Behaviour of cutting tool vibrations with the progress of tool wear in turning hardened AISI 52100 steel: An approach to tool condition monitoring system

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Abstract. Hardened Steel-AISI52100 is widely used in aerospace, automotive, railways components, bearing and dies industry etc. The high hardness of such material makes it difficult to machine. When turning such materials, the cutting tool is subjected to heavy mechanical loads and hence creates vibration throughout the process, which directly affects the surface quality of a product, provoke a high rate of tool wear lowering tool life. In this context, in this work, the changing behaviour of vibration signals varying with cutting parameters and with progress of tool wear is reported during turning of hardened AISI 52100 steel. The cutting tool vibration signals in the feed, radial and tangential directions were measured using piezoelectric tri-axial accelerometer. A multiple regression models for vibration signals have been developed to understand the interrelationship between cutting tool vibrations with the progress tool flank wear. The analysis of the result revealed existence of interrelationship between cutting tool vibrations and the progress of tool flank wear irrespective of the cutting conditions selected in the present study. However, amongst the vibrations measured in feed, radial, and tangential directions, it has been observed that cutting tool vibrations in radial direction are getting more affected with the progress of the tool wear. However, all the three vibration signals found to increase drastically when catastrophic failure of the tool occurred. This study suggested that tool wear could be examined reliably by monitoring the cutting tool vibrations.

Keywords: Hard turning, Vibration, Tool wear, FFT analyzer, Tool condition monitoring

1. Introduction

Hardened steels, generally has a hardness range of 45 -70 HRC, are being extensively used in aerospace, automotive industries, which include various part such as the shaft, bearings, camshaft gears and landing gear, engine attachment fittings, clutch sleeve and constant velocity joints etc. Various machining processes such as diamond grinding, electric-discharge machining etc are used for machining of hardened steel. The limitations of these processes are low surface finish and material removal rate; times consuming and high tool wear rate. Hence, to overcome these limitations, hardened materials are turned by using super-hard single point cutting tools and the process is called hard turning [1-5].

Now a day, hard turning is being popular in metal cutting industry as an alternative to the expensive and low productive grinding operations which contribute up to 50% of the final cost of a
machined part. Hard turning is usually performed without coolant and thus, the problem of storage, handling and disposal of cutting fluid is eliminated [6-7]. At the same time, it also favours the health of operators and eliminates the environmental issues. Hard turning without coolant can reduce up to 90% of the final cost of a machined part [8]. Hence hard turning has attracted considerable interest in aerospace, automotive, bearing and die industry. However some of the researchers favours the use of coolant [9-10].

Hardened steels are also referred as difficult-to-cut materials. Developments in tool materials in the last few years have made it possible to cut materials in their hardened state. Polycrystalline diamond (PCD), Polycrystalline cubic boron nitride (PCBN), and ceramics are the commonly used in tools for hardened steel turning applications due to its high hardness, wear resistance and thermal stability. Recently, cemented carbide tools with the different coating are being used as an economical alternative to costly PCBN and ceramics tools. The performance of carbide tools is further increased by the application of different layers of coating on the surface of the tool. The most frequently used coatings are PVD applied TiAlN, CVD applied Al2O3, TiC and combined CVD and PVD applied TiN, TiCN, Al2O3[3-4, 11-13].

Chinchanikar and Choudhury [4] investigated the effect of tool wear and cutting parameters on cutting forces using multi-layer coated TiCN/Al2O3/TiN carbide tool, during turning of AISI4340 alloy for two levels of workpiece hardness (35 and 45 HRC). The experimental results showed that the cutting forces induced due to flank wear alone get affected largely by tool wear and to some extent depends on the cutting condition, especially the depth of cut. Mozammel et al. [13] suggested a laser tempering based hard turning process using low-cost ceramic tool instead of costly CBN tool. The Author concluded that higher material removal rates are possible in the laser tempering based turning process with slightly scarifying surface finish.

In hard turning, the cutting tool is subjected to heavy mechanical loads and hence creates vibration throughout the process. In turning process, three types of vibration are observed, free, forced and self-excited vibrations [14]. The disadvantages of having tool vibration during turning of hard materials are poor surface quality of product, high rate of tool wear, reduction in tool life and create unpleasant noise in the working environment. Vibration can induce in turning due to lack of dynamic stiffness/rigidity of the machine tool system consisting tool, tool holder, workpiece and machine tool. The engagement and disengagement of cutting tool during machining play a notable role in the vibration produced. Non-homogeneity and properties variations in the workpiece material also increase the vibration in metal cutting process [15]. Hence, the composition of the machining vibration is complicated and need to be addressed properly.

Vibrations involved in metal cutting process are complex and stochastic in nature which contains number of sine waves of certain amplitudes and frequencies. The transformation of the measured signals from time to frequency domain is achieved by Fast Fourier Transform (FFT) analyzer. Abouelatta et al. [16] analyzed vibration signals FFT analyzer and developed regression models to correlate surface roughness with cutting tool vibration. The tool vibration was measured in feed and radial directions using a tri-axial accelerometer mounted near to the tip and connected to the FFT analyzer. R² values of the proposed models were fairly accurate. The experimental result of their study suggested that, consideration of tool vibration and cutting force together increases the accuracy of a model. Similar observation also reported by Kirby et al.[17]. In another study, Hessainia et al. [18] also investigated the combined effects of cutting parameters and tool vibration on surface roughness while turning 42CrMo4 hardened steel using Al2O3/TiC coated ceramic tool. Their study indicates that the feed rate is the dominant factor affecting the surface roughness, whereas vibrations on both tangential and radial directions have a low effect on it.

Bhuiyan et al. [19] experimentally investigated chip formation, tool wear and surface roughness under different cutting conditions using vibration signature during turning of ASSAB-705 steel. The results of their study revealed that vibration components can effectively respond to the different occurrences in turning including tool wear and surface roughness. The amplitude of vibration components Vx, Vy and Vz increased with the increase of feed rate, depth of cut and cutting speed
respectively. Upadhyay et al. [20] investigated acceleration amplitude of vibration in axial, radial and tangential directions for in-process prediction of surface roughness during turning of Ti-6Al-4V alloy. The Pearson correlation coefficient analysis is performed to understand the degree of association of cutting speed, depth of cut and feed rate with surface roughness. The results of their study showed that the feed is the most significant parameter on surface roughness followed by acceleration in a radial direction.

Alonso et al. [21] reported singular spectrum analysis and cluster analysis techniques for analyzing vibration signals capture during turning. The results showed that the vibration signals provide useful information about tool condition in certain frequency bandwidth. The flanks wear related information in the vibration signals contained in the high frequencies and in only certain low-frequency components. Chen et al. [22] developed logistic regression model by using vibration signals and presented a new reliability estimation approach to cutting tool. The characteristics of measured parameters have been studied using signal processing techniques and integrated in a logistic regression model to evaluate reliability of lathe cutting tools. Their study of analysis concluded that that the reliability indices and failure time of the tool can be accurately assessed by using the obtained model.

Bala et al. [23], evaluated the performance of uncoated carbide tool using displacement amplitude of cutting tool by considering the cutting parameters and different levels in work material hardness during face turning of AISI 4140 steel. They developed multiple linear regression models and coefficient of regression observed was near to 0.9, which indicated that the developed models are reliable and could be used to predict the responses within the domain of the cutting parameters. The ANOVA of their study showed that the displacement factor is influenced by the cutting speed and the workpiece hardness. Gonzalez et al. [24], analyzed vibration signals for different tool wear state using RMS and FFT spectral analysis. They observed from FFT analysis that acceleration level at some frequencies with increasing tool flank wear. They also observed that signal amplitude is influenced by workpiece diameter. Acceleration amplitude decreases in frequency spectra with decreases in workpiece diameter for constant cutting parameters.

From the literature it can be seen that various efforts have been made to effectively monitor the tool wear and effect of cutting parameters on tool wear and cutting tool vibrations. However, very few efforts have been made in understanding the behavior of cutting tool vibrations with the progress of tool wear. In the present work, changing behavior of cutting tool vibrations with the progress of tool wear is studied with a view to develop tool condition monitoring system during turning of hardened AISI 52100 steel.

2. Experimental setup
2.1. Preparation of workpiece material
The material used in this study is hardened AISI52100 alloy steel. This is widely used for many applications such as bearings, gears, chain parts and spindle, heavy vehicle crankshaft and aircraft landing gears. The workpiece is the form of cylindrical bar with diameter 62mm and 450 mm in length. The required hardness is achieved by hardening process. The rod is heated at 850°C then quenching in oil, then tempering around at 200°C for two hours, which yield a tempered martensitic microstructure. After heat treatment process a small circular piece is cut in order to conduct hardness test. The hardness of workpiece is obtained as 54±2 HRC. The chemical composition is obtained by testing the material in laboratory before hardening and is found as: 1.03% C, 1.38% Cr, 0.35% Mn, 0.16% Si, 0.002% P, 0.005% S and balance Fe. The hardened steel rods has been trued, centered, and cleaned at a moderate machining speed and feed before conducting experiments.

2.2. Cutting tool and holder
The cutting tool is selected on the basis of workpiece material; tool insert properties of such as hardness, toughness and wear resistance, tool manufacturer recommendation and the cost of cutting tool. The coated carbide insert of International Organization for Standardization (ISO) of designation CNMG120408-MF5 with TH1000 grade. This grade is very hard, super fine grained substrate with PVD coating TiSiN-TiAlN nano-laminate. It is suitable for turning of hardened steel and also can be
used for interrupted cuts. The top coatings provide high wear resistance, maximum toughness and high chipping resistance. The tool has rhombic shape with included angle 80°, 4.8mm thickness and nose radius 0.8mm. The tool holder used is PCLNR 2525M12 (Kennametal, India) with tool geometry as follows: including angles = 80°, back rake angle = 6°, clearance angle = 5°, approach angle = 95° and nose radius =0.8 mm.

2.3. Experimental Details
The experiments are performed in dry condition on SimpleTurn5076 CNC lathe. The lathe is equipped with 7.5 kW spindle power and maximum spindle speed 2000 rpm. It has a high degree of accuracy and rigidity. The workpiece was held in three jaws and supported by centre in the tailstock. A Bruel & Kjaer 4535B001 Type 30859 tri-axial piezoelectric accelerometer with sensitivity 9.8mV/g is mounted on tool holder as close as possible to the tool insert. The accelerometer has frequency range 0.3Hz to 10 kHz and measures vibration of cutting tool in three mutually perpendicular directions, feed(Vx), radial(Vy) and tangential (Vz). The accelerometer signals are taken to Bruel and Kjaer four channel signal analyzer type LDS DACTRON and RT Pro PHOTON Dynamic Signal Analysis Software. FFT analyzer has frequency range of up to 84.2 kHz (192 k samples per second) and on accuracy within 0.01%. Analyzer is able to compute and display the result, in both time and frequency domain. Dino Lite Digital microscope model: AD4113ZTA magnification rate 200x is employed to capture images of flank wear after each pass.

![Experimental Setup](image)

**Figure 1.** Experimental Setup

3. Result analysis and discussion
For each cutting condition, responses such as vibration of a cutting tool in feed Vx, radial Vy, tangential Vz, and tool wear Vb have been recorded. In each cutting condition, a fresh cutting tool was used and machining was carried out for turning length 450mm. Then tool insert was removed and flank wear has been measured using a digital microscope. This process was repeated till the failure of the cutting tool.

| Pass no. | Tool wear Vb (mm) | Acceleration (mm/s²) |
|----------|------------------|----------------------|
|          |                  | Vx       | Vy       | Vz       |
| 1        | 0.045            | 0.0011   | 0.0039   | 0.0046   |
| 2        | 0.051            | 0.0017   | 0.0048   | 0.0044   |
| 3        | 0.052            | 0.0019   | 0.0044   | 0.0061   |
| 4        | 0.061            | 0.0034   | 0.0061   | 0.0058   |

Table 1. For cutting condition V=120m/min, f=0.3mm/rev, d=0.3mm
Table 2. For cutting condition $V=90\text{m/min}$, $f=0.2\text{mm/rev}$, $d=0.4\text{mm}$

| Pass no. | Tool wear Vb (mm) | Acceleration (mm/s²) |
|----------|-------------------|----------------------|
|          |                   | Vx       | Vy       | Vz       |
| 1        | 0.051             | 0.0051   | 0.0058   | 0.0076   |
| 2        | 0.065             | 0.0056   | 0.0065   | 0.0082   |
| 3        | 0.076             | 0.0062   | 0.0076   | 0.0087   |
| 4        | 0.079             | 0.0071   | 0.0081   | 0.0081   |
| 5        | 0.081             | 0.0073   | 0.0086   | 0.0092   |
| 6        | 0.083             | 0.0072   | 0.0084   | 0.0094   |
| 7        | 0.085             | 0.0078   | 0.0087   | 0.0087   |
| 8        | 0.090             | 0.0081   | 0.0088   | 0.0097   |
| 9        | 0.094             | 0.0079   | 0.0089   | 0.0098   |
| 10       | 0.097             | 0.0083   | 0.0071   | 0.0079   |
| 11       | 0.103             | 0.0080   | 0.0093   | 0.0099   |
| 12       | 0.115             | 0.0074   | 0.0094   | 0.0104   |
| 13       | 0.125             | 0.0084   | 0.0097   | 0.0106   |
| 14       | 0.137             | 0.0087   | 0.0103   | 0.0111   |
| 15       | 0.143             | 0.0089   | 0.0086   | 0.0121   |
| 16       | 0.156             | 0.0092   | 0.0119   | 0.0131   |
Variation in vibration signals with tool wear

The behaviour of cutting tool vibrations measured along the cutting direction (tangential), feed direction and radial direction with the progress in tool wear at different cutting conditions is discussed with a view to find the interrelationship between cutting tool vibrations and tool wear. Cutting tool vibrations acceleration amplitude measured by tri-axial piezoelectric accelerometer. From the experimental results, it can be seen that increase in flank wear with time indicates three different zones; initial breakdown zone, uniform wear zone and rapid wear rate. Cutting tool vibrations varying with the progress of tool wear also can be seen following three zones as seen for the progression of tool flank wear with cutting time.

In the initial breakdown stage, the sharp edge of the flank quickly wears out due to high initial stress and which is correctly sensed by the increase in acceleration amplitude in feed, radial and tangential directions. On the other hand, more or less uniform variation of cutting tool vibrations along the three directions and progression of the tool flank wear at a uniform rate in the second stage shows the existence of interrelationship between cutting tool vibrations and tool flank wear. It can be seen that vibrations measured in tangential direction are highest and it is obvious also as cutting energy is required in tangential direction to get material machined. The vibrations measured in feed direction are lowest and in radial directions higher than the feed direction but lower than the tangential direction. However, at higher feed rate cutting tool vibrations in feed directions has been observed to approaching and sometimes exceeding the vibrations in radial direction.

In the rapid wear out region, the cutting tool wears out at a higher rate due to increase in interface temperature and the normal pressure on the flank resulting in sub-surface plastic flow and sometimes leads to catastrophic tool failure. The amplitude of cutting tool vibrations also observed to increase rapidly with the higher rate of tool wear. However, vibrations in radial directions seen to increase more rapidly with the progress of tool flank wear as compared to cutting tool vibrations in feed and radial directions. And, when tool fails catastrophically, it has been observed that vibrations in all the three directions increased rapidly. This behaviour of vibrations with the progress of tool wear shows the existence of interrelationship and boosts up that tool wear can be monitored using behaviour of cutting tool vibrations.

Figure 2 and Figure 3 shows the changing behaviour of acceleration amplitude with the progress of flank wears at cutting speed (a) 120 m/min, feed 0.3mm and depth of cut 0.3mm (b) V=90m/min, f=0.2mm/rev, d=0.4mm respectively. Acceleration in tangential directions is observed high followed by radial and feed directions. The trends in acceleration in all directions are also found to change with the change in cutting condition. Figure 4 shows the frequency domain signals at flank wear 0.092mm. The maximum acceleration values in feed, radial and tangential directions are observed respectively as 0.0067 mm/s^2, 0.0070 mm/s^2 and 0.0087mm/s^2. With new cutting edge, maximum acceleration is observed in lower and higher frequency zone. The fluctuation in vibration frequency is observed in all directions from 160 Hz to 18 kHz. However, the band of frequency remains within a certain range. Within selected cutting parameter range, for most of the cutting condition, the maximum acceleration amplitude is observed in the frequency band of 4 kHz - 9 kHz. The drastic rise and fall in acceleration amplitude is observed because of the continuous chips hammering the sensors placed close to the insert.
Figure 2. Acceleration vs. Flank wear at $V=120m/min$, $f=0.3mm/rev$, $d=0.3mm$.

Figure 3. Acceleration vs. Flank wear at $V=90m/min$, $f=0.2mm/rev$, $d=0.4mm$.

Figure 4. (a)

Figure 4. (b)
3.2. Modeling of acceleration-wear relationship

Better understanding of characterises of wear and acceleration and their inter-relationship may be obtained by mathematical modelling. Chelladurai et al. [25] developed mathematical models to predict acceleration in cutting and feed directions considering cutting parameters and tool wear. The vibration amplitude in terms of acceleration is correlated for different levels of tool wear. Balla and Babu [23] also developed regression model to express the relationship displacement amplitude and tool wear. In the present work, based on experimental results, polynomial equations of third order have been developed to express relationship between acceleration and tool wear. Equations are developed for two cutting condition (1) \( V=120 \text{ m/min}, f=0.3\text{mm/rev} \) and \( d=0.3\text{mm} \) and (2) \( V=90\text{m/min}, f=0.2\text{mm/rev}, d=0.4\text{mm} \), considering the values of acceleration in feed, radial and tangential directions obtained at different flank wear.

For \( V=120\text{m/min}, f=0.3\text{mm/rev} \) and \( d=0.3\text{mm} \)

\[
\begin{align*}
V_x &= -0.892V_B^3 - 0.09V_B^2 + 0.187V_B - 0.005 \\
R^2 &= 0.901 \\
V_y &= 7.13V_B^3 - 1.850V_B^2 + 0.268V_B - 0.005 \\
R^2 &= 0.876 \\
V_z &= -2.14V_B^3 - 1.345V_B^2 - 0.083V_B + 0.002 \\
R^2 &= 0.902
\end{align*}
\]

For \( V=90\text{m/min}, f=0.2\text{mm/rev}, d=0.4\text{mm} \)

\[
\begin{align*}
V_x &= -2.234V_B^3 + 1.381V_B^2 - 0.087V_B + 0.003 \\
R^2 &= 0.904 \\
V_y &= 9.392V_B^3 - 2.944V_B^2 + 0.337V_B - 0.005 \\
R^2 &= 0.875 \\
V_z &= -1.26V_B^3 + 0.233V_B^2 + 0.170V_B - 0.004 \\
R^2 &= 0.895
\end{align*}
\]

Figure 5 and Figure 6 represent the variation in acceleration amplitude with for different flank wear at cutting speed (a) 120 m/min, feed 0.3mm and depth of cut 0.3mm (b) \( V=90\text{m/min}, f=0.2\text{mm/rev}, d=0.4\text{mm} \) respectively. Acceleration in tangential directions is observed high followed by radial and feed directions.
The correlation coefficient ($R^2$) is observed in most of the equations is more than 0.87. The polynomials coefficients are obtained by methods of least squares. Acceleration amplitude have been observed to be increased with the progress of tool wear and hence, the developed model can be used to predict acceleration of cutting tool considering the effect of tool wear is extremely valuable in addressing the vibration issue in the field of development of reliable tool condition monitoring system.

4. Conclusion
This paper investigated the changing behaviour of acceleration amplitude with the progress of tool wear during turning of hardened AISI52100 steel. The cutting tool vibration signals in the feed, radial and tangential directions were measured using piezoelectric tri-axial accelerometer. A multiple regression models for vibration signals have been developed to understand the interrelationship between cutting tool vibrations with the progress tool flank wear. The analysis of the result revealed the existence of interrelationship between cutting tool vibrations and the progress of tool flank wear irrespective of the cutting conditions selected in the present study. However, amongst the vibrations measured in feed, radial and tangential directions, it has been observed that cutting tool vibrations in radial direction are getting more affected by the progress of the tool wear. It has been observed that all the three vibration signals found to increase drastically due to catastrophic failure of the tool. The fluctuation in frequency is observed along three mutually perpendicular directions due to varying cutting condition, progressive increase in tool wear. However, the band of frequency remains within a certain range. The maximum acceleration amplitude is observed in frequency band of 4 kHz - 9 kHz.

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