THE EFFECT OF TOOL WEAR ON THE WAVELENGTH STRUCTURE OF A TURNED SURFACE PROFILE

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ABSTRACT
An investigation into the effect of tool wear on a turned surface profile is presented. Vibration and surface generation models of the turning process are introduced and studied to predict the change of wavelength structure of the surface profile due to increased process damping. Experimentally obtained profiles under varying tool wear levels are characterized by a wavelength decomposition methodology. The behavior of the experimental profile wavelength structures as a function of wear is observed to match that predicted by the models. It is shown that the model predicted effect of process damping and the experimentally obtained effect of tool wear on the wavelength structure of a surface profile are similar.

INTRODUCTION
Surface texture is an important feature in determining the quality of a machined product. Many metrics have been proposed, and much research has been performed to succinctly quantify or characterize surfaces. Wavelength decomposition has been applied to surface profiles since it uniquely characterizes the profile and provides a better understanding of the surface pattern (O’Connor and Spedding, 1992, Pandit and Shumugam, 1992). For a turning operation, the surface texture embeds the history of the process that was used to form the part. Recently, Moon and Sutherland (1993) have shown that the wavelength structure of a surface profile provides a link between the turning process mechanics and the resulting surface pattern.

Tool wear is generated by the interaction of the chip and cutting tool during a machining process, and tool wear has a significant effect on the surface texture of a workpiece. Work in the area of tool wear life has focused on relating tool life to the cutting conditions. Recent efforts have monitored tool wear during machining operations by utilizing a variety of sensors including light (Lister and Barrow, 1986), laser (Gomayel and Bregger, 1986), cutting force (Mackinnon, et al., 1986), and acoustic emission (Liang and Dornfeld, 1989). Research has also been performed to determine the optimal control actions for machining processes through sensor integration, for which tool wear estimation plays an essential role. For example, Rangwala and Dornfeld (1990) produced an estimate of tool wear using an acoustic emission and force sensor system. The tool wear estimate was utilized to produce control actions for a machining process.

The purpose of this paper is to understand how process damping and tool wear change the wavelength structure or spatial frequency content of a turned surface profile. For this purpose, a vibration model is introduced and utilized to investigate the effect of process dynamics on turned surfaces. The model is then applied to understand how the behavior of the wavelength components within the surface profile are affected by changes in the cutting dynamics due to process damping. In addition, a surface generation model is developed and used to predict changes in the surface profile and its wavelength structure due to process damping. Finally, experimentally collected surface profiles produced with worn tools are studied to identify how the profile wavelength structure is impacted by tool wear. The experimental data are then compared with the model predicted results.

VIBRATION MODEL FOR A TURNING PROCESS
The dynamic behavior of a machining process is very complex, and for this work a simplified model of the process has been used. Figure 1 shows a single degree of freedom model which consists of a mass, spring, and a damper.

Figure 1: TOP VIEW OF THE TURNING PROCESS

Based on the system structure and radial force $F_s(t)$, the equation of motion for the system is:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F_s(t)$$  \hspace{1cm} (1)

where, $m$, $k$, and $c$ are the mass, stiffness, and damping coefficient, respectively.

It is known that the radial cutting force is, in part, a function of the chip load and tool flank interference force (Montgomery and Alintas, 1991, and Endres, 1992). Because of the nature of the process, material left uncut during one workpiece revolution will increase the material to be removed during subsequent revolutions. The dependence of the chip load on both present and past displacements suggests that the radial force may be represented as (Merritt, 1965):

$$F_s(t) = K_s f[d_0 - x(t) + x(t-t_r)]$$  \hspace{1cm} (2)

where, $x(t)$ is the radial displacement at time $t$, $x(t-t_r)$ is the radial...
displacement at time \( t \), \( t \) is the time required for one revolution of the workpiece, the nominal depth of cut for the turning operation is \( d_p \), the feed, the distance moved by the tool in one revolution of the workpiece, is \( f \), and the coefficient \( K_a \) relates the chip load to the force.

Tool wear changes the shape of the tool, and the cutting dynamics are also affected by changes in the tool shape. Based on geometrical considerations, tool flank wear will increase the flank interference effect and thus the amount of process damping (Morgan and Alintas, 1991 and Endres, 1992). Since the flank interference effect is difficult to model simply, a viscous damping term has been added to the left side of Eq. (1). The effect of increased flank wear may be modeled by increasing the amount of process damping, i.e., the damping coefficient \( c \). If such an assumption is appropriate, increasing tool wear and increasing levels for damping should produce similar changes in the surface texture.

Considering Eqs. (1) and (2), and taking the Laplace transform with zero initial conditions, Eq. (3) is obtained:

\[
X(s) = \left[ s^2 m + cs + k + Kf - Kfe^{-st} \right] = R(s)
\]

where, \( R(s) = L[Kfd_p] \) is the forcing function without displacement feedback (open loop forcing function) in the frequency domain and \( X(s) \) is the radial displacement in the frequency domain. The terms inside the brackets on the left side of Eq. (3) when set equal to zero give the characteristic equation of the system. Owing to the presence of the term, \( e^{-st} \), there are an infinite number of roots to the characteristic equation

\[
P(s) = s^2 m + cs + Kf = 0
\]

The spectral density function for the radial displacement is then:

\[
S_X(\omega) = \left| S_R(\omega) P^{-1}(\omega) \right|^2
\]

where, \( S_R(\omega) \) is the spectral density function of the force in the absence of displacement. Assuming \( S_R(\omega) \) to be a constant (i.e., a white noise open loop forcing function), the shape of the spectrum, \( S_X(\omega) \), depends entirely on the shape of \( P^{-1}(\omega)^2 \). This behavior is displayed in Fig. 2 for \( m = 2 \text{ kg}, c = 1000 \text{ N/m}, k = 10000 \text{ kN/m}, K_a = 1.5 \text{ GPa}, f = 0.21 \text{ mm/s}, d_p = 2 \text{ mm}, \) and \( \tau = 0.2 \text{ s} \). From the figure it can be noted that most of the variation in the radial displacement data is due to frequencies near 350 Hz.

As has been described, the effect of increased tool wear may be characterized by increasing the value for \( c \) in Eq. (1). Increasing \( c \) changes the spectral density function for the radial displacement. The effect of \( c \) on the spectral density function is illustrated in Fig. 2. From the figure, it is apparent that the relative contribution of frequencies near 350 Hz to the total variation in the data is reduced as \( c \) is increased. In other words, the relative contribution of the other frequencies to the total variation is increased.

\[
\text{Figure 2: SPECTRAL DENSITY FUNCTIONS FOR RADIAL DISPLACEMENT}
\]

Usually, surface profiles are collected along the axis of the workpiece rather than in the radial direction. Moon and Sutherland (1993) suggest that profile generation can be viewed as a sampling process, where once every revolution, the radial displacement is "captured" and used to position the feed groove within the profile. Under the sampling process analogy, the sampling frequency of the radial displacement signal will be \( 1/\tau \) and the Nyquist frequency, \( f_{Nyq} \), will be \( 1/(2\tau) \). Therefore, the frequencies within the radial displacement spectrum will be aliased. Aliasing superimposes the contribution of frequencies beyond the Nyquist frequency by folding about 0 and \( f_{Nyq} \), until the frequency lies between 0 and \( f_{Nyq} \). Figure 3 shows the spectra of the sampled data from Fig. 2, i.e., the displacement along the workpiece axis (one point per revolution). It may be noted that Moon and Sutherland (1993) showed that the frequencies within the sampled radial displacement signal manifest themselves as low spatial frequencies (long wavelengths) within a profile.

Examining Fig. 3 it is readily apparent that the spectra for the sampled displacements along the workpiece axis are much different than the circumferential radial displacement spectra (Fig. 2). Although the overall magnitudes of the spectra are comparable, the shapes are much different. Also evident from the figure is the fact that many of the folded frequencies lie close together. Note that the spectral information presented has been converted from the time to the space domain.

Comparing the three spectra in Fig. 3 a very similar phenomenon to that of Fig. 2 is observed. In the first spectrum (c=1000) several strong frequencies in the data are observed, however, their relative strengths diminish as \( c \) is increased. Given the behavior of the displacement spectra as a function of \( c \), it may be reasoned that the spectra of surface profiles will have a similar behavior as a tool wears. In other words, it is suspected that as the tool wear increases, the power spectrum of the surface profile will become flatter at low spatial frequencies.
SURFACE GENERATION MODEL

The profile along the axis of the workpiece is formed in part by the tool geometry generating one feed groove for each rotation of the workpiece and the displacement of the tool relative to the workpiece. Figure 4 shows a block diagram illustrating how the tool motion and tool tip geometry is imparted to the surface profile.

![Figure 4: BLOCK DIAGRAM OF SURFACE GENERATION MODEL](image)

The simulated motion of the cutting tool with respect to the workpiece as a function of the time is displayed in Fig. 5 for two levels of damping, and the power spectra for the simulated circumferential displacement profiles are shown in Fig. 6. The circumferential displacements, when sampled once per revolution to generate the surface, will impact the vertical position of the feed grooves. It is evident from Fig. 5 that the amplitude of tool vibration shown in the second graph (\(\omega=3000\)) is smaller than that of the first graph (\(\omega=1000\)). It appears that increased damping (greater tool wear) will reduce the magnitude of vertical fluctuation in the feed grooves. In examining Fig. 6 it is evident that the simulated radial displacement spectra match the analytical results shown in Fig. 2. However, some differences between Figs. (2) and (6) exist. The slight differences may be due to the random number streams (stochastic input) used for the simulation.

![Figure 5: SIMULATED CUTTING TOOL MOTIONS](image)

The simulated surface profiles based on the tool geometry, process kinematics, and cutting tool displacements (from Fig. 5) are displayed in Fig. 7. It is seen that the fluctuation of the feed grooves is in fact reduced by increased damping. Figure 8 gives the power spectra associated with the surface profiles of Fig. 7. Since the feed used for the simulation tests was 0.21 mm, the spike in the spatial frequency spectrum at 4.76 mm\(^{-1}\) (1/0.21 = 4.76) is expected. The frequency spectra of Fig. 8 are relatively free of frequencies between 4.76 mm\(^{-1}\) (feed frequency) and 2.38 mm\(^{-1}\) (the spatial frequency corresponding to \(f_{\text{wpp}}\)). From Fig. 8 it is apparent that there are a number of strong frequencies less than 2.38 mm\(^{-1}\). These frequencies are due to the process dynamics described previously. Figure 8 shows that the power associated with the feed frequency increases as the damping increases. This effect is due to the previously described effect of damping on the displacement signal. Finally, from Fig. 8, it is evident that due to the damping increase, a shift in power from low frequencies (due to process dynamics) to feed frequency occurs. The experimental work in the next section examines the effect of tool wear on the spatial frequency content of the surface profiles.

![Figure 6: POWER SPECTRA FOR SIMULATED RADIAL DISPLACEMENT DATA](image)

![Figure 7: SIMULATED SURFACE PROFILES](image)
EXPERIMENTAL WORK

A number of turning tests were carried out to generate actual surface profiles under varying levels of tool wear. A large workpiece (approximately 120 mm in diameter and 1000 mm in length) of 4140 steel was used to generate varying amounts of flank wear on different cutting tools. Each tool was then used to machine a small cylindrical workpiece using the conditions of Table 1. The surface generated on the small workpiece was then measured with a profilometer. A Monarch lathe was used to perform all the turning operations.

Table 1: CONDITIONS FOR A TURNING EXPERIMENT

<table>
<thead>
<tr>
<th>Work material</th>
<th>1020 steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work diameter, length</td>
<td>50 mm, 126 mm</td>
</tr>
<tr>
<td>Carbide Insert Type</td>
<td>SPG422-C2</td>
</tr>
<tr>
<td>Nose radius</td>
<td>0.80 mm</td>
</tr>
<tr>
<td>Spindle speed</td>
<td>RPM</td>
</tr>
<tr>
<td>Feed</td>
<td>0.21 mm/rev</td>
</tr>
<tr>
<td>Depth of cut</td>
<td>2.00 mm</td>
</tr>
</tbody>
</table>

The surface profiles generated on the small workpieces were collected by measuring along their longitudinal axis. Figure 9 displays three experimentally collected surface profiles generated by cutting tools with different amounts of wear: 0 mm, 0.05 mm, 0.127 mm (cumulative machining times of 0, 2, and 4 minutes). From the figures it is apparent that the profile height variation is mainly due to the feed groove geometry, and the vertical fluctuation of the feed grooves. The profile height variation is seen to decrease as the amount of wear is increased. This same behavior was exhibited previously as the process damping was increased.

To assist in the analysis and interpretation of the profiles of Fig. 9, the spatial frequencies or wavelengths for the profiles were determined. The power spectrum (obtained from a numerical Fourier transform) of the profiles of Fig. 9 are displayed in Fig. 10. From the figure it is evident that most of the variation in the surface profiles is due to a spatial frequency associated with the feed, 4.76 mm⁻¹ (a wavelength of 0.21 mm), and a number of frequencies less than 2.38 mm⁻¹ (0.42 mm). In case of the data from the fresh tool test (0 min. of cutting), the feed frequency and its harmonics account for about 2% of the total variation in the data. The fraction of the variation described by the feed frequency is seen to increase as the tool wears (compare 0 min. of cutting to 2 and 4 min. of cutting). The contribution of the low frequencies (less than 2.38 mm⁻¹) to the variation in the data is decreased as the tool wears. A shift in the power from the low frequencies to the feed frequency occurs as the tool wears; this same behavior was seen previously as the level of damping was increased. In summary, it may be concluded that damping and tool wear have similar effects on the wavelength structure of the surface profile.

CONCLUSIONS

An investigation of the wavelength structure of turned surface profiles has been presented. This study has examined the effects of both process damping and tool wear. To investigate the effects of process damping on the surface profile, vibration and surface generation models for the turning process were developed. Physical machining experiments were conducted under varying tool wear levels, and the surface profiles produced under these varying conditions were obtained. The experimentally collected profiles and associated wavelength structures were compared to the model predictions under different levels of process damping. The comparisons showed that model predicted behavior of the surface profile spatial frequency structure as the damping is increased corresponds quite well with the behavior of experimentally obtained spatial frequency structures generated as the tool wear is increased.

The results of this investigation into the effects of process damping and tool wear on turned surface profiles may be summarized as follows:

- As expected, increased levels of process damping tend to flatten the spectra associated with the radial displacement and the sampled radial displacement signals.
- Increasing the level of process damping reduces the magnitude of the radial tool displacement relative to the workpiece, and therefore decreases the variation within the surface profile heights.
- Increased process damping shifts the spatial frequency content of a surface profile away from low frequencies to the feed frequency.
- Like the simulated effect of increased process damping, increasing the level of tool wear causes two changes in the surface profile spatial frequency spectrum. First, for low spatial frequencies, the spectrum is flattened. Secondly, there is also a shift in power from low spatial frequencies to the feed frequency.

Note that the results described above may be applied to only the early stages of tool wear. A new vibration and surface generation model may be needed to explain the surface texture generated by a seriously worn cutting tool.

The paper has explored a link between the dynamics of a machining process and the surface texture generated by the process. It has been seen that process dynamics can detrimentally impact the surface texture through powerful, long wavelength signals. Tool wear has been observed to produce effects similar to that of process damping with regard to surface texture.

Finally, although a wide variety of techniques have been developed for tool wear monitoring over the years, only a few have been applied successfully outside of laboratory environments. Although not an objective of this study, the findings of this paper suggest that through monitoring of the frequency content of the radial displacement signal, knowledge relating to both the tool wear and surface texture may be inferred. Additional research is required, however, before this technique can be used in the on-line estimation of tool wear in the turning process.

REFERENCES


Figure 10: POWER SPECTRA FOR EXPERIMENTALLY OBTAINED PROFILES

Figure 9: EXPERIMENTALLY OBTAINED SURFACE PROFILES