Comprehensive Tool Wear Estimation in Finish-Machining via Multivariate Time-Series Analysis of 3-D Cutting Forces

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SUMMARY

In finish-machining, geometric accuracy and surface quality are adversely affected by the tool wear at the minor flank and nose area. This paper describes an investigation into a comprehensive tool wear estimation, including flank-, crater-, minor flank-, and nose-wear, based on an analysis of dynamic cutting force in oblique machining. The force, measured in terms of its three orthogonal components, was used to develop trivariate Autoregressive Moving Average Vector (ARMAX) time series models, based on these, dispersion analysis (DA) was used to determine the rate of various types of wear. The results show that minor flank wear reaches a critical value first in finish-machining, so that optimum cutting conditions or an appropriate tool change strategy must be determined on the basis of minor flank wear. The results also show that the method is a feasible means for on-line tool wear monitoring in finish-machining.

KEY WORDS: Multivariate Time-Series, Tool Wear, Dispersion Analysis, Finish-Machining, Minor Flank Wear, Nose Wear.

1. INTRODUCTION

The necessity of effective tool wear estimation in real-time has been recognized in recent years, but efficient tool change policies, tool life and cost savings, and the productivity of the finished product. It is obviously desirable for these wear states to be reached critical points earlier than those in the flank and crater, such that the optimum cutting conditions or tool change policy have to be set based on these wear types. Therefore, a more comprehensive monitoring strategy involving multi-sensor or multi-modeling is called for.

Employing multi-sensor or multi-modeling strategies has been identified in a recent survey conducted for CIRP [17] as one of the three promising directions in machining process monitoring and control research. Interesting work has been reported in integrating force and acoustic emission (AE) signals via neural networks [14]. Chrysoulouris [2] evaluated the effectiveness of sensor integration for tool wear estimation by neural network, least-squares regression, and the group method of data handling (GMDH) algorithm using simulation data. Both papers reported better estimation of flank wear by integrating multi-sensor information than by using a single sensor. For finish-machining where more than one quantity is to be estimated, however, a multi-sensor and multi-modeling strategy as suggested in [17] becomes necessary.

The "comprehensive" monitoring strategy has been addressed less frequently, perhaps because of the complexity of the machining process. If more than one quantity is to be estimated, more complexity will be encountered. This places higher demands on signal pre-processing and analysis techniques which shall be able to "single out" from the signals particular ingredients sensitive to particular quantities to be estimated. Otherwise, multi-sensor techniques will do more harm than help. The spectrum analysis is a technique commonly used to single out frequency components to be correlated to tool wear [3,8,15]. Time domain methods, such as examining autocorrelation coefficients of cutting force signals have been reported [19]. It, however, has been recognized that the cutting process is a stochastic process due to the existence of inevitable material property variations and other uncertainties. The necessity of employing stochastic analysis for cutting dynamics was emphasized in [6]. Interesting work on correlating coefficients of Autoregressive Moving Average Vector (ARMAX) models [11] were developed. The dispersion analysis (DA) based on the ARMAX models [4,5] led to the discrimination between various modes of force variations in a quantitative way, such that correlating them to various quantities to be estimated was made possible. The correlation results were supported by physical interpretations.

2. TRIVARIATE ARMAX TIME SERIES MODELS FOR TOOL WEAR ESTIMATION

It is known that the dynamic cutting force, which is the variation from the average cutting force, contains richer information about tool/workpiece interactions during machining than the latter alone [17]. It has been shown that the dynamic cutting force is a stochastic signal which roughly obeys the normal distribution [18]. It is also appropriate to regard the dynamic force as stationary processes at different stages of wear. In this way, it can be set only a fraction of a second for a set of a few hundred data points to be sampled each time. In summary, it is appropriate to apply statistical methods for stationary normal processes to the dynamic cutting force signal. As a way of analyzing the dynamics in cutting force measurements, trivariate time series models, developed from the data, are used, since they give a concise parametric representation of the signals.

When a dynamic cutting force represented by its three orthogonal components is sampled at uniform intervals, the resulting discrete series of observation vectors, receive the following natural representation:

\[ X_i = \sum_{j=1}^{p} a_j X_{i-j} + \sum_{j=1}^{q} b_j a_{i-j} \]

where the 3-dimensional vector of process variables is given by \( X_i = [X_{i1}, X_{i2}, X_{i3}]^T \), \( a_j = [a_{i1}, a_{i2}, a_{i3}]^T \), and \( E[a_{i1}, a_{i2}, a_{i3}] = \bar{a}_j \), \( \bar{a}_j \) is the Kronecker delta function, \( \sigma_i \) the covariance of \( a_i \).

The model in Eq.1 is termed as an Autoregressive Moving Average Vector model of autoregressive order \( p \) and moving average order \( q \) denoted by ARMAX\( p,q,m \)\( \phi \)\( \theta \).

A model of the form of Eq.1 is evaluated the effectiveness of sensor integration for tool wear estimation by neural network, least-squares regression, and the group method of data handling (GMDH) algorithm using simulation data. Both papers reported better estimation of flank wear by integrating multi-sensor information than by using a single sensor.

The residual analysis has been proven to be very effective to detect abrupt changes in the cutting process. 

\[ \Phi_{1} = \begin{bmatrix} \Phi_{1} & \Phi_{2} & \cdots & \Phi_{q} \\ I & 0 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & \cdots & 0 \end{bmatrix} \]

where \( A \) is a matrix of eigenvalues and \( T \) the eigenvectors. It can be shown [11] that the correlation matrix of the measured variables is a weighted linear combination of the eigenvalues, \( \lambda_i = 1, 2, \ldots, 3n \), as follows:

\[ Y_i = E[X_i] = \Phi_{1} \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_q \end{bmatrix} = \Phi_{1} \begin{bmatrix} \lambda_{1} \lambda_{2} \cdots \lambda_{q} \end{bmatrix} \]

where \( df \) is the dispersion associated with eigenvalue \( \lambda_i \) and given by

\[ df = \sum_{j=1}^{q} d_j \]

and \( \lambda_i \) the products of submatrices of \( T \) and \( T^\dagger \).

The significance of Eq.4 lies in the fact that the process variation \( \gamma_0 \) is decomposed into contributions of process eigenvalues in terms of dispersion \( d_i \) quantitatively. Of particular interest is the \( d_i \) associated with eigenvalues occurring in complex conjugate pairs which contribute to the oscillating or periodic variation of the process. The frequency corresponding to a pair of complex conjugate eigenvalues is given by

\[ f_i = \frac{1}{2\pi} \tan^{-1} \left( \frac{\Im(\lambda_i)}{\Re(\lambda_i)} \right) \]

where \( \Delta \) is the sample interval in seconds. By decomposing the process variation \( \gamma_0 \) into dispersion \( d_i \) which correspond to eigenvalues and ultimately correspond to frequencies, an order of merit of the existing frequencies (oscillating modes)
can be established such that analysis and interpretation in terms of physical phenomena, such as natural frequencies of the tool/tool holder system and machine tool structural frequencies can be carried out in a quantitative manner.

3. EXPERIMENTS AND TOOL WEAR MEASUREMENTS

3.1 Description of Experiments

The tool wear experiments were carried out using a dynamometer (KISTLER 9297A). Table 1 gives the machining conditions used in the experiments.

<table>
<thead>
<tr>
<th>Machine Tool</th>
<th>Tool Insert Type</th>
<th>Tool Geometry</th>
<th>Work Material</th>
<th>Workpiece Dimension</th>
<th>Cutting Conditions</th>
<th>Cutting Fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colchester Mascot (600 9.3 kW)</td>
<td>TNMA160408R (Carbide)</td>
<td>Rake Angle 6°, Inclination Angle 6°, Relief Angle 5°, Cutting Edge Angle 6°</td>
<td>A414HT20 (THIN-35 320)</td>
<td>Length = 197mm and Diameter = 10mm</td>
<td>Group 1: V=145m/min f=0.01mm/rev d=0.5mm</td>
<td>No</td>
</tr>
</tbody>
</table>

To assure the experimental conditions being as close as possible to practical machining operations, the machining process was interrupted periodically with an increment in period of about 5 minutes under cutting condition Group 1 and 2.5 minutes under Groups 2 and 3. The tool was replaced by a fresh one at each interruption such that only one tool remained in thermal continuity until it was replaced. Just before each tool replacement, a set of data points was sampled for each channel and a typical record is shown in Fig.1. Therefore, the experimental results consist of 8 tools and 8 sets of data from each channel under Groups 1 and 7 tools and 7 sets of data from each channel under Groups 2 and 3.

Before the dynamic cutting force in terms of its three orthogonal components were sampled into a multi-channel data acquisition system with a sample interval equal to 60 μs (about 16.7 KHz), low-pass filters with a cut-off frequency of 4 kHz were applied, considering the 4 kHz-natural frequency of the dynamometer.

3.2 Definition of Comprehensive Tool Wear Parameters and Their Measurement

Eight parameters were selected to describe the tool wear states as shown in Fig.2, primarily in accordance with CIRP tool wear terminology [13]. The eight tool wear parameters are roughly classified into three categories with respect to different tool faces, i.e., the major flank area (VB, KS & VG), crater area (KT, KB & KK) and minor flank area (VB' & N). Table 2 gives the measurement results for Group 1 by microscopy, and the tool wear developments for all three cutting conditions are plotted in Figs. 3 and 4.

### Table 1 Machining Conditions Used in Tool Wear Experiments

<table>
<thead>
<tr>
<th>Machine Tool</th>
<th>Tool Insert Type</th>
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<td>Group 1: V=145m/min f=0.01mm/rev d=0.5mm</td>
<td>No</td>
</tr>
</tbody>
</table>

### Table 2 Tool Wear Measurements Results for Cutting Condition Group 1

<table>
<thead>
<tr>
<th>Time (minutes)</th>
<th>VB (mm)</th>
<th>KB (μm)</th>
<th>KK (μm)</th>
<th>VG (μm)</th>
<th>KT (μm)</th>
<th>KB'KK (mm²)</th>
<th>N (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0.12</td>
<td>1.3</td>
<td>0.4</td>
<td>1.1</td>
<td>0.6</td>
<td>1.5</td>
<td>0.15</td>
</tr>
<tr>
<td>10</td>
<td>0.28</td>
<td>3.5</td>
<td>0.7</td>
<td>3.2</td>
<td>1.5</td>
<td>3.3</td>
<td>0.25</td>
</tr>
<tr>
<td>15</td>
<td>0.34</td>
<td>4.5</td>
<td>0.8</td>
<td>4.5</td>
<td>2.5</td>
<td>4.5</td>
<td>0.3</td>
</tr>
<tr>
<td>20</td>
<td>0.38</td>
<td>5.5</td>
<td>1.0</td>
<td>5.6</td>
<td>3.5</td>
<td>6.5</td>
<td>0.35</td>
</tr>
<tr>
<td>25</td>
<td>0.64</td>
<td>8.5</td>
<td>1.3</td>
<td>8.6</td>
<td>4.5</td>
<td>9.5</td>
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<tr>
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<td>0.73</td>
<td>10.5</td>
<td>1.5</td>
<td>10.6</td>
<td>5.5</td>
<td>12.5</td>
<td>0.45</td>
</tr>
<tr>
<td>35</td>
<td>0.82</td>
<td>12.5</td>
<td>1.8</td>
<td>12.6</td>
<td>6.5</td>
<td>15.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

### Fig. 1 Dynamic Cutting Force Measured in Terms of Its Three Orthogonal Components

(a) Major Flank Area

(b) Crater Area

(c) Minor Flank Area

### Fig. 2 Definition of Comprehensive Tool Wear Parameters

VB: major flank wear

KS: crater width on the face

KB: crater length on the rake face

VG: length of the groove (notch)

KB': crater width on the rake face

KK: crater length on the rake face

N: minor flank wear

### Fig. 3 Comprehensive Tool Wear Results for Cutting Condition Group 1

(V=115m/min, f=0.01mm/rev, d=0.5mm)
4.2. Analysis Associated with Physical Interpretation

Feed Direction: For an oblique turning operation of a bar, it is known that the feed force $F_f$ is primarily associated with the normal force acting on the major flank $F_n$, and the horizontal friction force acting on the minor flank $F_{ph}$ (Fig. 7). Therefore, the tool/workpiece interactions on both flanks should be reflected in the dynamic feed force characteristics.

By examining the trend of LF dispersions of 500-550 Hz shown in Fig. 5(a), it is found that the percentage values decrease to a minimum between 10 to 15 minutes (major flank $VB = 0.35$ mm), after which they increase. It is well known from experience that cutting tools are replaced or changed when the major flank wear reaches the critical values of 0.25-0.38 mm. Beyond this critical wear, the rate of wear increases very rapidly, below it the rate first decreases and then becomes constant. Thus, the behaviour of the LF dispersions isolated from the dynamic feed force is very similar to the well-known rate of major flank wear curves and could be used as a good indicator for major flank wear.

By comparing the HF dispersion curve of 3.4-3.5 KHz shown in Fig. 5(a) with the minor flank wear, $VB$ curve shown in Fig. 3(c), it is again found the former resembles the slope (rate) of the latter. The acceleration of $VB$ at about 10 minutes could be detected by the maximum value of the HF dispersions.

Thrust Direction: The dynamic thrust force $F_t$ mainly reflects the tool/workpiece interactions on both the rake face and the minor flank. The small depth of cut used in finish-machining produces a large chip flow angle such that the rake face

Table 3 Dominant Dispersions (%) for Group 1

<table>
<thead>
<tr>
<th>Feed Force $F_f$</th>
<th>Thrust Force $F_t$</th>
<th>Main Cutting Force $F_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$LF = (500-550)$ Hz</td>
<td>$HF = (3.4-3.5)$ KHz</td>
<td>$LF = (650-750)$ Hz</td>
</tr>
<tr>
<td>Time (min)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>98.28</td>
<td>1.35</td>
</tr>
<tr>
<td>5</td>
<td>89.37</td>
<td>7.28</td>
</tr>
<tr>
<td>10</td>
<td>72.77</td>
<td>16.79</td>
</tr>
<tr>
<td>15</td>
<td>63.96</td>
<td>38.25</td>
</tr>
<tr>
<td>20</td>
<td>51.14</td>
<td>51.86</td>
</tr>
<tr>
<td>25</td>
<td>42.90</td>
<td>9.21</td>
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<tr>
<td>30</td>
<td>37.74</td>
<td>8.80</td>
</tr>
<tr>
<td>35</td>
<td>60.00</td>
<td>20.83</td>
</tr>
</tbody>
</table>

4.2 Group 3

Group 2

Fig. 5 Dispersion Diagram for Cutting Condition Group 3

(a) LF=400-500Hz, HF=3.3KHz
(b) LF=450-550Hz, HF=3.3-3.5KHz
(c) LF=500-550Hz, HF=3.4-3.5KHz
(d) LF=650-750Hz, HF=3.3-3.5KHz
(e) LF=900-1050Hz, HF=2.6-2.8KHz
friction force $F_y$ is almost along the y direction. The normal force acting on the minor flank $F_{pn}$ is also associated with $F_y$. In a similar manner, the HF dispersions of 3.3-3.5 kHz shown in Fig. 3(c) can be related to the rate of crater wear $\Gamma_T$ shown in Fig. 3(b), and the LF dispersions of 650-750 Hz shown in Fig. 5(c) related to the rate of the minor flank wear $V_B$ shown in Fig. 3(c). Therefore, they can be used for minor flank and crater wear monitoring purposes.

**Cutting Direction:** The dynamic cutting force $F_y$ is primarily associated with the normal force acting on the major flank $F_{pn}$, the vertical friction force on the minor flank $F_{rv}$. By examining the LF and HF dispersions of 950-1050 Hz and 2.6-2.8 kHz shown in Fig. 3(c), it was found that they reflect the rate of the rake wear and the minor flank wear shown in Figs 3(b) and 3(c), respectively.

As summarized in Table 4, the trends of the LF dispersions isolated from all three components of the dynamic cutting force reflect the wear rate mechanism associated with normal forces, and the HF dispersions reflect the wear rate mechanism associated with tangential (friction) forces. Similar results were obtained for experiments under cutting condition Groups 2 and 3 as shown in Figs. 4 and 6.

**5. DISCUSSION**

### 5.1 Critical Tool Wear in Finish-Machining and Sensing Strategy

It is clear from the above results that the HF dispersion of $F_y$, the LF dispersion of $F_{pn}$, and the HF dispersion of $F_{rv}$ can all be used as indicators of the rate of minor flank wear $V_B$. They all reached a maximum value when $V_B$ accelerated at about 10 minutes under cutting condition Group 1. Among them, the most sensitive one is the HF dispersion of $F_y$. The horizontal friction force on the minor flank $F_{rv}$, which has been shown to be associated with the HF dispersion of $F_y$, is more a static than a dynamic one, because of the slow feed motion. The LF dispersion of $F_{pn}$ is also relatively less sensitive due to the fact that there is no feeding motion in the thrust direction. Therefore, HF dispersion of $F_{rv}$ can be used as the main indicator of the minor flank wear $V_B$, and the other two as auxiliary ones. When one or more of them reaches the maximum, the accelerated minor flank wear is indicated.

In comparison to major flank and crater wear, both of which did not reach their critical points until after about 15 minutes under cutting condition Group 1, it becomes obvious that for operations such as a finish-turning of a bar, the adaptive control and effective tool change policy has to be set based on the wear states of the minor flank area, to assure geometric accuracy and surface quality of the finished workpiece.

### 5.2 Structural Dynamics and Idle Disturbances

Clear patterns linking the force variations in terms of dispersions and associated frequencies, isolated from dynamic cutting force, to the various wear development rates have been identified. However, the physical nature of the relationship of wear and is the purpose of this section to identify physical origins of these relationships and interpret accordingly.

Since almost the same HF's appear in all three groups, these frequencies are then inherent in the tool holder and hence may be conjectured to relate to its natural frequencies. Tests revealed that the natural frequencies of the tool holder/dynamometer system were 3320 Hz in the x-, 3310 Hz in the y-, and 2647 Hz in the z-directions, respectively. These values match reasonably well with the HF's isolated from the dynamic cutting force (Figs. 3 and 4).

Tests on dynamometer frequency response to idle speed excitation alone revealed idle frequencies of 573 Hz for x, 715 Hz for y, and 975 Hz for z under cutting condition Group 1. These frequencies are reasonably close to the LF's listed in Table 3. From the above tests, it becomes clear that tool/workpiece interaction at the LF's are related to the idle frequencies, and the HF's are mainly associated with the natural frequencies of the tool-holder/dynamometer system.

**6. CONCLUSIONS**

1. Dispersion analysis based on trivariate ARMAV time series models was used to quantitatively decompose the dynamic cutting force in terms of dispersions (relative importance of modes of force variation) and associated frequencies. The merit of the method is its ability to isolate from the dynamic cutting force the ingredients, each of which is particularly sensitive to a particular wear state, thereby providing much more comprehensive yet sensitive estimates than those possible by using the force signal in a lump-sum manner.

2. The patterns of change of the dispersions resemble the rate of various wear parameters and the resemblance is physically interpreted. The rapidly increasing rate of the minor flank wear occurring before the accelerating stage of the major flank wear is due to the fact that the gradually increasing major flank wear, and retreat of the cutting edge, sharpens the nose and puts more burden on the minor flank and edge, to a point where drastic minor flank wear is inevitable. Therefore, for operations such as a finish-turning of a bar, optimum cutting conditions or effective tool change strategy have to be determined based on the minor flank wear instead of others, to assure geometric accuracy and surface quality of the finished workpiece.

3. It was the purpose of this investigation to establish relationships between the off-line measurements of wear and dispersions of dynamic force measurements, such that the latter alone will be capable of predicting wear on-line. For machining processes at normal speeds, the algorithm introduced above is sufficiently fast to determine wear states in real time. For processes with a higher speed, the algorithm could be readily reformulated into a recursive one such that faster wear developments can be traced.

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**REFERENCES**


