the theory of abrasion and grinding to give an appreciation of the importance of surface form and asperity density in the prediction of grinding performance. Examples of both optical and scanning electron stereoscopy, applied to particles and surfaces, are finally presented.

## 2. Grinding models and mechanisms

### 2.1. Simple abrasive wear model

The simplest model of abrasion involves a rigid conical asperity traversing a softer planar surface (workpiece). The volume of material removed $V$ is given by [1],

$$V = \frac{kPL}{H} \tag{1}$$

where $L$ is the lateral displacement of the asperity, $H$ is the hardness of the workpiece material, and $P$ is the normal force applied to the asperity. The wear coefficient $k$ is a function of the slope tan $\theta$, where $\theta$ is the attack angle defined by the cone's tangent and the workpiece surface.

This simple abrasive model is supported by experimental data which correlates wear resistance against hardness for different pure metals abraded against paper coated with silicon carbide particles [2]. Yet, when the experiment is performed with most other materials, direct proportionality with hardness is lost. The most likely explanation is that material properties other than hardness influence wear resistance; e.g. microstructure scale and bulk fracture toughness.

### 2.2. Deformation wear models

Other reasons exist that can cause real data to deviate from the linear characteristics predicted by the simple abrasion model. The stress fields in the deforming material cause real groove profiles to deviate from those assumed by the simple model, as shown in Fig. 1.

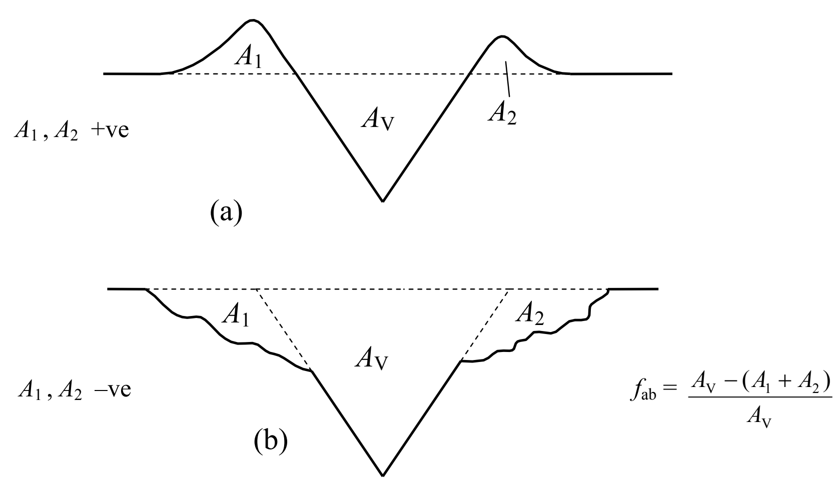



Fig. 1. Groove cross-section demonstrating concept of grooving efficiency in: (a) micro-cutting, and (b) micro-cracking.

Zuhm Gahr [3] classifies wear into four categories: micro-ploughing, micro-cutting, micro-fatigue and micro-cracking. In micro-ploughing, material is plastically deformed either side of the groove without detachment. The other extreme is micro-cutting, which gives rise to little plastic deformation of the surrounding material. The material occupying the groove is cleanly cut away from the surface. In reality, there will always be some degree of both ploughing and cutting. It becomes natural to talk about the grooving process in terms of efficiency.

The abrasion efficiency is described by the parameter $f_{ab}$ – the ratio material removed to the volume of the scratch, i.e.,

$$f_{ab} = \frac{A_V - (A_1 + A_2)}{A_V} \tag{2}$$

$A_V$ is the groove area measured relative to the plane of the original surface, while $A_1$ and $A_2$ are the cross sectional areas of the plastically deformed ridges either side of the groove. If the material undergoes brittle fracture then spalling of the surface can result in $A_1$ and $A_2$ having negative values. Ductile materials tend to exhibit cutting efficiencies $f_{ab}$ less than 1, while for brittle materials $f_{ab}$ can be greater than 1.

Values of $f_{ab}$ ranging from 0.15 to 1.0 have been found for 30 different metals and alloys [3]. For these conditions, $f_{ab}$ can be approximated by,

$$f_{ab} = 1 - \left(\frac{\varphi_{lim}}{\varphi_s}\right)^{\sqrt[3]{8H/H_{def}}} \tag{3}$$

where $H_{def}$ is the hardness of the deformed material or wear debris, $H$ is the undeformed material hardness, $\varphi_s$ is the effective strain imposed by the scratch, and $\varphi_{lim}$ is the effective strain required for cutting. Eq. (3) is defined only when $\varphi_s \geq \varphi_{lim}$, otherwise no material separation is possible; i.e. $f_{ab} = 0$.

The linear wear rate per unit length $w$, can thus be given by,

$$w = C.f_{ab}.\frac{p}{H_{def}} = C.\left[1 - \left(\frac{\varphi_{lim}}{\varphi_s}\right)^{\sqrt[3]{8H/H_{def}}}\right].\frac{p}{H_{def}} \tag{4}$$

where $p$ is the applied surface pressure and $C$ is a geometrical factor that takes into consideration the geometry of the contact and the average shape of the abrasive particles. It is evident that wear loss is decreased by increasing either $\varphi_{lim}$ (the capacity for plastic deformation) or $H_{def}$ (the deformed material hardness).

The fracture toughness of a material becomes important when micro-cracking occurs as a result of material brittleness. Several models exist that give wear rate $w$ as functions of both hardness $H$ and fracture toughness $K_C$ when the micro-cracking mode dominates. For example [4],

$$w = C.\frac{D^{1/2} p^{5/4}}{K_C^{3/4} H^{1/2}} \tag{5}$$

where $C$ is a constant and $D$ is a measure of the abrasive size. Hardness and toughness are linked by a relationship that often sees toughness decrease with increasing hardness. Therefore, abrasive wear resistance is not expected to increase as a linear function of hardness as predicted by the simple abrasion model. The ratio $H/K_{IC}$ (where $K_{IC}$ is the first-mode fracture toughness) provides a measure of brittleness – the higher its value the more brittle the material. The competition between hardness and toughness in relation to wear resistance is summarised in Fig. 2.

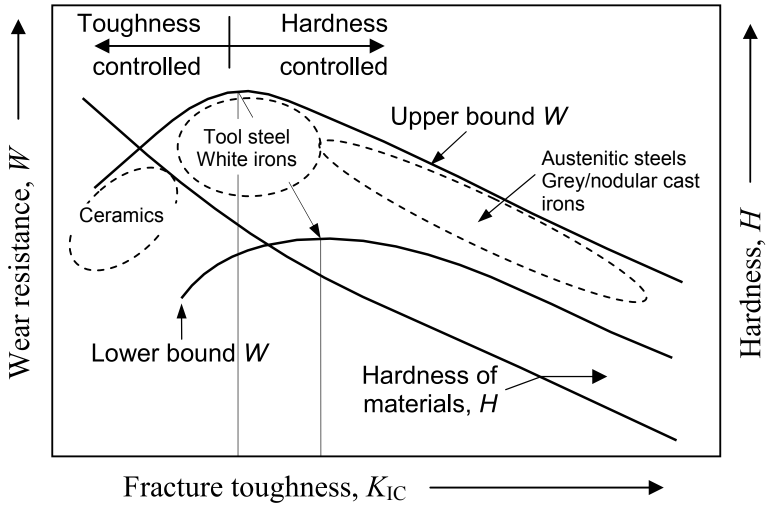



Fig. 2. Influence of fracture toughness and hardness on wear resistance of materials [4].

It is worth noting that, in micro-cracking dominated mode represented by Eq. (5), the wear rate increases with an exponent greater than unity on the applied pressure, $p$. This is because increased indenter/grit pressure causes a non-linear increase in the tendency to spall the surface by lateral cracking. By comparison, ductile materials undergo a linear increase in wear rate with pressure (Eq. (4)).

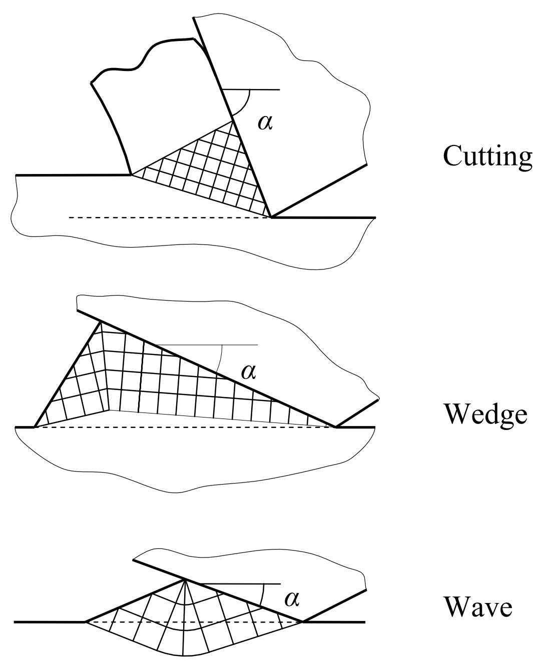



Fig. 3. Challen and Oxley's orthogonal modes of abrasion [5].

## 2.3. Orthogonal cutting models

The deformation models described in the previous section concentrate on material properties, while abrasive shape is taken into consideration indirectly by means of an empirical constant. A different approach is to use two-dimensional slip-line field models to predict forces as a function of asperity attack angle $\alpha$ and the coefficient of friction between the material and the asperity face. These models describe different types of wear regimes, i.e. wave, wedge and cutting [5], as shown in Fig. 3.

Challen and Oxley's slip line field models permit the estimation of forces involved and the conditions that lead to cutting. Cutting is predicted to be possible at attack angles as small as 22º. This result is important because average attack angles of many abrasive surfaces are in this region. Consequently, abrasive wear tends to be very sensitive to minor changes in the average slope of asperities, because a small change can result in a sudden transition from the relatively benign wave/wedge modes to the aggressive cutting mode.

## 2.4. Wear maps

Orthogonal models assist in understanding interactions between asperities and surfaces. They are limited however by their two-dimensional nature. Real asperities are three-dimensional and the cutting face is not usually perpendicular to the direction of motion. Hokkirigawa and Kato's experiments [6] with spherical indenters agree notionally with Oxley's models. In these tests, the grooving mode was experimentally observed relative to the variables degree of penetration $D_p$ and interfacial shear strength $f$, for brass, carbon steel and stainless steel. The interfacial shear strength $f$ is defined as the ratio of the interface shear stress to the yield shear strength of the deforming solid. The three wear regimes are classed as cutting, ploughing and wedge formation, as indicated on the wear map shown in Fig. 5.

Considering $D_p$ to be related to the equivalent or effective attack angle $\alpha$, by

$$D_p = \frac{0.8(1 - \cos\alpha)}{\sin\alpha} \tag{6}$$

then it is apparent that for small values of $f$, typical of well lubricated conditions, that cutting occurs at equivalent attack angles similar to those predicted by the Oxley cutting model; i.e. ~20º.

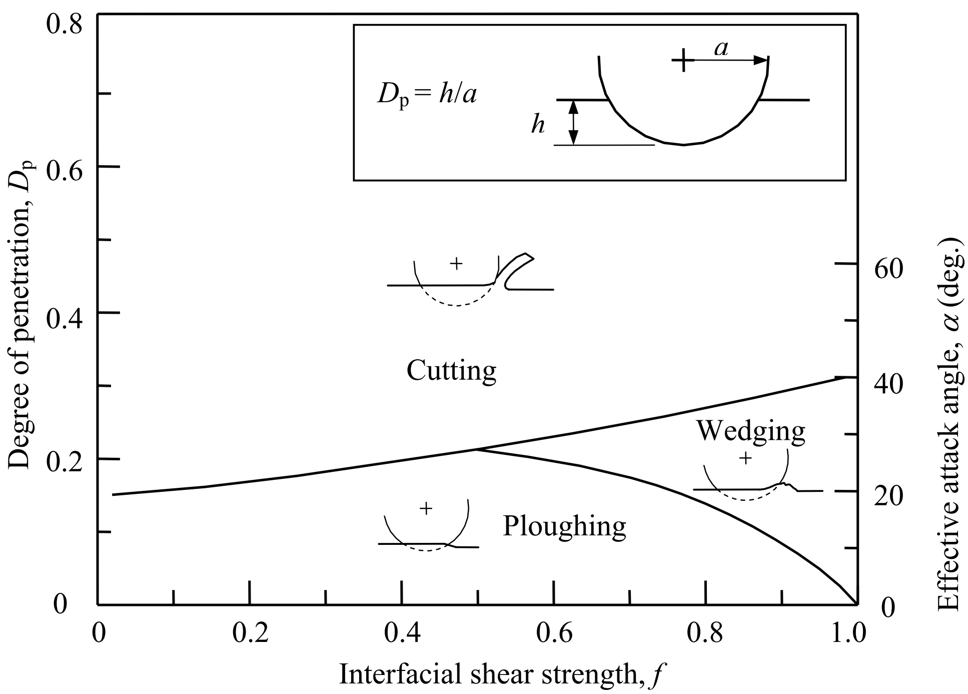



Fig. 4. Wear map showing different wear modes for a spherical indenter as a function of degree of penetration $D_p$ and interfacial shear strength $f$ [6].

2.5. Energy methods in cutting

In spite of the importance of the orthogonal models and wear maps, one important difference exists in real abrasion that is not taken into account by any of the aforementioned models. In reality, the obliqueness of the cutting asperity is further compounded by the fact that cutting occurs on a grooved surface. Experimental investigations and models have been developed to understand this important effect. One approach is to create a deformation field with a presumed set of shear planes. The deformation energy is minimised by altering the orientation of the planes.

Based on this technique the following equations were developed by Xie and Williams [7] to estimate the friction coefficient $\mu$ and wear coefficient $K$ under the assumptions of a pyramidal-shaped indenter and micro-cutting,

$$\mu_{\text{cut}} \approx \sqrt{\frac{2}{\pi}} \frac{\tan\alpha}{l^{0.25}} \left\{ 1 - \frac{f}{3\sqrt{3}} \left( 1 + \frac{\pi}{4\tan^2\alpha} \right)^{0.5} \right\} \quad (7)$$

$$K_{\text{cut}} \approx 0.003 \frac{27\tan^3\alpha}{f H_{\text{def}} l^{0.5}} \sqrt{\frac{H}{H_{def}}} \quad (8)$$

where $l$ is the relative overlap of successive scratches (i.e. overlap/scratch width), $f$ is the interfacial shear strength as defined in Section 2.4., and $\alpha$ is the attack angle of the leading edge of the pyramidal indenter. Provided that $f$ and $l$ are small enough, cutting can occur for $\alpha$ less than 10º because the effective attack angle is greater due to the asymmetrical groove boundary, not to mention the favourable oblique cutting conditions, as shown in Fig. 5.

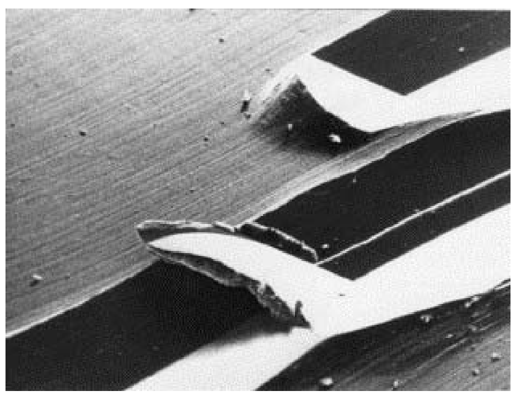


Fig. 5. Increased cutting efficiency due to side stripping of a previously existing groove.

Using Eqs. (7) and (8), combined with values of surface slope obtained from stylus profilometer measurements and estimates of asperity density, it has been possible to develop a model of grinding forces relative to undeformed chip thickness $h_{eq}$ [8]. Yet many aspects of this model could benefit from more detailed investigation. For example, the assumptions relating to asperity slope and the importance of three-dimensional form on the grinding process need to be reviewed. It is therefore important to develop new, more accurate techniques that can reliably measure the shape of abrasive surfaces.

## 3. Particle and surface measurement

### 3.1. Particle analysis

Particles are fundamental elements of abrasive systems, including grinding wheels. Crushed ceramic particles exhibit dramatic variation of form. To express this form in a way that is relevant to abrasive machining can be challenging, and some attempts are presented subsequently.

#### *3.1.1. Particle profile analysis techniques*

The easiest way to obtain particle information is to analyse projected boundaries from microscopic images. The boundary can be used to make inferences about a particle's ability to cause wear by abrasion. The concept of boundary angularity has been shown to be very important in wear correlation. This makes sense in view of the derivation of the simple abrasion model. The 'cone-fit analysis' (CFA), and later the 'sharpness analysis' (SA) techniques [9] were developed to show that the particle boundary plays an important role in determining wear rates.

Sharpness analysis essentially determines the statistical relationship between two orthogonal areas with increasing penetration, as shown schematically for a single asperity in Fig. 6. This relationship is called the 'groove function'.

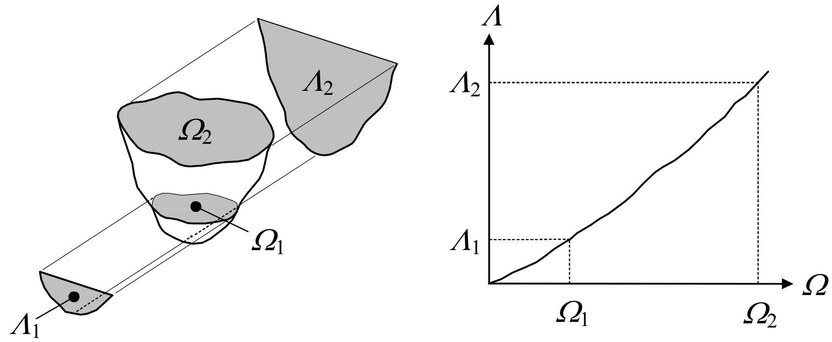



Fig. 6. Schematic representation of an asperity and its corresponding 'groove function' [10].

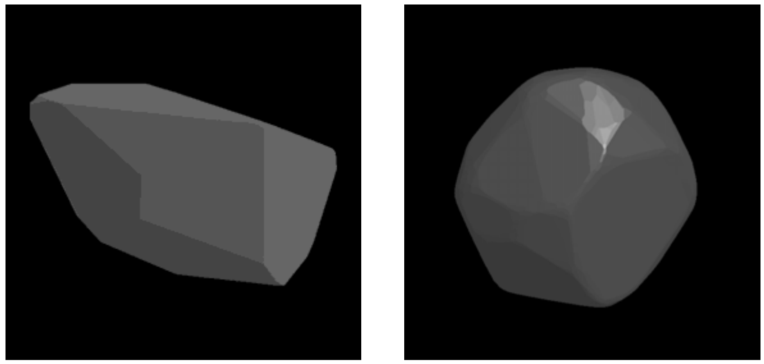
It has been shown that the groove functions of different particle types can be approximated by a body-of-revolution with a power-law generatrix [10]. This equivalent body-of-revolution is easy to represent as three parameters which also describe the statistical variation of asperity shape. The power-law representation for the asperity is given by,

$$y = Bx^{E} \tag{9}$$

where $E$ is a fixed exponent usually ranging between 1 and 1.4, and the coefficient $B$ is a log-normally distributed random variable with parameters $\mu_{B,\log}$, $\sigma_{B,\log}$. This type of analysis is ideal for simulating grit coated abrasives, and metal bonded super-abrasive wheels, where individual grits are easily distinguished.

#### *3.1.2. Particle simulation*

A solid of revolution is a fairly crude approximation of the true complexity of real surface asperities. Most real asperities are asymmetric and present themselves obliquely to the workpiece surface. A study was undertaken to determine if randomly generated polyhedral particles resemble real abrasive particles [11]. These particles satisfied the condition of asymmetry, and when their boundary projections were analysed they exhibited similar attributes to the boundary projections of real particles. The statistical strategy chosen to generate each particle had notable influence on the final form produced, as shown in Fig. 7.



(a) (b)

Fig. 7. Random polyhedrons created with different generating strategies. (a) sharp, (b) rounded [11].

The two particle types shown in Fig. 7 have substantially different effects on wear rate, however, particle distribution and density can be just as important as average shape. Particle shape characterisation alone is important, but shape measurement of the surfaces that they constitute is the only way to reliably predict grinding wheel performance.

## 3.2. Surface measurement

### *3.2.1. Slope technique*

The invention of the Abbott profilometer over 70 years ago led to great advances in the characterisation of surfaces and the modelling of friction and wear. Surface topography has a strong influence on material removal rates and grinding forces. Surface slope in particular has a direct impact on grinding performance.

Most surfaces exhibit statistically non-stationary behaviour. That is, they possess height distributions that depend on the size of the region sampled. Parameters derived from the surface profile also depend on the resolution and filtering characteristics of a particular instrument. For example, Sayles and Thomas [12] found that the random component of roughness $R_q$ is proportional to the square root of the sample length. Surface roughness is therefore related to band-width just as much as it is to the nature of the surface itself.

Slope measurement and peak counting present similar problems. If contact phenomena are to be predicted, then both the short- and long- wavelength cut-offs must be specified. According to Torrance [13], the long wavelength cut-off recommended was the mean asperity spacing, calculated from the wheel specification. Such a cut-off specification filters out the long-wavelength undulations that are introduced by the use of replication techniques. Because the average slope is calculated as the derivative of the profile, some distance below the contact zone, it is very sensitive to the lower wavelength cut-off. Torrance [13] chose the average length of the asperities in contact, for a given penetration depth, as the value for the lower wavelength cut-off.

The preceding analysis gives rise to a relationship between depth into the wheel and average surface slope of the profile, as shown in Fig. 8 for an alumina grinding wheel (77A 601 LNAA) dressed with a single point diamond. The figure also shows the estimated asperity density with increasing depth into the wheel surface. Grit density is necessary to estimate grinding forces, however its measurement is sensitive to the method used to identify adjacent peaks.

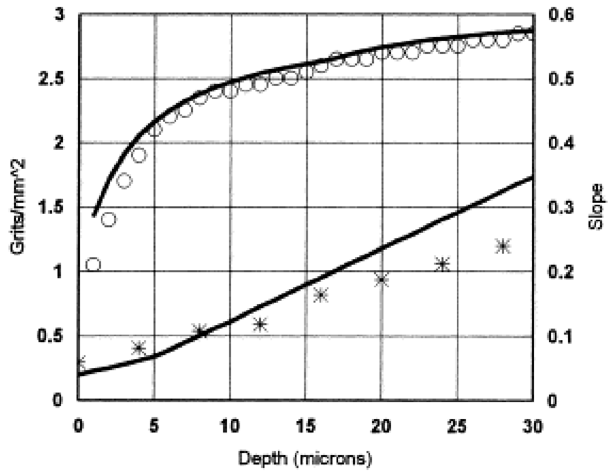



Fig. 8. Surface slope and grit density as functions of depth into the wheel's surface [8].

The slope for grinding wheel surfaces shown in Fig. 8 suggests hyperbolic grit profiles [8]. This simple model of grit profile, gives a continuous representation of attack angle with increasing depth of penetration. Grinding forces can be calculated using Eqs. (7) and (8), combined with undeformed chip thickness, grit density and material properties. Good correlations with experimental data have been obtained over a variety of operating conditions [8].

*3.2.2. Three-dimensional wheel measurement*

Two-dimensional stylus profilometry has been used with success to estimate grinding wheel performance, yet it is easy to argue that three-dimensional stylus profilometry would provide better estimates of surface shape. Numerous parameters have been developed to characterise surfaces, but the ones identified by Butler [14] to be most significant in grinding are: summit curvature, summit density and r.m.s. roughness.

The statistically non-stationary nature of surfaces requires that long and short wavelength cut-offs be specified. In this technique the short cut-off is implemented by specifying the optimal sample spacing, $\delta_{opt}$, relative to the grain size of the wheel $d_g$, i.e.,

$$\frac{d_g}{4} \leq \delta_{opt} \leq \frac{d_g}{3} \tag{10}$$

The long wavelength cut-off is implemented implicitly by the dimension of the sample, typically 2×2 mm. While it was shown that parameters changed substantially with wheel usage, no prediction of forces was made.

## 4. Stereoscopic profilometry

Stylus profilometry is a well-tested and robust technique for characterising grinding wheel surfaces, yet new techniques that overcome existing limitations must be investigated. Stereoscopy is one such technique and is subsequently discussed.

### 4.1. Theory of stereoscopy

Stereoscopy works on the principle that the height differences between points can be determined by their relative lateral movement as the viewing position is changed. It is imperative that each point can be identified uniquely in each image. The concept of point matching is critical to the success of the technique. In practice, a pair of images is generated by one of two methods. The first involves using two cameras separated by a set angle; while the second involves tilting the specimen eucentrically and taking separate pictures. The latter is often more practical. The choice of tilt angle must be large enough to obtain measurable disparity, but sufficiently small so that the points do not disappear from view, nor change their brightness profile excessively [15].

Ideal conditions require: (1) Uniqueness – each point is matched with only one corresponding point on each image and (2) Continuity – the change in position of the points varies smoothly across the surface. Where these conditions are violated filtering must be used to permit approximate surface reconstruction. The algorithm for stereoscopic reconstruction can be divided into the following steps:

1. Identifying points that are suitable for stereoscopic matching, e.g. edges or other points of high brightness or contrast change.
2. Unique matching of points on both images.
3. Disparity measurement and surface interpolation.

Software implementing the stereoscopic technique is commercially available. The software used in this research is specifically intended for use with scanning electron microscope (SEM) images. These are preferred because of their large depth-of-field, high resolution and progressive brightness variation. Optical techniques are often unsatisfactory because of limited depth of field and image saturation due to the non-linear brightness variation attributed to surface specularity. The economic and practical advantages of optical microscopy over SEM provide motivation to further develop optical techniques.

## 4.2. Practical implementation

The nature of the sample to be measured has direct influence on the success of the technique. Excessively smooth, texture free surfaces are unsuitable for imaging because of the difficulty in identifying unique matching points. The images obtained must also have good contrast levels with no saturated regions (i.e. 0 or 255 pixel-values on the gray-scale image).

The condition of eucentric tilting is also important. This requires that the specimen be tilted about an axis parallel and centrally located relative to the image frame, and near the surface of the specimen. A large angle of tilt is desirable to increase height resolution, however, this benefit is negated by the fact that features with large slopes can become hidden, or that their pixel brightness profile changes too much, thus violating the uniqueness condition. The image resolution also needs to be taken into account since smaller tilt angles can be utilised to register lateral movement of matching points if the image resolution is high.

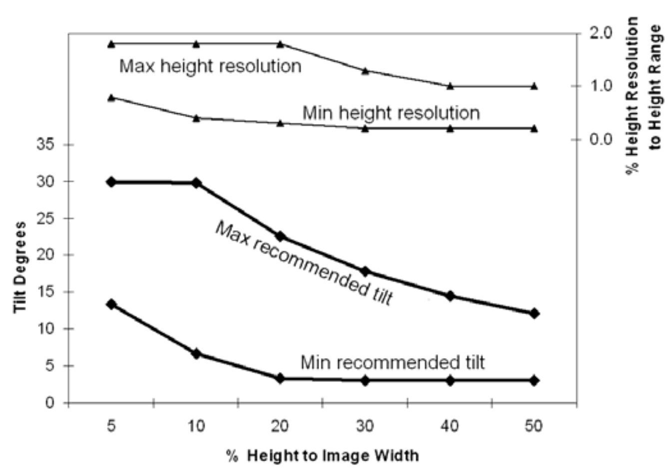



Fig. 9. Recommended tilt angles and corresponding resolution for images with different relief (height range relative to image width). Figures apply to image 1200 pixels wide.

A suitable tilt angle can be chosen depending on the estimated ratio of height relative to width of the surface, and image resolution, as shown in Fig. 9. Height resolution is very good with large tilt angles and moderate relief. Errors in tilt angle can result in distortion of the height profile. The height difference $\Delta h$ between two points, separated by $d_1$ in one image and $d_2$ in the second image (at angle $\theta$ relative to the first), is given by,

$$\Delta h = \frac{d_1 \cos\theta - d_2}{\sin\theta} \tag{11}$$

It is clear that the error in $\Delta h$ is greater when $\theta$ is small. Calibration to ascertain the accuracy of stage tilt and image magnification will be necessary for quantitative analysis of surface features, e.g. surface slope, roughness measurements, etc.

4.3. SEM stereoscopy of particles and surfaces

Preliminary experiments were conducted to investigate the potential of stereoscopy for particle and surface reconstruction. The advantage of SEM stereoscopy is that it can measure very small particles without contact. Abrasives consisting of particles in the order of several microns can be measured quite easily. This is the same order of magnitude as the tip radius of many stylus profilometers. The additional benefit of stereoscopy is that surface slopes of up to 80 degrees can be measured, depending on the angle of tilt used.

A diamond grit of size 140/170 (~100 µm) is shown in Fig. 10. The particle exhibits featureless planar facets. These present a problem in stereoscopic reconstruction owing to the increased difficulty of identifying matching points. Mismatched points give rise to substantial error of reconstructed form. Some progress has been made using very thin coatings that add texture without altering form.

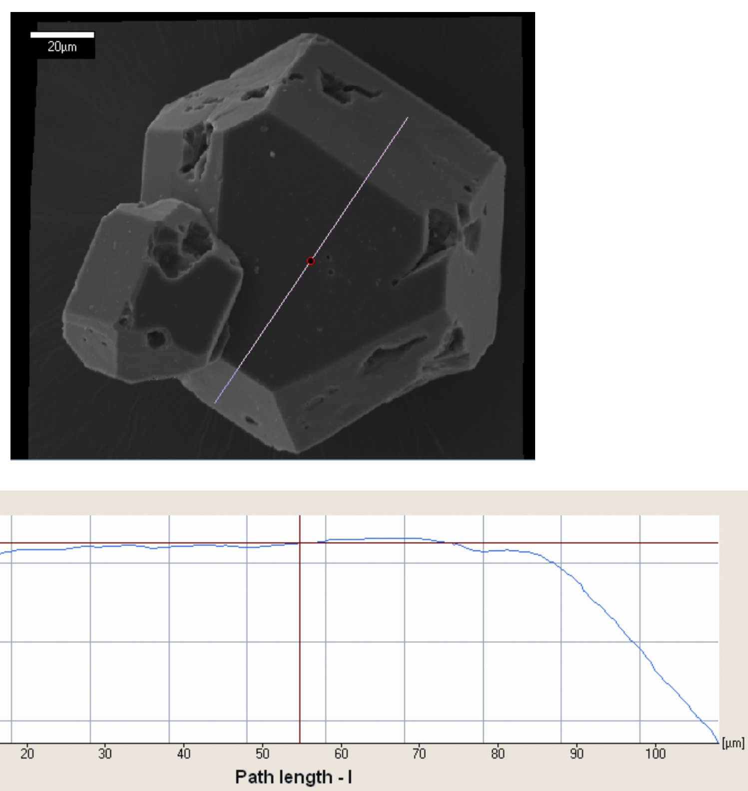



Fig. 10. Diamond grit showing and selected profile across digital elevation model obtained by SEM stereoscopy. Tilt angle: 10º.

The technique can also be applied to grinding surfaces as shown in Fig 11. In this example we see that the grinding surface is undressed and that the surface distribution is highly skewed. The cutting edges are concentrated near the surface and have very small slopes. Although the higher slopes would not significantly partake in grinding, the example serves to demonstrate the steep angles that can be measured effectively by the stereoscopic technique.

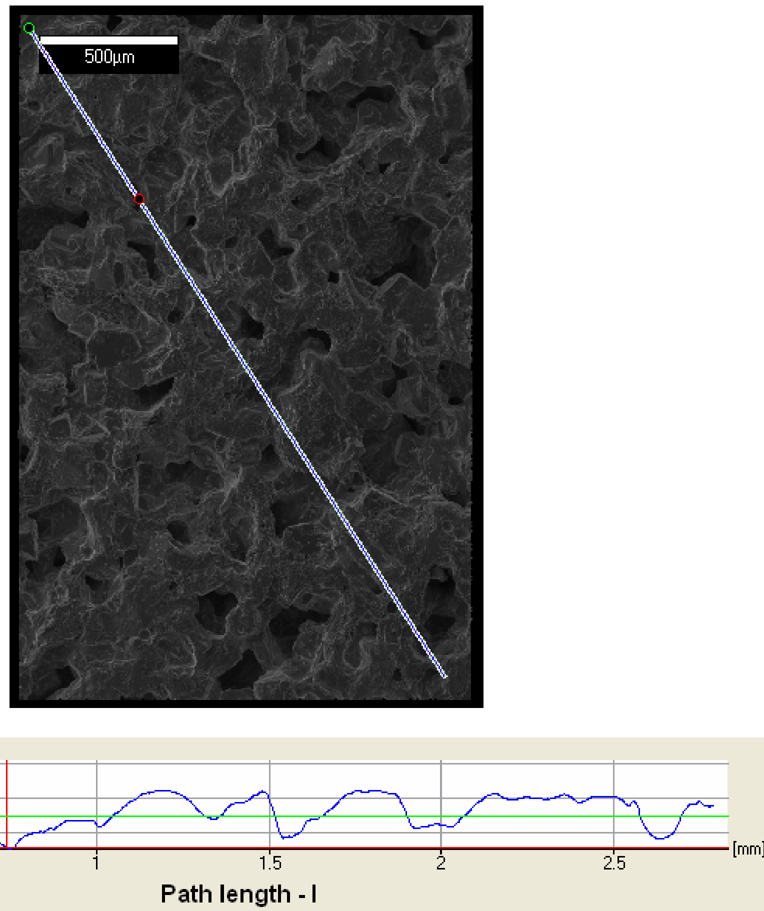



Fig. 11. Image of grinding surface and selected trace across digital elevation model. Tilt angle: 16º.

## 4.4. Optical stereoscopy

Optical stereoscopy provides some very interesting challenges, mainly related to the reflectivity and transparency of the surfaces to be measured, as shown for example in Fig. 12. The bonding agent is highly reflective and results in a number of regions consisting of saturated pixels. In these regions there is no feature information and correct matching of points is impossible. Consequently, surface reconstructions in these regions exhibit large errors.

Image enhancement techniques have been developed specifically for removing the saturated zones. A multi directional light source is used to illuminate the specimen. Identical images with different light sources are enhanced by replacing the saturated fields with the equivalent unsaturated field from another image. Stereoscopic surface reconstruction using the enhanced images results in outstanding results compared to those obtained with un-enhanced photos. Further tests need to be carried out, however, the possibility for wheel condition monitoring using optical stereoscopy would greatly benefit grinding technology.

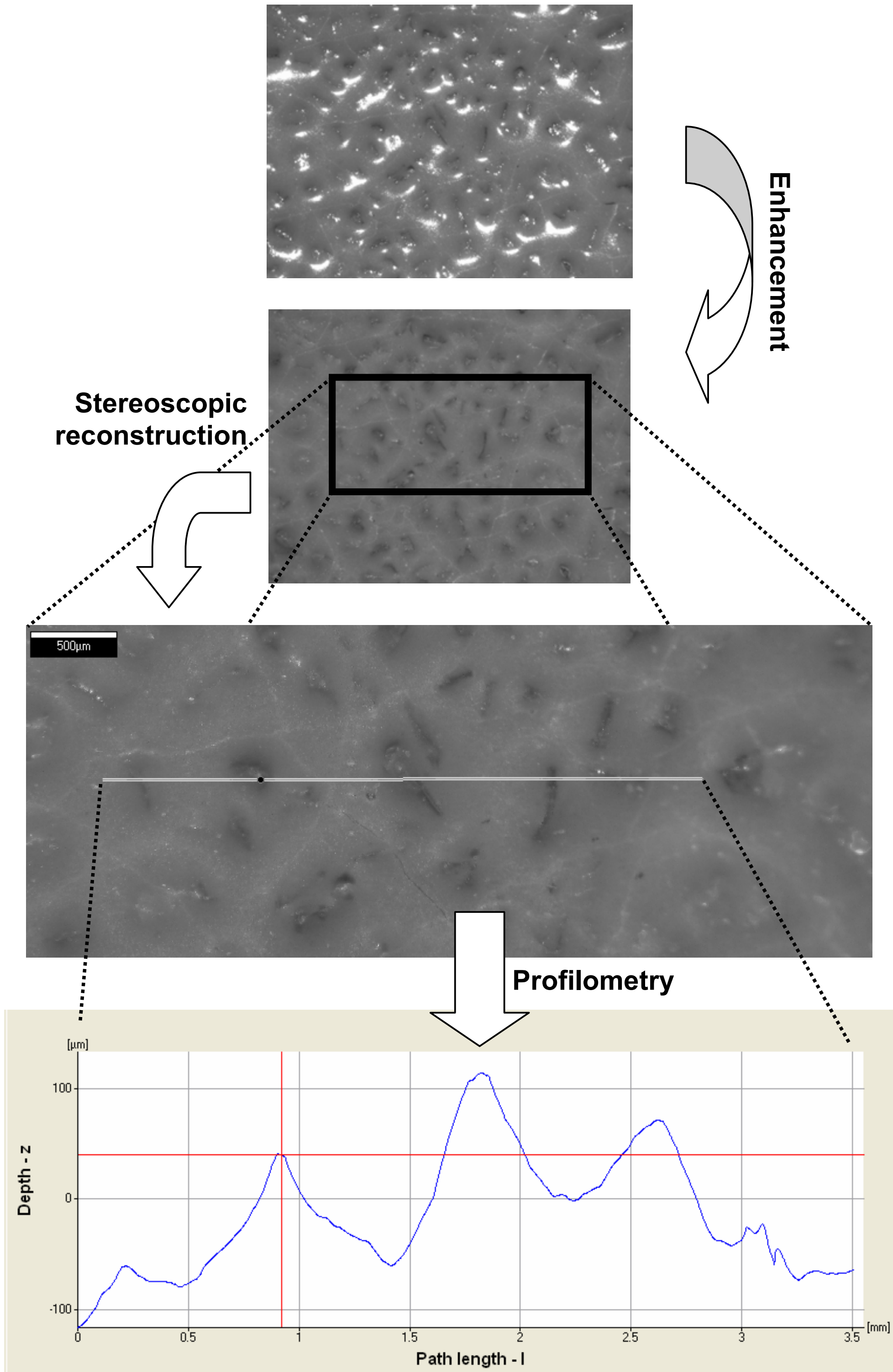



Fig. 12. Stages in optical stereoscopy. Images of alumina coated abrasive paper are first enhanced to remove saturated pixels. Correct stereoscopic reconstruction as shown by the selected trace of digital elevation model. Tilt angle: 10º.

## 5. Conclusion

From this work the following important observations are made:

- Diamond particles are very important in abrasive machining. Their mechanical properties, combined with their shape make them very effective abrasives.
- It is worthwhile to measure abrasive shape in order to better predict grinding performance.
- Improved methods of abrasive measurement and shape characterisation are required in order to predict grinding forces and temperatures.
- Stereoscopy is a non-contact profiling technique that promises some important advantages over stylus techniques.
- Work is continuing to establish the dimensional fidelity of stereoscopic surface reconstructions.
- Techniques are being developed to enable stereoscopy to be applied using optical images.

## References


[1] E. Rabinowicz, Friction and Wear of Materials, 2nd ed., John Wiley, New York, 1995, pp. 192–5.

[2] M. M. Kruschov, Principles of abrasive wear, Wear, 28 (1974).

[3] K. H. Zum Gahr, Microstructure and Wear of Materials, Tribology Series 10, Elsevier, Amsterdam, 1987.

[4] K. H. Zum Gahr, Wear by hard particles, in New Directions in Tribology, ed. I. M. Hutchings, MEP, 1997.

[5] J. M. Challen, P. L. B. Oxley, An explanation of the different regimes of friction and wear using asperity deformation models, Wear 53 (1978) 229–243.

[6] K. Hokkirigawa, K. Kato, An experimental and theoretical investigation of ploughing, cutting and wedge formation during abrasive wear, Trib. Int. 21 (1988) 51–57.

[7] Y. Xie, J. A. Williams, The prediction of friction and wear when a soft surface slides against a hard rough surface, Wear 196 (1996) 21–34.

[8] A. A. Torrance, J. A. Badger, The relation between the traverse dressing of vitrified grinding wheels and their performance, Int. J. Mach. Tool Manuf. Des. Res. 40 (2000) 1787–1800.

[9] D. V. De Pellegrin, G. W. Stachowiak, Assessing the role of particle shape and scale in abrasion using 'sharpness analysis', Part I. Technique development, Wear 253 (2002) 1016–1025.

[10] D. V. De Pellegrin, G. W. Stachowiak, Evaluating the role of particle distribution and shape in two body abrasion by statistical simulation, Trib. Int. 37 (2004) 255–270.

[11] D. V. De Pellegrin, G. W. Stachowiak, Simulation of 3-dimensional abrasive particles, Wear 258 (2004) 255–270.

[12] R.S. Sayles, T. R. Thomas, Surface topography as a nonstationary random process, Nature 271 (1978) 431–434.

[13] A. A. Torrance, The statistics of the extrema of surfaces as a means of assessing their mechanical performance, Wear 156 (1992) 281–299.

[14] D. L. Butler, L. A. Blunt, B. K. See, J. A. Webster, K. J. Stout, The characterisation of grinding wheels using 3D surface measurement techniques, J. Mat. Proc. Tech. 127 (2002) 234–237.

[15] P. Podsiadlo, G. W. Stachowiak, Characterization of surface topography of wear particles by SEM stereoscopy, Wear 206 (1997) 39–52.

**Acknowledgments**

The authors wish to acknowledge the financial support of the Irish Research Council for Science Engineering and Technology, Embark Initiative. Special recognition is given to Dmitry Dubovitskiy for providing image enhancement algorithms. Thank you also to the Department of Mechanical and Manufacturing Engineering, University of Dublin for logistical support, and to Karl Tuffy of Element 6, Ireland, for discussions and interest in the current research.