A Study of the Three-Dimensional Structure of a Ground Surface

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abstract

The surface texture created by the grinding process is an important feature of the product influencing wear, friction, etc. It is important to understand how the grinding wheel surface is mapped onto the workpiece. In this regard, a study of the three-dimensional structure of a ground surface is presented. The topographic map of both a grinding wheel surface and a workpiece surface are decomposed into their wavelength structures using three-dimensional spectral analysis techniques. These decompositions provide information that will allow a link between the grinding wheel surface, the process kinematics, and the ground surface to be determined.

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terms

Spectrum Analysis  Grinding Wheels
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1. INTRODUCTION

Grinding is the oldest material removal process known to mankind, and has been put to use in various forms since the stone age. The earliest tools and implements came into being as a result of this process in a crude form. It is still used to prepare tools and is perhaps the most popular finishing operation for engineering materials, primarily because of the close tolerances that can be achieved. It is also used for bulk material removal, wherein a subsequent finishing operation determines the final surface geometry. In spite of it's wide usage, it is the least understood process, mainly due to the multitude of variables involved including wheel composition, thermal effects, elastic wheel deflection, wheel wear, etc. Additionally, the random distribution of the uneven grits on the grinding wheel adds an extra dimension to the complexity of the surface generation mechanism when compared to manufacturing processes such as milling and turning.

In all machining processes, the geometry of the tool is imparted to the surface, for example, in turning, the geometry of the tool with the side and edge cutting edge angles and tool tip radius is repeated at the intervals of feed on the surface. The effect of a change in cutting edge geometry on the geometry of a turned surface can be easily seen in Fig. 1a. In the case of milling, see Fig. 1b, the problem of developing a relationship between the workpiece surface and tool geometry is two-fold, due to the presence of multiple cutting edges. However, since the geometry of the edges is defined, the problem is not very severe. Several models for surfaces generated by turning/boring [1] and milling [2] have been reported. A defined tool signature is difficult to extract from a cursory examination of the ground surface (due to the presence of both multiple cutting edges of undefined geometry and the random distribution of these edges), see Fig. 2, although it is known that the spatial dynamics of the surface is a direct consequence of that from the wheel. An understanding of the evolution of the surface in a manner that would enable in relating a particular feature in the finished product to a causative
FIGURE 1: SURFACE GENERATION IN TURNING AND END-MILLING

(a) TURNING

Geometry of workpiece formed by a tool with nose radius

Geometry of workpiece formed by tool with side and edge cutting angles

(b) END-MILLING

Schematic of an Endmilling Operation

$N_t$ - Number of teeth

Tool Path direction

Cross-section of the workpiece

FIGURE 2: SURFACE GENERATION IN STRAIGHT SURFACE GRINDING

- $N$ - RPM
- $R$ - Wheel Radius
- $f$ - Feedrate
- $d$ - Depth of Cut

Feed Direction

Axial Direction
mechanism, is essential for the ability to control the surface formation. Knowing how the wheel influences the workpiece surface, it would then be possible in a design sense, to specify changes to be made in the wheel to obtain a required workpiece surface texture.

The role of surface finish in the performance of a product is of utmost significance when the product applications involve surface related properties such as surface interaction, optical reflection, electrical resistivity, etc. Two-dimensional surface parameters such as $R_a$, $R_q$ do not completely characterize the surface, since they neither indicate the presence of features such as pits and troughs that span perpendicular to the profile, nor do they indicate the nature of the surface, i.e., whether the surface is isotropic or anisotropic. Features such as pits and troughs alter the general properties of the surface (for e.g., the lubricant retention capacity), so much so, that the evaluation of the product performance is then translated into quantifying these features (determining the length and number of such features). Only a three-dimensional representation of the surface would enable such an evaluation, and give a complete description of the surface.

Surfaces generated in a straight surface grinding process, as shown in Fig. 2, due to the geometry alone (i.e., not influenced by disturbances such as vibration, spindle runout, out-of-round wheel, improper fixturing, misaligned table, etc.) are completely characterizable by two-dimensional parameters. However, when the disturbances mentioned previously exist, the geometry of the surface may be affected in the feed direction (vibration, spindle runout, out-of-round wheel) or in an oblique direction (table misalignment, improper fixturing, etc.). In the presence of the aforementioned process disturbances, the roughness parameters $R_a$ and $R_q$ obtained along the axis of the wheel can not account for the altered surface geometry. This necessitates the use of an areal assessment of surfaces for fault detection purposes.

In this paper, the need for a three-dimensional surface texture evaluation is illustrated for a surface generated by straight surface grinding. It will be demonstrated that such a process ideally creates a uni-directional surface that can be represented completely by a two-dimensional spectrum. However in the presence of process faults such as machine tool dynamics, spindle runout, improper fixturing, etc. as mentioned previously, a three-dimensional spectrum becomes necessary for the recognition and identification of these process faults. Initial knowledge of the frequency content of an ideal surface (without disturbances), will permit the identification of frequencies caused by process faults. It will then be shown how these defect frequencies can be linked to specific process defects. This procedure will be illustrated for the case of surface grinding, but may be extended to surfaces generated by other manufacturing processes as well.

The remainder of the paper is organized broadly into four sections. Section 2 briefly discusses the literature related to this work. Section 3 presents the mathematical fundamentals of three-dimensional spectral analysis. The fourth section provides a discussion of the experimental results and provides some interpretation. Finally, the paper is summarized and some conclusions are made in Section 5.

2. LITERATURE REVIEW

Considerable research in grinding has been reported over the last few decades in areas including surface generation models, grinding wheel texture and the structure of ground surfaces. A brief review of the relevant literature will be presented here.
Numerous models of how the grinding wheel texture affects the surface texture of the ground surface in two dimensions are available in the literature. Reichenbach, et al. [3] developed a two-dimensional model by taking into account the grain count and width of cut vs. depth of cut. A model assuming a uniform grain spacing was developed to predict parameters such as $R_a$ and $R_q$ associated with a ground surface [4]. A three-dimensional simulation procedure for the grinding process using the Monte Carlo method was developed assuming uniform distributions to describe the grain spacing in the axial and peripheral directions [5]. However, actual distributions of the grains are not symmetrical, but exhibit negative skewness, wherein valleys are deeper than the summits are high [6]. A statistical approach to describing the surface profiles in terms of averages and autocorrelation functions viewing the process as a random input and output model and a linear transfer function was developed in [7].

A number of models for specific processes have also been developed. A two dimensional study of the surface topography generation in a conventional plunge grinding process was done assuming that the cutting path of a grain is circular [8]. A model was developed for the surface generated by a radiused wheel during contour grinding by considering the grinding process as a fly cutting operation using a single tool, with a radius equal to the nose radius of the wheel [9]. A three-dimensional geometric model for the surface texture generated in a surface grinding process using experimentally obtained grinding wheel texture as an input was developed in [10]. A review of the merits and deficiencies of a few of the surface roughness and topography models is given in [11].

A variety of experimental studies of the surface texture of ground surfaces, the majority only two dimensional, have been performed. Hahn and Lindsay examined the influence of a number of process variables on the two-dimensional surface finish in a conventional surface grinding process [12]. The two-dimensional wavelength structure of a ground surface profile was examined in [13]. Salisbury et al. characterized the surface texture of computer hard disks using three-dimensional spectral analysis [14].

Along with the development of surface generation models and studies of the texture of ground surface, research on the surface texture of the grinding wheel has been reported. A modelling procedure was developed where model parameters describing the distribution of the heights of grain summits and grain apex-angle were estimated [15]. The cutting area of the grinding wheel was characterized by combining two distribution functions, each independent of the other, to give a multi-dimensional distribution curve [16]. Shoji et al. studied the depth distribution of cutting edges on a dressed grinding wheel, and considered their relation between dressing feed and patterns produced by it [17]. A parameter called successive cutting profile contribution was proposed to quantify the functional parameters of the grinding wheel [18]. An optical-digital approach for classifying rough surfaces using Fourier spectrum sampling was developed in [19]. Koshy et al. formulated a model for the estimation of planar grain density, percentage area due to the abrasives, and abrasive protrusion height for diamond grinding wheels assuming spherical grits [20]. A two wavelength model for representing the grain in a grinding wheel was proposed by Pandit and Sathyanarayan [21]. This model however, does not account for wavelengths greater than the grain size, and essentially form the major component in the surface generation mechanism.

Little work has been done to link the three dimensional features of the wheel and
workpiece surfaces. This work is part of an ongoing research effort in grinding wheel characterization and the modeling of the surface generation mechanisms in straight surface grinding that attempts fill that gap. Here a study of the texture of both grinding wheels and ground surfaces in three dimensions is presented using a three-dimensional frequency decomposition technique to characterize the underlying wavelength structure.

3. THREE-DIMENSIONAL SPECTRAL ANALYSIS

Both wheel and ground surfaces may be considered to be two-dimensional spatial functions. Therefore, analytical tools developed for multi-dimensional signal processing need to be employed for characterizing them. Three-dimensional spectral analysis, which will be used in this paper is discussed briefly in the following section.

Spectral analysis is the outcome of statistical estimation theory and forms the workhorse of random signal-analysis procedures. It is usually implemented in the discrete version by using FFT algorithms. An adequate treatment of this technique in three-dimensions for areal applications is described in [22,23,24].

Fourier transform techniques applied to spatial data, will yield the following relation for the Fourier coefficient \( F(\omega_x, \omega_y) \) for a continuous function:

\[
F(\omega_x, \omega_y) = \int \int S(x_c, y_c) \cdot e^{-j2\pi(\omega_x x_c + \omega_y y_c)} \cdot dx \cdot dy \tag{1}
\]

where \( S(x_c, y_c) \) is the continuous surface. It's equivalent in the discrete case is as follows:

\[
F(\omega_p, \omega_q) = \frac{1}{MN} \sum_{y=1}^{N} \sum_{x=1}^{M} S(x, y) \cdot e^{-j2\pi\left(\frac{P x}{M} + \frac{q y}{N}\right)} \tag{2}
\]

where \( p=0,1,..., M-1; \) \( q=0,1,...,N-1; \) and \( S(x, y) \) is an array of surface heights. Correspondingly \( F(\omega_p, \omega_q) \) is a matrix of Fourier coefficients, and \( \omega_p \) and \( \omega_q \) are the angular frequencies in the two orthogonal directions. Also,

\[
\omega_p = \frac{p}{\Delta x M} \quad \text{and} \quad \omega_q = \frac{q}{\Delta y N} \tag{3}
\]

The Fourier coefficients are complex numbers of the form \( a_{pq} + ib_{pq} \), where \( p \) and \( q \) are the indices associated with the x and y directions. The surface is composed of a set of cosine waves given by:

\[
S(x, y) = \cos \left[ 2\pi \left( \frac{P x}{M} \right) + \left( \frac{q y}{N} \right) \right] \tag{4}
\]

where each wave results in a spike at point \((p, \pm q)\) in the spectrum. The wavelength of each
wave $W(\omega_p, \omega_q)$ can be determined by:

$$W(\omega_p, \omega_q) = \frac{MN}{\sqrt{M^2 \omega^2 + N^2 \omega^2}}$$  \hspace{1cm} (5)

and the direction in which the wave traverses or the phase $\theta(\omega_p, \omega_q)$, associated the waveform can be determined by:

$$\theta(\omega_p, \omega_q) = \arctan\left(\frac{Np}{Mq}\right)$$  \hspace{1cm} (6)

where $0 \leq \theta(\omega_1, \omega_2) < \pi$. The power spectral density or the power associated with each frequency, $P(\omega_p, \omega_q)$, can be obtained by:

$$P(\omega_p, \omega_q) = F(\omega_p, \omega_q) \cdot F^*(\omega_p, \omega_q) = \frac{MN}{M} \sum_{x=1}^{M} \sum_{y=1}^{N} \frac{a_{pq}^2 + b_{pq}^2}{\sigma_s^2}$$  \hspace{1cm} (7)

where $F^*$ is the complex conjugate of $F$ and

$$\sigma_s^2 = \frac{\sum_{x=1}^{M} \sum_{y=1}^{N} s^2(x, y)}{MN}$$  \hspace{1cm} (8)

The magnitude of the power will determine the extent of significance of a certain frequency and hence can be used as a measure of relative importance.

4. GRINDING EXPERIMENTS, RESULTS AND INTERPRETATION

4.1 Initial Experiments

To develop the relationship between the surface properties of the wheel and the resulting ground workpiece, a series of initial experiments were run. Initially, a three-dimensional measurement of the surface of the wheel (32A1201-J8VBE) using a computer integrated Mahr-Perthen profilometer was conducted with the resulting topographic map shown in Fig. 3. Figure 3 shows an apparent random distribution of grits as would be expected. The frequency decomposition of the wheel surface using Eqs. (1-8) is shown in Fig. 4. As can be seen in Fig. 4, the spatial frequency content of the wheel surface is symmetrically dispersed about the origin, suggesting that the wheel is nearly isotropic in nature.

A set of grinding experiments using the aforementioned wheel were performed on a Brown and Sharpe - Micromaster surface grinding machine. The purpose of these tests was to illustrate how the spectral content of the workpiece surface geometry changes as grinding progresses. For these tests, the depth of cut was set at 200 microns, a feedrate of 0.33 m/sec
FIGURE 3: TOPOGRAPHIC MAP OF THE WHEEL SURFACE

FIGURE 4: SPECTRAL PLOT OF THE WHEEL SURFACE
was used. The wheel was dressed prior to grinding using a single-point diamond dressing stick. The 4140 steel workpiece was polished to eliminate the effect of the previous surface texture and no coolant was used. Three different grinding tests were conducted with the wheel, by generating surfaces with 5, 10 and 15 grinding passes. The topographic map of the 5 pass surface is shown in Fig. 5, and it can be seen that the majority of the texture is in the axial direction as would be expected. The measured surfaces from the 10 and 15 pass tests also appear as expected, but are not included here due to space considerations. The frequency decompositions of the surfaces resulting from the three tests are shown in Figs. 6-8 respectively. In comparing Figs. 6-8, it can be observed that the spectrum from the 5 pass surface, Fig. 6, has the highest peaks, while the spectrum for the 10 and 15 pass surfaces, Figs. 7-8 respectively, have peaks of comparable height.

4.2 Relationship Between Ground Surface and Wheel Surface

As mentioned previously, the spatial dynamics of the wheel and workpiece surfaces are related. Due to the kinematics of the straight surface grinding process (one-dimensional motion in the feed direction), the concentric distribution of the peaks (frequencies) in the wheel surface spectrum transforms into a distribution along a line perpendicular to the feed direction on the workpiece surface as seen in Figs. 6-8. To understand how the wheel spatial characteristics map onto the workpiece spatial pattern, the one-dimensional motion of the grits must be considered. This one-dimensional motion causes the power due to the frequencies that lie on either side of the axial spatial frequency axis of the grinding wheel (Fig. 4) to be projected onto a line in the axial direction at the origin. This projection is then mapped into the workpiece surface resulting in one-dimensional surface texture as shown in Figs. 5-6.

It can be observed that the maximum power in the spectral plot of the wheel surface (approx. $9 \times 10^8$), Fig. 4, is higher than that of the ground surface (approx. $15 \times 10^8$ for 5 passes), Fig. 6. This implies that the variance of the wheel surface is not fully being imparted to the surface. This observation compliments prior knowledge and earlier reports [25] that only a portion of the wheel surface is involved in cutting. The edges involved in cutting are typically referred to as dynamic cutting edges. The ratio of the edges involved in cutting and those that are not involved in cutting is called the cutting edge ratio [25]. The ratio of the total power in the wheel surface and the total power in the ground surface may give a measure of the cutting edge ratio or the wear flat area (a measure of wheel dullness) in a three-dimensional sense. This lower power in the ground surface may also be explained by considering a particular section of the workpiece surface, which is the resultant of many grains passing over it successively. The higher peaks on the wheel surface remove material continuously from the same section making it smoother, hence leading to a lower power in the spectrum.

Additionally, it can be observed in comparing Figs. 6-8 that as grinding progresses the power decreases implying that the surface is getting smoother, as would be expected. The maximum power decreases from $15 \times 10^8$ for 5 passes to $6 \times 10^8$ for 10 passes and remains at $6 \times 10^8$ for 15 passes. Therefore, it can be determined that between 10 and 15 passes spark-out (i.e. no material removal) occurred. This increasing smoothness in the surface is translated into the spectral plots as peaks with reduced amplitudes (hence lower total power). Although, maximum power is being used to compare the surfaces since it is easier to identify from the plots, strictly the total power should be used (it was verified that similar trends were observed
FIGURE 5: WORKPIECE SURFACE AFTER 5 PASSES

FIGURE 6: SPECTRUM OF WORKPIECE SURFACE AFTER 5 PASSES
FIGURE 7: SPECTRUM OF SURFACE AFTER 10 PASSES OF 120 GRIT WHEEL

FIGURE 8: SPECTRUM OF SURFACE AFTER 15 PASSES OF 120 GRIT WHEEL
with the total power).

To understand the contribution of the grit size to the frequency content of the ground surface, an average value obtained from the different relations given in Malkin [26] was used to obtain the nominal grain diameter. The nominal grain diameter corresponding to a120 grit wheel was calculated to be approximately 118 microns. The frequency corresponding to the grain diameter is 0.0085 (micron)$^{-1}$. It would be expected that a frequency contribution due to the nominal grain diameter be present in the spectral plot (Fig. 6). Interestingly, the power due to the frequency component that relates to the grain size (power is approx. $1 \times 10^8$) was observed to be very small compared to the contribution due to some low frequency components (power is approx. $15 \times 10^8$). The origin of these long wavelengths is rather obvious, as they exist in the spectrum of the wheel surface and are therefore mapped onto the ground surface. These long wavelengths suggest that something in the wheel that is larger than the average grain diameter, is contributing to the ground surface. It is possible that during the manufacture of the wheels, the grits tend to agglomerate in the bonding medium due to a cohesive force between them. This clustering phenomenon could result in a lump of grains being bonded together instead of the grains being bonded individually to the vitreous medium. The ability to control the surface is reduced when this grouping of grains occurs since the size of the clusters is difficult to control. Hence, it is suggested that steps must be taken during manufacture to avoid this agglomeration.

Although the disturbance-free ground surface texture may be fully characterized by two-dimensional spectral plots, as is apparent from the previous results, the information regarding direction of lay or anisotropy in the surface is difficult to realize from them. Further, evidence of any texture oblique to or in the feed direction that may exist in the surface due to process defects, can not be extracted from two-dimensional spectral plots, therefore three-dimensional spectra are required. This will be demonstrated in the following section.

4.3 Experiments with Significant Disturbance Effects

To illustrate the effect of process disturbances on ground surface texture, and the need for three-dimensional assessment for fault diagnosis, a workpiece that was ground under the influence of process defects was evaluated. The workpiece material is 4140 steel. It was ground at a feed 0.4 m/sec and at depth of cut of 200 microns. The measured surface is shown in Fig. 9. The topographic map clearly indicates the presence of texture in the feed direction due to disturbances. These marks could be either due to the machine dynamics, spindle runout or an out-of-round wheel. The spectral plot of the surface is shown in Fig. 10. The texture in the feed direction is also clearly evident from the spectral plot.

Due to a system constraint (the data-acquisition software limitations on areal measurements), the maximum area that could be measured was 16mm x 2.5 mm. This length (16 mm) does not give adequate resolution in the frequency domain at lower frequencies. Hence a profile of length 50 mm was measured. It is to be noted that the choice of a single profile for surface characterization is very critical, and is not recommended since it involves the danger of overlooking texture that may exist in directions other than that of the profile. In this paper, it was ensured that no dominant texture existed in any direction other than the profile direction by using the three-dimensional spectral plot.
Figure 9: Workpiece surface with dominant texture in the feed direction

Figure 10: Spectrum of workpiece surface with disturbance effects
The resulting profile and its two-dimensional spectrum is shown in Fig. 11. It is clear from the spectrum that there are five significant frequencies present in the surface profile and are labelled in Fig. 11. These frequencies are tabulated in Table 1. The frequency labelled 1 has a spatial frequency of 0.0004 (1/microns) which corresponds to a frequency of 15.9 Hz, through Eq. (9).

\[ \text{Freq (Hz)} = \text{feed (micron/s)} \cdot \text{Freq (1/\text{micron})} \]  

(9)

The frequency of 15.9 Hz in the surface profile corresponds to the spindle speed (930rpm/60s=15.5 Hz). The peaks labelled 2 and 3 are the first and second harmonics of 1. The presence of a spatial frequency corresponding to the spindle speed may suggest that the grinding wheel was out-of-round or that spindle runout existed during the operation. With the process knowledge available, no link could be made to the other significant frequencies (4 & 5). The possibility that these were the result of machine tool vibration was then investigated.

To accomplish this, vibration data was obtained from the machine tool spindle using a PCB piezoelectric accelerometer. The resulting vibration signal and its spectrum are shown in Fig. 12. The spectral plot shows the presence of three significant vibration modes which are listed in Table 2. The frequency labeled as A is at 16.6 Hz and corresponds to the spindle speed. The frequencies, B and C, occur at 85.9 Hz and 155.3 Hz respectively, and relate to the spatial frequencies labeled as 4 and 5 that occur at 79.8 Hz and 151.7 Hz.

<table>
<thead>
<tr>
<th>Peak Label</th>
<th>Spatial Frequency, (microns)(^{-1})</th>
<th>Wavelength microns</th>
<th>Frequency, Hz</th>
<th>Power,%</th>
<th>Cause (related frequency in the vibration spectrum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00004</td>
<td>25000.00</td>
<td>15.9</td>
<td>13.93</td>
<td>Spindle RPM (Peak A)</td>
</tr>
<tr>
<td>2</td>
<td>0.00008</td>
<td>12500.00</td>
<td>31.9</td>
<td>9.57</td>
<td>1\textsuperscript{st} harmonic (Peak A)</td>
</tr>
<tr>
<td>3</td>
<td>0.00012</td>
<td>8333.33</td>
<td>47.9</td>
<td>5.51</td>
<td>2\textsuperscript{nd} harmonic (Peak A)</td>
</tr>
<tr>
<td>4</td>
<td>0.00020</td>
<td>5000.00</td>
<td>79.8</td>
<td>30.88</td>
<td>M.T. Vibration (Peak B)</td>
</tr>
<tr>
<td>5</td>
<td>0.00038</td>
<td>2631.57</td>
<td>151.7</td>
<td>4.88</td>
<td>M.T. Vibration (Peak C)</td>
</tr>
</tbody>
</table>

Table 2: Frequency Composition of the Vibration Signal

<table>
<thead>
<tr>
<th>Peak Label</th>
<th>Frequency, Hz</th>
<th>Power,%</th>
<th>Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>16.6</td>
<td>1.77</td>
<td>Spindle RPM</td>
</tr>
<tr>
<td>B</td>
<td>85.9</td>
<td>3.09</td>
<td>Machine-tool vibration</td>
</tr>
<tr>
<td>C</td>
<td>155.3</td>
<td>1.76</td>
<td>Machine-tool vibration</td>
</tr>
</tbody>
</table>
FIGURE 11: WORKPIECE SURFACE PROFILE AND IT'S POWER SPECTRUM

FIGURE 12: THE VIBRATION SIGNAL AND IT'S POWER SPECTRUM
This study has identified three process disturbances that contribute to texture in the feed direction; out-of-round wheel or spindle runout, and two vibration modes. The disturbance at the spindle rpm is likely due to an out-of-round wheel, because a spindle runout condition would occur for all grinding experiments since it is machine specific. However, this effect was not observed in all cases. It is believed that the out-of-round wheel disturbance causes a fluctuation in the grinding forces that excites the vibration modes in the machine tool.

5. SUMMARY AND CONCLUSIONS

In this paper, a description of three-dimensional spectral analysis and its application to the assessment of ground surface texture has been given. The grinding wheel surface texture was measured and characterized via three-dimensional spectral analysis. Then a set of initial experiments were run, varying the number of grinding passes, to attempt to understand how the frequency content of the ground surface changes with an increasing number of passes. Finally, three-dimensional spectral analysis was used to identify the presence of a process defect on the surface texture of a ground part. To aid in fault diagnosis, the vibration characteristics of the machine tool were measured and the resulting modes were linked to the spatial frequency content of the surface.

Specific research findings resulting from this work include:

- Three-dimensional spectral analysis can be used to characterize the surface texture of grinding wheels, and can indicate the underlying isotropic nature of these surfaces.

- The grinding wheel has many low frequency components that may be due to a clustering phenomenon of the abrasive particles in the bonding medium. The mapping of the low frequency components of the wheel onto the workpiece, due to the clustering phenomenon, may have a deleterious effect on the resulting ground surface texture. Therefore, this clustering of grits should be avoided in the wheel manufacturing process.

- The ratio of the total power of the workpiece surface to the total power of the wheel surface may provide a measure of the wear flat area or the cutting edge ratio in a three-dimensional sense.

- Three-dimensional spectral analysis can be used in fault diagnosis applications to identify the presence of undesirable texture in the workpiece surface. The frequency components in the workpiece surface can then be linked to the specific cause in the process and corrective action can be taken.

REFERENCES


