Vibration signal analysis for monitoring tool wear in high speed turning of Ti-6Al-4V

P Srinivasa Pai* & Grynal D’Mello
Department of Mechanical Engineering, NMAM Institute of Technology, Nitte 574 110, India

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Vibration signals from metal cutting processes have been investigated for various purposes, including in-process tool wear monitoring. High speed machining is a machining process, where the speeds are at least 2-50 times greater than conventional machining. Titanium based alloys are difficult-to-machine materials which are widely used in various applications. Tool wear is a major problem in these materials because of their lower thermal conductivity and high hardness. In this context, this paper studies vibration signals acquired during high speed turning of Ti-6Al-4V, which is a widely used titanium based alloy for evaluating tool wear, mainly flank wear. Two types of inserts have been considered in the investigation namely an uncoated and a coated carbide insert. The experiments have been conducted with coolant and without coolant. The vibration signals have been subjected to wavelet transform (WT). The average energy of wavelet coefficients calculated from the vibration signals can be employed to monitor the tool wear in both the types of inserts investigated.

Keywords: Ti-6Al-4V, High speed turning, Wavelet transform, Vibration, Flank wear

Titanium alloys are used in various applications like aerospace, automotive, biomedical, marine, mining, railways and oil and piping industry. These alloys have a peculiar combination of properties namely high specific strength (strength-to-weight ratio), which is maintained at elevated temperatures, their fracture resistant characteristics and their exceptional resistance to corrosion. But their machinability is generally considered to be poor owing to several inherent properties of the materials. They are highly chemically reactive, have a tendency to weld to the cutting tool, which may lead to chipping and premature tool failure. According to Siekman (1955), “machining of titanium and its alloys would always be a problem, no matter what techniques are employed to transfer this metal into chips”. Komanduri and Reed (1983) have commented that “this is still true in so far as cutting tool materials are concerned”. High speed machining is an advanced machining technology that yields high productivity and product quality, while simultaneously reducing manufacturing costs. There has been increasing attention and wide applications of high speed machining in modern manufacturing in areas like aerospace, defence, automotive and die and mold making industries. Depending on the work-piece and tool materials and tool life requirements, the cutting speeds used in high speed machining can be as high as 2-50 times higher than those employed in conventional machining. One of the major problems during machining of titanium alloys at high speeds is the high cutting temperatures and the rapid tool wear. Some of the machining characteristics, which cause tool wear include – poor thermal conductivity, which causes heat concentration on the cutting edge and tool face, strong chemical reactivity with the cutting tool material at tool operating temperatures, the shear strains induced in the chip are not uniform and are localized in a narrow band that form serrated chips, the contact length between the chip and tool is extremely short and serrated chips create fluctuations in the cutting force.

One of the significant phenomena during machining is cutting vibrations, which significantly affect the machining process and quality (dimension and tolerances) of the final machined products. Titanium based alloys during machining pose lot of problems which include formation of segmented chip (saw-tooth chip), which is due to the growth of cracks, adiabatic shear band formation, which occurs due to predominance of strain hardening over thermal softening and the difficulty of dislocation.

*Corresponding author (E-mail: srinivasapai@rediffmail.com)
motion through the microstructure. This segmented chip leads to variation in chip thickness.

Cutting vibrations is a major problem during machining of titanium based alloys, because of its characteristics like low elastic modulus, which allow deflection of slender work-piece under tool pressure, causing its deflection and moving away from the cutting tool. When the cutting edge moves forward, the work-piece springs back. This leads to deflection, vibration and chatter thereby causing tolerance problems. The cutting vibrations contain information related to the machining process. This vibration is superimposed on other vibrations, because of a dynamic interaction between the tool and the machining process. The vibration signals can be used for in-process diagnosis of many critical machining problems, including tool wear. Several research efforts have been made regarding use of vibration signals for monitoring the condition of the cutting tool. According to Fang et al., research on cutting vibrations generated in machining has focused on certain aspects which include: (i) developing various vibration theory-based or cutting-experiment based, dynamics models to predict stability and chatter in machining, (ii) developing a variety of sensors to detect and measure cutting vibrations, (iii) applying a variety of signal processing techniques to analyze and process vibration signals and (iv) using the cutting vibration signals for monitoring the condition of the cutting tool.

This work is concerned with the (iii) and (iv) aspects namely using a relatively new signal processing technique called wavelet transform (WT) for processing the vibration signals and using the features extracted from the vibration signals, to monitor the condition of the cutting tool.

Experimental Procedure

Work material

High speed turning experiments were performed on a high speed turning centre (HMT Make Stalion 100 SU) with a speed range of 100-3500 rpm, on commercially available Ti-6Al-4V alloy. The work material has the following chemical compositions in percentage of weight: Al – 6.02%, Cr – 0.03%, Fe – 0.13%, Mn – 0.04%, V – 3.85%, Ti – 89.93%.

Tool inserts and measurement of flank wear

Experiments were carried out on two types of inserts: (i) uncoated carbide insert and (ii) coated carbide insert. The uncoated carbide insert is 883 with MR4 chip breaker (SECO make) and the coated carbide insert is TP 2500 (SECO make), which makes use of Duratomic® coating technology for applying aluminium oxide coating. The specifications of the inserts are CNMG 12 04 08, which is flat faced and rhomboidal in shape with back and side rake angle of -6°, end cutting angle of 5° and tool nose radius of 0.8 mm. The tool holder used is PCLNL 2020 K12 (SECO make).

The flank wear experienced by the inserts were measured using Mitutoyo make Tool makers' microscope (TM 505/510) with a magnification of 15x, with provision for measurement using micrometers in X and Y direction with a least count of 0.005 mm. The flank wear was measured after every cut (length of cut was 20 mm for uncoated carbide insert and 40 mm for coated carbide insert).

Cutting conditions

Since the focus of this work has been a comparison between vibration signals and flank wear with uncoated and coated carbide inserts, with and without coolant, experiments have been conducted at one speed, feed and depth of cut namely 150 m/min, 0.15 mm/rev and 0.8 mm, respectively. This is considered as lower speed and feed in the complete scheme of experimentation (experiments with higher speeds and feeds will be carried out) and depth of cut is equal to the nose radius of the inserts used. Experiments have been conducted with and without coolant. The coolant used was water-based mineral oil (Castrol Cool Edge B1) and was used in flooded condition.

Measurement and processing of cutting vibration signals

The cutting vibration signals were measured using a Model 65-10 Isotron® triaxial accelerometer (Meggitt make). The accelerometer has been fastened to the tool holder using cellophane tape, as close to the cutting zone as possible during the turning operation. The tool overhang length was 50 mm. The sensitivity of the accelerometer is 10 mV/g (±15%) and measurement range is ±10 g pk. The
accelerometer sensed the vibration signals in the x, y and z directions, i.e., depth of cut, speed and feed directions, respectively. The signal along the cutting speed direction (v_y) is more sensitive to the flank wear and other machining phenomena during turning and hence has been considered for evaluation. The sensed vibration signals, at a sampling frequency of 10 kHz were sent to a DNA-PPCx, PowerDNA cube (UEI make). The conditioned signal is finally sent to a PC (or laptop) with LABVIEW based display software (.vi) for display and storage. The vibration signal data is stored in a notepad file for further processing and analysis.

The collected vibration signals have been subjected to both time and time-frequency domain (WT) analysis. In the time domain analysis, the RMS value of vibration signals was calculated for each cut (experiment). The advantage of using RMS is that it gives positive values of the vibration amplitude.

DWT was performed on the vibration signals in the time-frequency domain, not only for analyzing the amplitude of vibration signals at the natural frequency of the tool holder, but also for extracting coefficients, which are sensitive to tool flank wear.

Results and Discussion

Tool wear

The flank wear is measured at the end of every cut using tool makers’ microscope. VB_{max} has been considered for evaluation of flank wear. A value of 0.4 mm has been considered as the limiting value as per ISO 3685.1977 standard. In case of coated carbide insert, turning was carried out till the limiting value and each cut was of 40 mm, whereas in case of uncoated carbide insert, turning was carried out till 0.31 mm which was achieved in 45 cuts, each of 20 mm. Figure 1(a) and (b) shows the variation of flank wear with number of cuts for coated and uncoated carbide inserts. The results for only last 10 cuts have been shown for comparison. All the tools have not been subjected to the same cutting time/number of cuts.

The flank wear increases gradually with cutting time in case of uncoated carbide insert, whereas in case of coated insert, it is almost uniform. Coated carbide insert was found to reach higher flank wear, when compared to uncoated carbide insert. A typical three stage pattern of wear can be observed – initial, normal and abnormal beyond 0.4 mm, as reported by Jawaid et al., when titanium alloy was machined using coated and uncoated carbide tools. This also establishes the superiority of straight tungsten carbide cutting tools in machining titanium alloys, as reviewed by Ezugwu.

Figure 2(a) and (b) shows the variation of flank wear with number of cuts for coated and uncoated carbide insert with coolant. The variation of flank wear with number of cuts, using coolant is almost similar when compared to that without the use of coolant. The use of coolant has definitely reduced the magnitude of flank wear that can be reached at the considered, speed, feed and depth of cut. The effect of coolant is more significant when using coated carbide insert, than when using an uncoated carbide insert, where the difference in magnitude is not very significant. This can be attributed to the difference in the mechanism of tool wear, which is more severe for coated carbide inserts. The coolant is more effective, if it penetrates into the tool-chip and tool-work-piece interfaces during the cutting process.

Cutting vibration

Figure 3(a) and (b) shows the variation of the vibration amplitude in the depth of cut direction (v_x), cutting speed direction (v_y) and feed direction (v_z) with number of cuts for coated and uncoated carbide inserts.

A comparison of figures shows that the vibration amplitudes have significantly higher values in case of coated inserts. The vibration amplitude in cutting
speed direction is significantly higher in both cases, thereby making it sensitive to the variation of flank wear on the insert with increasing cutting time. In case of coated inserts, the vibration amplitudes in other two directions namely $v_x$ and $v_z$ do not show much variation, whereas in case of uncoated insert, $v_x$ is less significant, with less variation, whereas $v_z$ shows sensitivity similar to $v_y$. A similar observation was made by Fang et al.\textsuperscript{4} in connection with tool edge wear studies during machining Inconel 718. This variation in the behavior of the vibration amplitudes with flank wear can be attributed not only to the initial condition of the tool edge (which is relatively sharp in case of uncoated insert and has a significant edge radius in case of coated insert) but also to the behavior of the flank wear as it develops on the tool. Development of flank wear is more severe in case of coated insert, when compared to uncoated insert. Vibration is significant during machining of titanium alloys, because of significant relative motion between tool and work-piece, which causes self-excited vibrations, leading to generation of cyclic forces and thereby chatter. This causes waviness of the surface, which may lead to further variation of chip thickness and forces, leading to increased vibration\textsuperscript{6}.

Figure 4(a) and (b) shows the variation of the vibration amplitude in the depth of cut direction ($v_x$), cutting speed direction ($v_y$) and feed direction ($v_z$) with number of cuts for coated and uncoated carbide inserts with coolant. As in the previous cases vibration amplitude in cutting speed direction is significantly higher, when compared to other two directions. With regard to uncoated carbide insert, the difference is not much significant between the three vibration amplitudes, when compared to coated inserts as before. Except for variation in the vibration amplitude values, there has not been a significant

![Fig. 2 – Variation of flank wear with number of cuts (a) coated carbide insert with coolant and (b) uncoated carbide insert with coolant](image)

![Fig. 3 – Variation of vibration amplitude in x, y and z directions with number of cuts (a) coated carbide insert and (b) uncoated carbide insert](image)

![Fig. 4 – Variation of vibration amplitude in x, y and z directions with number of cuts (a) coated carbide insert with coolant and (b) uncoated carbide insert with coolant](image)
effect of coolant on the cutting vibrations generated during turning. In fact the average vibration amplitude values are higher with coolant, than without coolant.

As observed by Lee et al.\textsuperscript{12}, vibration signals generated during machining carries lot of information, it is a formidable challenge for researchers to isolate and characterize only those specific signatures relevant for the diagnosis of a particular condition. To a certain extent to overcome this limitation, wavelet transform a well known signal processing tool has been used for the analysis of the cutting vibration signals.

**Wavelet transform**

Wavelet transform is a relatively new signal processing technique, which can overcome the limitations of time domain and frequency domain analysis. Conventional Fourier transform, which is a frequency domain technique, does not provide enough information when used on non-stationary signals. It determines only the frequency components, but not their location in time. Wavelet transform (WT) enables analysis of signals in both time and frequency domains simultaneously using multiple windows of different durations, which allows dilation and compression of the signal and its different features can be extracted\textsuperscript{13}. WT is capable of compressing or denoising a signal without appreciable degradation. It is generally a mathematical function that multiplies the signal during all its length, with elongated and compressed versions of a mother wavelet that satisfies

\[
\int_{-\infty}^{\infty} \psi(t) dt = 0 \quad \ldots (1)
\]

The translation and scaling operations on \( \psi(t) \) creates a family of functions as

\[
\psi_{a,b}(t) = \frac{1}{\sqrt{a}} \psi \left( \frac{t-b}{a} \right) \quad \ldots (2)
\]

where the parameter \( a \) is a scaling factor and stretches or compresses the mother wavelet. The parameter \( b \) is translation, which simply shifts a wavelet and so delays or advances the time at which it is activated. The factor \( \sqrt{a} \) is used to ensure that the energy of the scaled and translated versions is same as the mother wavelet\textsuperscript{4}. The multi-resolution formulation by WT is designed to represent signals in finer and finer details. This can be implemented using discrete wavelet transform (DWT). In the multi-resolution analysis, a pair of high pass and low pass filters is used to process an incoming signal. The output from the low pass filter represents the “approximations” of the signal and that from the high pass filter represent the “details”. The approximations can be further processed by another pair of high pass and low pass filters with the half of the previous cut off frequency to generate further “approximations” and “details”. This can be carried to the extent of desired information. After the multi-resolution decomposition, the original signal can be represented as the union of the last “approximations” and all “details” from all levels of decomposition\textsuperscript{14}.

The discrete wavelet transform uses scale and position values based on powers of two (dyadic scales and positions) and makes the analysis more efficient and accurate. The discretization of the time and scale parameters are done as:

\[
a = a_0^m \quad \ldots (3)
\]

\[
b = n b_0 \quad \ldots (4)
\]

where \( m \) and \( n \) are integers.

The family of wavelets is given by

\[
\psi_{m,n}(t) = a_0^{-m/2} \psi \left( a_0^{-m} t - nb_0 \right) \quad \ldots (5)
\]

resulting in a DWT of the form given by

\[
DWT_F (m,n) = \left< f, \psi_{m,n} \right> = a_0^{-m/2} \int_{-\infty}^{\infty} f(t) \psi \left( a_0^{-m} t - nb_0 \right) \quad \ldots (6)
\]

**Wavelet analysis of the cutting vibration signals**

In order to evaluate the cutting vibration signals collected using a sensitive accelerometer, the signals were subjected to DWT analysis. DWT was carried out using Daubechies 8 (db 8) mother wavelet. This mother wavelet has been selected after a thorough literature survey and the number of levels of decomposition has been selected as 5 by trial and error\textsuperscript{3}. Figure 5(a) and (b) shows the multi-resolution decomposition of cutting vibration signals for coated carbide insert, when the tool is less worn (0.295 mm) and fully worn out (0.4 mm) respectively. The results are based on DWT of the cutting vibration signals, reconstruction of the signal and then subjecting the reconstructed signal to FFT analysis. Similarly Fig. 6(a) and (b) shows the multi-
resolution decomposition of cutting vibration signals for uncoated carbide insert for 0.2 and 0.295 mm flank wear.

With respect to use of coated inserts for turning operation, there is a peak, showing a substantial increase in the vibration amplitude at around 3 kHz, corresponding to the natural frequency of the tool holder which is around 3.1 kHz, for a tool overhang length of 60 mm, with increase in tool wear. Similar observations were made by Fang et al. while analyzing vibration signals during high speed machining of Inconel 718, where a comparison of wavelet based denoising techniques was carried out. For uncoated insert, with increase in tool wear, there is a substantial decrease in the vibration amplitude. To a certain extent this phenomenon can be explained by the observations made by Taglia et al. (1976) cited in Lee et al. According to them, there was change in the vibration energy content of the power spectrum in different frequency bands. There is no regular correlation between the progress of tool wear and the change of the total spectrum power. However, spectrum power in certain narrow bands showed strong relationship to tool wear. Also they observed that the frequency band which is sensitive to tool wear started to decrease rapidly as the cutting edge developed excessive wear.

Similar investigations were carried out using coolant. Figure 7(a) and (b) shows the results for coated carbide insert for two states of tool wear for 0.205 and 0.31 mm flank wear. Figure 8(a) and (b) shows the results for uncoated carbide insert for two states of tool wear for 0.205 and 0.27 mm flank wear.

With regard to use of coolant, the trend is similar to that obtained without the coolant for both types of inserts. In case of coated insert, the increase in vibration amplitude is almost 8 times for the fully

Fig. 5 – Multi-resolution decomposition of cutting vibrations $v_y$ for coated carbide insert (a) 0.295 and (b) 0.4 mm flank wear

Fig. 6 – Multi-resolution decomposition of cutting vibrations $v_y$ for uncoated carbide insert (a) 0.2 and (b) 0.295 mm flank wear
worn case, compared to less worn. Also in case of uncoated insert, the decrease in vibration amplitude is not very substantial.

**Energy of wavelet coefficients**

To further understand the use of wavelets for flank wear detection and monitoring, the average energy of the detailed wavelet coefficients have been extracted from the vibration signal. Only the detailed coefficients have been considered for analysis, as they represent the high frequency components.

Let the detailed coefficient vectors be denoted as $\mathbf{d}_j$ where $j=1,2,\ldots$ are the number of levels or the scale of decomposition of the signal and represents the individual coefficient values. The average energy of the detailed coefficients is given by

$$E_j = \frac{1}{T_j} \sum_{k=1}^{T_j} d_j^2,$$  \hspace{1cm} \cdots \hspace{1cm} (7)

Where $T_j$ is the number of coefficients in each scale. The value of $T_j$ is different for different scales, since the time spacing of wavelet coefficients varies with the resolution $j$.

Figure 9(a) and (b) shows the variation of average energy of detailed wavelet coefficients for all the five levels represented as $cD1$, $cD2$, $cD3$, $cD4$ and $cD5$, in the order of decreasing frequency for coated and uncoated carbide inserts. The results have been presented only for $v_y$ vibration component, as it is the sensitive component to variation in tool wear.

$cD1$ corresponding to average energy of detailed coefficient at level 1 is dominant in both cases, with maximum values, when compared to the energy of detailed coefficients at other levels namely $cD2$, $cD3$, $cD4$ and $cD5$, which almost have energy values in the same range. This detailed level at 1 corresponds to a frequency range of 2.5-4.0 kHz. This finding establishes the results obtained from multi-resolution decomposition, where there was variation in the amplitude at a frequency value of around 3 kHz. Also the variation of average energy of detailed

![Fig. 7 – Multi-resolution decomposition of cutting vibrations $v_y$ for coated carbide insert (a) 0.205 and (b) 0.31 mm flank wear with coolant](image)

![Fig. 8 – Multi-resolution decomposition of cutting vibrations $v_y$ for uncoated carbide insert (a) 0.205 and (b) 0.27 mm flank wear with coolant](image)
The coefficient cD1 is very similar to the variation of amplitude of \( v_y \) with time (flank wear).

The values of the average energy of detailed coefficients in case of coated carbide inserts are several times higher than that for uncoated carbide insert. This can be attributed to increased flank wear with coated insert having a larger edge radius, leading to increased vibration amplitude. A similar observation was made by Fang et al.\(^4\).

Figure 10(a) and (b) shows the variation of average energy of detailed wavelet coefficients for all the five levels represented as cD1, cD2, cD3, cD4 and cD5, in the order of decreasing frequency for coated and uncoated carbide inserts with coolant.

The value of the energy of cD1 coefficients is higher when compared to other level coefficients. In case of coated carbide insert, cD1 and cD2 are significant, when compared to other level coefficients, which are almost insignificant. In case of uncoated carbide insert, a similar behavior is exhibited, with cD1 and cD2 energy values being almost closer and exhibiting a similar trend and the remaining energy values being significantly lesser and shows a similar trend. Overall the energy values of the detailed wavelet coefficients are lesser for experiments conducted with coolant, than without.

Thus cD1 is a significant and sensitive feature, which can be used effectively for monitoring flank wear during high speed turning of Ti-6Al-4V alloy, both with or without coolant. Irrespective of the type of insert used and machining with or without coolant, cD1 is sensitive to changes in tool flank wear, which is an advantage in tool wear monitoring applications. Figure 11 (a)-(d) shows the tool wear for experiments...
with coated and uncoated carbide inserts with and without coolant respectively. These figures correspond to the final flank wear state reached on the insert.

Conclusions
In the present study, four experiments have been carried out with coated and uncoated carbide inserts at 150 m/min cutting speed, 0.15 mm/rev feed rate and 0.8 mm depth of cut on high speed turning of Ti-6Al-4V alloy, with and without coolant. Cutting vibration signals were measured online in three directions (v_x, v_y, and v_z) and flank wear was measured offline. The measured vibration signals were subjected to DWT analysis. The following conclusions can be drawn from this work:

(i) Flank wear is more severe in coated carbide inserts, when compared to uncoated carbide insert. Hence uncoated carbide insert can be effectively used for high speed turning of Ti-6Al-4V alloy, which is a difficult to machine material.

(ii) Cutting vibration signals are sensitive to variation in flank wear on the tool and can be used effectively for tool wear monitoring. This is true for both with and without coolant conditions.

(iii) Cutting vibration signals in cutting speed direction (v_y) is more sensitive when compared to feed rate (v_z) and depth of cut (v_x) directions.

(iv) DWT analysis of vibration signals has been effective in showing the variation in vibration amplitude at the tool holder natural frequency, with variation in flank wear. Similar results were obtained with and without coolant, with a quantitative difference.

(v) The average energy of the detailed wavelet coefficients is sensitive to variation in flank wear.

(vi) Average energy of detailed wavelet coefficients at the first level (cD1) is the most sensitive when compared to other detailed wavelet coefficients and can be effectively used to evaluate flank wear in high speed turning with both coated and uncoated carbide inserts, with and without coolant.

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References