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Surface analysis techniques to optimise the performance of CNC machine tools

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Abstract

A series of cutting trails have been carried out utilising milling operations and the development of chatter on the machined surface has been analysed. 3D surface metrology techniques have been used to characterise the surface and particular attention has been paid to the use of Areal Auto Correlation Function (AACF) and Areal Power Spectral Densities (APSD). Both the AACF and APSD have been shown to effectively characterise the development and appearance of chatter and the implications of the use of these techniques for potentially controlling the machining process have been outlined.

1 Introduction

The three main areas of concern affecting the performance of a CNC machine are environmental effects, user effects and machine accuracy. In general, there are three major research fields focused on the study of these matters. The first is the metal cutting field; study here considers cutting process modelling and adaptive machining techniques, and concentrates on cutting forces, the identification of cutting geometry and load/cutting forces in a real-time environment. The second field is machine tool errors; this field concerns error measurement of machine tools, identification and correction of geometric, load and thermal errors of machines. The third field of study concerns surface assessment and focuses on development of profile and areal surface analysis techniques for controlling and monitoring of manufacturing process. Although all of these fields have played a significant part in the development of 'state-of-the art' performance of CNC machines, the three aspects of study have not as yet been integrated into a single entity technology for application to CNC machine tool performance.

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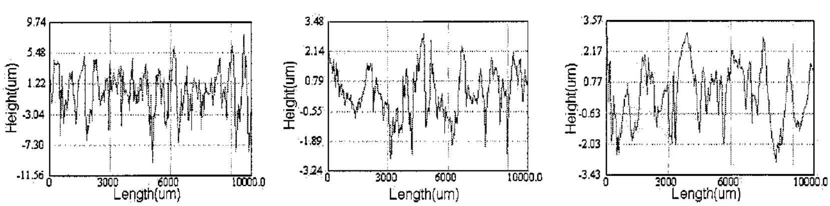
Recently, under the support of the Engineering and Physical Sciences Research Council of the UK, a joint research programme has started to explore a possible and acceptable method to optimise the performance of a CNC machine tool under cutting conditions [1]. It attempts to build up correction algorithms by combining the above three knowledge bases and implementing them into 'state of the art' control methodologies affecting dimensional accuracy, form, surface finish and integrity of a given workpiece. The aim of the project is to control all cutting parameters, and allow a component to be produced automatically whilst controlling all aspects of the machine workpiece interaction [1-3].

This paper presents a part of this programme, and describes the use of areal surface knowledge to diagnose the development of chatter during cutting. In this work, surfaces are generated by using three axis vertical CNC milling machines, the Beaver VC35 and the Cincinnati Arrow 2-500. The surface measurement is performed using the Form Talysurf PGI.

2 Analysis techniques for controlling the surface creation process

It is well known that the nature of a machined surface has three-dimensional topography, which means that all the machining information is distributing in a three-dimensional space, thus traditional two-dimensional evaluation can not completely reflect the change of the machining performance across a given area of workpiece surface [4]. Figure 1 shows two-dimensional profiles taken under different cutting conditions (from stable cutting, early chatter and heavy chatter) when facing milling using a Beaver VC35. These figures look very similar, and are very difficulty to directly use to understand, interpret and evaluate the manufacturing performance. In comparison with Figure 1, Figure 2 it is clear the 3D analysis provides a better visualisation, and easily illustrates the development of chatter on the machined surface.



(a) stable cutting *(b) early chatter* *(c) heavy chatter*

Figure 1 Milled surface profiles under three different cutting conditions

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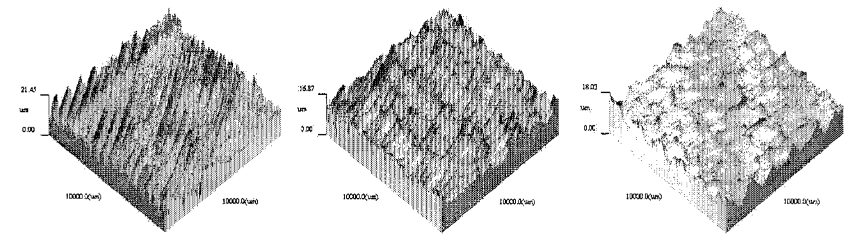


(a) stable cutting *(b) early chatter* *(c) heavy chatter*

Figure 2 3D areal analyses of milled areal surfaces under three different cutting conditions

In recent years considerable progress has been made in the characterisation of surface finish and the surface generation processes. Areal surface characterization includes numerical parametric evaluation and areal spectrum analysis for manufacturing monitoring and control [4-5]. The merits of parametric evaluation are simple and convenient, and it can easily reflect the precision of the manufacturing process but cannot directly indicate the state of machining process, consequently, it is very difficulty to describe the relationship between the numerical parameters of surface topography and adjustable control parameters of the CNC machine tools.

However, surface spectrum analysis, including areal autocorrelation function (AACF), areal power spectrum (ASPD) and angular spectrum can play a significant role in the possible monitoring of the development of chatter. Initial results shows that surface spectrum information will clearly reflect the cutting conditions. It is possible that spectrum analysis can become a tool to facilitate a better understanding of the process and to adjust the machine control parameters via a feedback loop as shown in Figure 3.

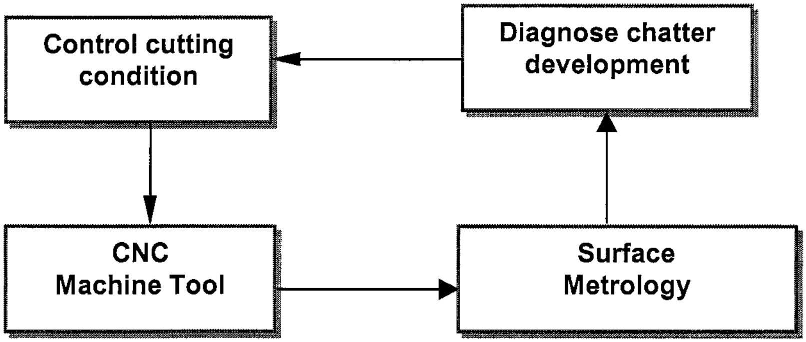


Figure 3 the feedback loop for manufacture performance

2.1 Areal autocorrelation function

Autocorrelation function is a very useful tool for processing random signals. It describes the general dependence of the topographical values at one position on the topographical values at another position. For areal surface evaluation, it could not only describe the spatial relation dependences of the surface topography, but also describe the direction and periodicity of the surface texture.

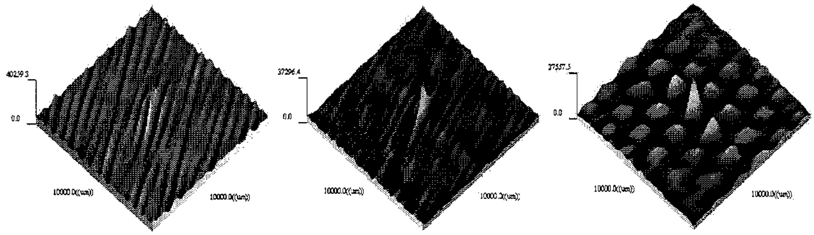
Areal autocorrelation function is defined in mathematics as: [5-6]

$$R(\tau_x,\tau_y) = E\left[\eta(x,y)\eta(x+\tau_x,y+\tau_y)\right] = \lim_{l_x,l_y\to\infty}\frac{1}{4l_xl_y}\int_{-l_y}^{l_y}\int_{-l_x}^{l_x}\eta(x,y)\eta(x+\tau_x,y+\tau_y)dxdy \quad (1)$$

$\eta(x_k,y_l)$ is a surface measured data set after form removal, it can be digitalized into

$$R(\tau_i,\tau_j) = \frac{1}{(M-i)(N-j)}\sum_{l=1}^{N-j}\sum_{k=1}^{M-i}\eta(x_k,y_l)\eta(x_{k+i},y_{l+j}) \quad (2)$$
$$i = 0,1,\ldots\ldots,m < M; j = 0,1,\ldots\ldots,n < N; \tau_i = i\cdot\Delta x; \tau_j = j\cdot\Delta y$$

The AACF of areal surface signal has three properties: (1) Symmetry, $R(\tau_i,\tau_j) = R(\tau_{-i},\tau_{-j})$; (2) The maximum value at the central point; (3) The similar pattern and periodicity with the surface texture. Figure 4 shows the AACFs from the face milled surfaces shown in figure 2, during chatter development.



(a) stable cutting (b) early chatter (c) heavy chatter

Figure 4 AACFs of the milled surfaces as shown in Figure 2

3 Areal power spectrum density analyses

Power spectrum analysis is widely used to obtain the frequency distribution, and texture spatial distribution of surface topography. A two-dimensional discrete Fourier transformation of an areal surface topography is given by: [5-6]

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$$F(\omega_p, \omega_q) = \sum_{l=0}^{N-1} \sum_{k=0}^{M-1} \eta(x_{k+1}, y_{l+1}) e^{-j2\pi\left(\frac{p}{M}k + \frac{q}{N}l\right)}$$

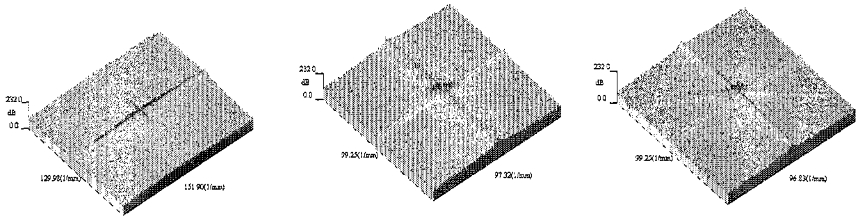
$$p = 0,1,\cdots,M-1; \quad q = 0,1,\cdots,N-1; \quad \omega_p = \frac{p}{\Delta x \cdot M}; \ \omega_q = \frac{q}{\Delta y \cdot N} \tag{3}$$

Its spatial power spectrum density is

$$G(\omega_p, \omega_q) = \frac{F(\omega_p, \omega_q) F^*(\omega_p, \omega_q)}{MN\Delta x \Delta y} \tag{4}$$

where $F^*(\omega_p, \omega_q)$ is the complex conjugate of $F(\omega_p, \omega_q)$.

The APSD has also three properties: (1) the energy in the frequency is concentrated in the centre; (2) for a random isotropic surface, its APSD is also isotropic; (3) for a periodic and directional surface, the main energy of the APSD would be concentrated on the specific frequency of the periodicity and along the same directions. Figure 5 shows the ASPDs from the face milled surfaces during the chatter development (Figure 2).



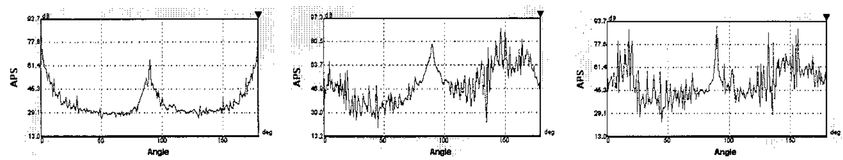
(a) stable cutting *(b) early chatter* *(c) heavy chatter*

Figure 5 APSDs of the milled areal surfaces as shown in Figure 2

Integrating ASPD spectral energy in a number of given angular directions will give an angular spectrum. This can be calculated by:

$$A(\theta) = \int_0^{R(\theta)} G_\theta(\omega_p, \omega_q) dr$$

The most significant feature of angular spectrum is that there is a peak at the direction of the surface distributed periodically. Figure 6 shows the angular spectra from the face milled surfaces during the chatter development (Figure 2).



(a) stable cutting *(b) start chatter* *(c) heavy chatter*

Figure 6 Angle APSDs of the milled areal surface as shown in Figure 2

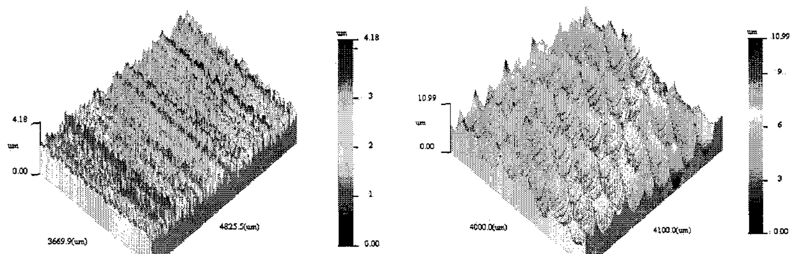
4 Experiments

In order to further verify the above techniques, a series of cutting trials has been carried out. In this case, milled surfaces were generated by using the Cincinnati Arrow2-500. The workpiece material was plain mild steel Steel (EN8). Vibrations in two orthogonal directions X and Y were monitored using piezoelectric accelerometers mounted on the spindle head and the workpiece. Through changing the machining condition (spindle speed, federate, axial cutting depth and radial cutting depth), stable cutting and the development of chatter cutting were generated [7]. Two trials of a series of cutting tests are selected to demonstrate the feasible and applicable assessment techniques.

The first cutting test utilises different cutting spindle speeds and feed rates as shown in Table 1. Figure 7 is measured raw data of cutting trials (cut14 and cut 16) from these conditions. Figure 8-10 are the corresponding AACFs, APSDs and angular spectra.

Table 1 Cutting trail 1

Label	Spindle Speed (rpm)	Feedrate (mm/min)	Axial depth (mm)	Radial depth (mm)	Marked Position (mm)
Cut14	1751	263	5	11	14.5
Cut16	2228	334	15	7	15.25



(a) Cut 14 *(b) Cut 16*

Figure 7 Surface topographies in peripheral milling

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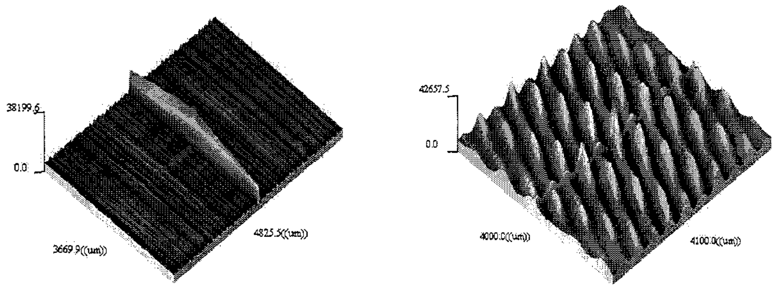
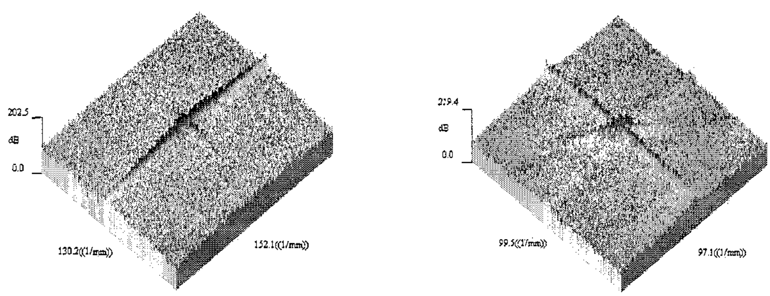


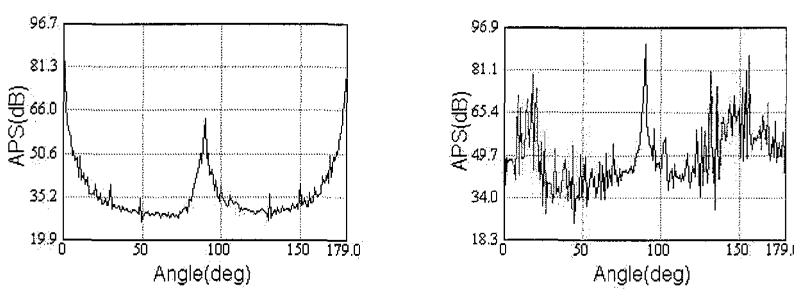
(a) Cut 14 *(b) Cut 16*

Figure 8 AACF of the milled areal surface as shown in Figure 7



(a) Cut 14 *(b) Cut 16*

Figure 9 APSD of the milled areal surface as shown in Figure 7



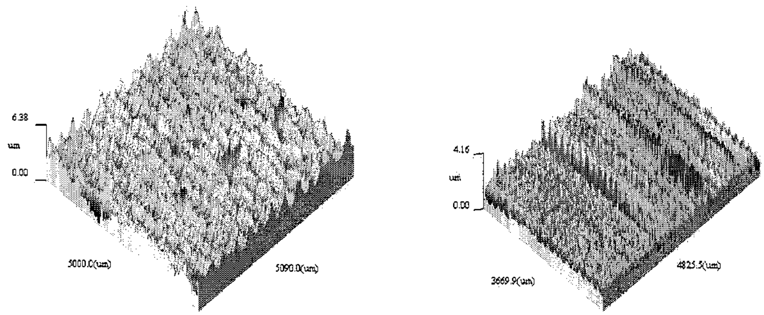
(a) Cut 14 *(b) Cut 16*

Figure 10 Angular Spectra of the milled areal surface as shown in Figure 7

The second cutting trial uses same machine spindle speed with different feed rates as shown in Table 2. Cut30 and Cut37 were selected to demonstrate the analysis results. Figure 11 shows the raw data, and Figure 12-13 the corresponding AACFs, angular spectra.

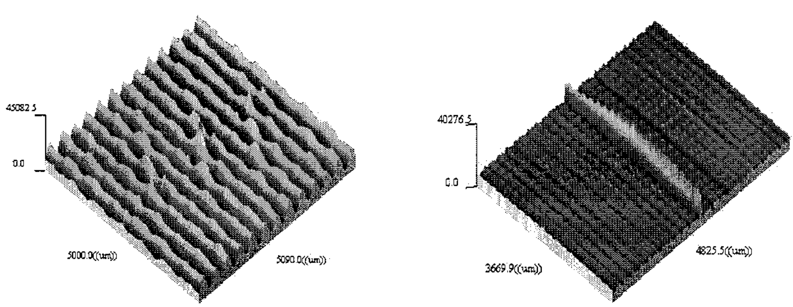
Table 2 Cutting trial 2

Label	Spindle Speed (rpm)	Feedrate (mm/min)	Axial depth (mm)	Radial depth (mm)	Marked Position (mm)
Cut30	1592	764	15	2	
Cut37	1592	287	15	2	



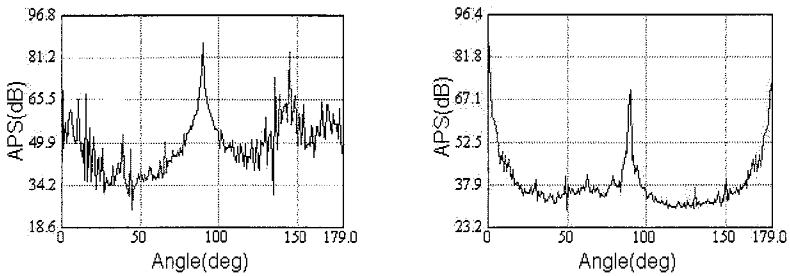
(a) Cut 30 *(d) Cut 37*

Figure 11 Surfaces topographies in peripheral milling



(a) Cut 30 *(d) Cut 37*

Figure 12 APSD of the milled areal surfaces as shown in Figure 11



(a) Cut 30 *(b) Cut 37*

Figure 13 Angle APSD of the milled areal surfaces as shown in Figure 11

5. Discussion

Analysing the measured results shown in the Figure 2, 7 and 11, it is clear that when there is no chatter visible within the topography, the texture distribution of the milling is very regularly and is dominated by the machining feed direction. When chatter occurs, due to fact that the random chatter has been added to the relative movement between the cutting tools and the surface of workpiece, the surface texture is significantly affected by the periodic depth of cut changes and a series of cusps shaped depressions are clearly visible.

This phenomenon is shown more distinctly in the AACF (Figure 4, 8 and 12). With no chatter present, the AACF will have a maximum peak in the centre which attenuates along the dominant texture distribution direction much faster than in the perpendicular direction and it consequently appears as a uniform milled surface distribution. When chatter is present, the AACF "scatters" rapidly from centre to form a multi-peaked distribution indicative of the frequency of the chatter.

When considering the APSD, angular spectrum and radial spectrum analyse for the above data, figure 5-6, 9-10 and 13 show that when there is no chatter, the energy of frequency is concentrated on a spectral line which has the same direction as the texture direction. The angular spectrum yields a peak at the position of the dominant texture direction of machining. When chatter occurs, because of the correspond vibration between the machine tool and the workpiece, the topography on the surface is composed of the changing cutter movement producing changing cutting depth. This is reflected on the APSD in such a manner so that the energy of the spectral line that reflects the main cutting direction is relatively weakened and new spectral "line" which reflects the direction of chatter development. In the angular spectrum, besides the main peak, which reflects the main machining direction, new signal peaks appear which illustrate the direction of chatter present and the whole angular spectrum become "rough".

It can be clearly seen that in the first cutting trial, cut14 is the result of stable cutting and cut16 results from the presence of chatter. In the second trial, cut37 is stable cutting and cut30 represents the presence of chatter.

6. Conclusions

From the experimental demonstration, conclusions be drawn as follows: When chatter occurs, (1) the AACF will scatter from the centre to give a multi peak appearance whose spacing reflects the chatter signal frequency, (2) APSD will show new significant spectrum lines which illustrate the energy and the direction of chatter, (3) new peaks which reflect the direction of chatter will appear in the angular spectrum.

Overall it is clear that, the areal spectra of 3D surface topographies show significant changes in information in the presence of chatter and it is this information change that can form the basis for controlling the machine tool to avoid the development of chatter.

The future work will focus on identifying a target function within the machine tool control parameters which can eliminate chatter. Following this identification an effective algorithm to predict the chatter and adjust the machine performance will be developed.

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